Northern Forested Wetlands

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CHAPTER 29

Effects of Forest Management on Wetland Functions in a Sub-Boreal Swamp

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INTRODUCTION

Forested ecosystems of the upper Great Lakes represent an extremely important natural resource for the region and the nation. They are the headwaters of the largest freshwater lake system in the world and harbor some of the most productive forest lands in North America. In terms of habitat, these forested

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Table 1 Predevelopment and Current Estimate of Total Wetland Area in Michigan, Minnesota, and Wisconsin

State	Original area (circa 1780) (ha x 10^6)	Current area (circa 1980) (ha x 10^6)	% Loss (ha x 10^6)
Michigan	4.5	2.3	50
Minnesota	6.1	3.5	58
Wisconsin	3.9	2.2	54

Adapted from Dahl, T. E., Wetlands Losses in the United States 1780's to 1980's, Fish and Wildlife Service, U.S. Department of the Interior, Washington, D.C., 1990, 13 pp. With permission.

landscapes are quite diverse and include representatives of the central hardwood and northern hardwood types, boreal forests, as well as oak/pine savannas, and true prairie communities. Extensive wetlands are interspersed through these forest types and are a key component to habitat, freshwater resources, and forest product values of the region. Consequently, forested wetlands have become a focal point of national and regional environmental concern (Conservation Foundation, 1988). Typical positioning of local landform types indicates a close ecological relationship between wetlands, adjacent uplands, riparian, and lacustrine communities.

Recent surveys have shown that approximately 50 percent of the original wetland resource in the Upper Great Lakes region have been destroyed (Table 1). Within that region approximately 51 percent of the remaining wetland area is forested (Cubbage and Flather, 1993). Forest inventory data obtained by the Forest Service shows that potential wetland cover comprises a significant proportion of commercial forest land in the Upper Great Lakes region (Table 2). More than 90 percent of the land in Michigan's Upper Peninsula (4.3 x 10^6 ha) is estimated to be forested (USDA, 1968).

Table 2 Area of Forest Cover Types That Are Characteristic of Wetlands in Michigan, Minnesota, and Wisconsin

Cover type	Minnesota (ha x 10^3)	Michigan (ha x 10^3)	Wisconsin (ha x 10^3)
Balsam fir	324	246	170
Black spruce	420	208	111
White cedar	201	480	150
Tamarack	190	44	90
Elm-ash-cottonwood	288	513	502
Total wet types	1423	1490	1023
Total timberland	5494	7018	5978
Wet forest sites (%)	26	21	17

Note: Estimates are based on Forest Inventory and Analysis cover-types (Smith and Hahn, 1987, 1989; Hahn and Smith, 1987) and do not include nonproductive or nonstocked lands.

From Smith, W. B. and Hahn, J. T., Michigan's Forest Statistics, 1987: Inventory Update, General Technical Report, NC-112, USDA Forest Service, NC For. Exp. Stn., St. Paul, MN, 1989, 48 pp.; from Smith, W. B. and Hahn, J. T., Michigan's Forest Statistics, 1989: An Inventory Update, General Technical Report, NC-130, USDA Forest Service, NC For. Exp. Stn., St. Paul, MN, 1989, 48 pp.; from Hahn, J. T. and Smith, W. B., Minnesota's Forest Statistics, 1987: An Inventory Update, General Technical Report, NC-118, USDA Forest Service, NC For. Exp. Stn., St. Paul, MN, 1987, 44 pp. With permission.

A major obstacle to address regulatory and conservation policy, as well as development of "Best Management Practices" on forest wetlands in this region, is a lack of information on basic functional processes and how forest management activities affect those processes. The relative importance of forest wetlands to water quality of the adjoining Great Lakes, groundwater hydrology, wildlife habitat, and overall biological diversity of the region is clear. However, it is difficult to quantify the cumulative impacts of management activities with the present information available. It is also evident from the spatial distribution of landforms within the region that forest wetlands are the focal point from which to address these issues.

The principal objective of this study was to evaluate the effect of silvicultural practices on ecosystem dynamics and plant community production in a forested wetland in the Upper Peninsula of Michigan. Specific objectives of the study were to (1) evaluate timber harvesting and site preparation impacts on wetland water quality and hydrology, soil nutrients, and vegetation, and (2) assess wetland recovery following these forest management practices. The following discussion summarizes results obtained from 5 years of monitoring soil, vegetation, and water responses to the forest management treatments.

APPROACH

Study Site

The study was conducted in the central Upper Peninsula of Michigan (46° 10′N, 86°43′N) located adjacent to the West Branch River, the outlet for West Branch Lake (Figure 1). The site is located within the Sturgeon River watershed of the Lake Michigan drainage basin. The geological setting of the site is within the Wetmore Outwash Plain, which is underlain by middle ordovician limestone (Trenton Limestone). The drift thickness in the vicinity of the site ranges from 30 to 75 m. Overstory vegetation consists primarily of black spruce (*Picea mariana* [Miller] BSP), tamarack (*Larix laricina* [Du Roi] K. Kock), and jack pine (*Pinus banksiana* [Lamb.]). The dominant species in the shrub layer are *Vaccinium* spp., leatherleaf (*Chameadaphne calyculata* [L.] Moench), and labrador tea (*Ledum groenlandicum* [Oeder.]). The surface vegetation is dominated by *Sphagnum* spp., with minor components of starflower (*Trientalis borealis* [Raf.]), golden rod (*Solidago* spp.), bunchberry (*Cornus canadensis* [L.]), and *Carex* spp.

The soil has been mapped as a histic mineral soil in the Kinross series (Histic endoaquod, sandy, mixed, frigid), which is poorly drained with a fine sand solum overlain by a 5 to 15 cm organic horizon of mostly decomposed *sphagnum*. The soil is uniform to a depth of 2.5 m, is acid throughout, and has a clay content of less than 2 percent (Table 3). The water table is at or near the surface through much of the growing season. The study site is located within Region III — Luce district ecosystem as defined by Albert et al. (1986), which is characterized by a mean growing season length of 144 d, total annual precipitation of 849 mm, mean

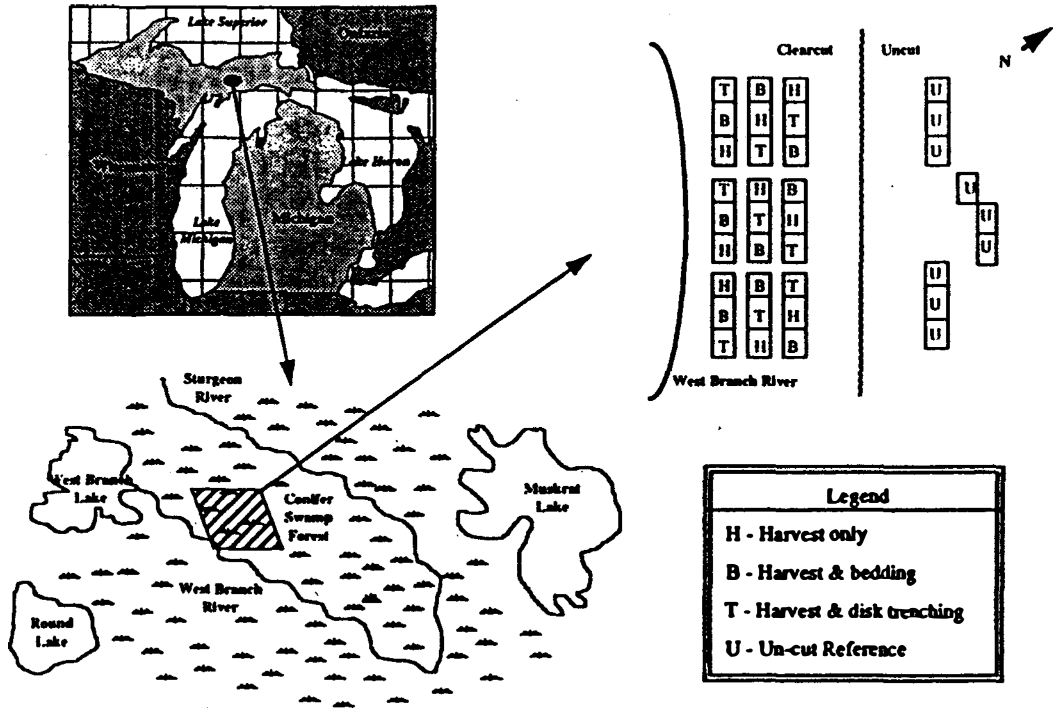

Figure 1 Location of the study site within the Great Lakes basin and the experimental layout.

annual temperature of 5°C, and a mean growing season (May to September) temperature of 14.4°C.

A 14.5 ha parcel of the study site was whole-tree harvested (WTH) in July 1988 using feller-bunchers. Tree bundles were skidded to a landing where they were sorted into fiber and fuel product classes. Fuel wood was chipped, while the fiber wood was delimbed and topped at the landing, and bucked into pulpwood bolts. This harvest regime resulted in all tree stems approximately 5 cm and greater being removed from the site.

After the WTH was completed, two site preparation treatments were randomly applied within the three Latin squares. The bedded treatment was installed using an Eden Relief bedding plow pulled by a John Deere 648 skidder, equipped with high flotation tires. The plow disks and mounds the soil, which results in an elevated planting bed flanked by two furrows. A single pass of the bedding plow tilled a strip approximately 3-m wide, creating an elevated 1-m wide planting bed. This prescription resulted in 100 percent tillage of the soil surface (Figure 2). The disk trench treatment consisted of a single pass of a TTS-disk trencher, which produced an alternating pattern of furrows and berms. The treatment resulted in approximately 50 percent tillage of the soil surface, with the intertrench area relatively undisturbed. Both the bed and trench treatments were sprayed with herbicide (glyphosate, 4.7 L ha^{-1}) to control competing vegetation. Three blocks were also established in an uncut stand adjacent to the harvested area to serve as a control to original soil conditions. The overall design is shown in Figure 1. Jack pine seedlings were planted immediately after the site was prepared.

Soil, water, and vegetation were monitored for 5 years following harvesting. Detailed descriptions of the initial instrumentation for the soil and water mea-

Table 3 Selected Morphological, Chemical, and Physical Properties for the Kinross Soil Sampled on the Study Site

Horizon	Depth range (cm)	Clay (%)	Silt (%)	Sand (%)	pH	Ext. acidity (meq 100 cm^{-3})	Ca (meq 100 cm^{-3})	K (meq 100 cm^{-3})
E	0–20	<0.1	4.2	95.8	4.3	17.2	0.53	0.16
Bs	20–44	<0.1	1.5	98.5	4.7	20.8	0.08	0.01
BC	44–72	<0.1	1.7	98.3	5.0	14.5	0.10	0.01
C	72–100	<0.1	0.7	99.3	4.3	9.5	0.07	0.01

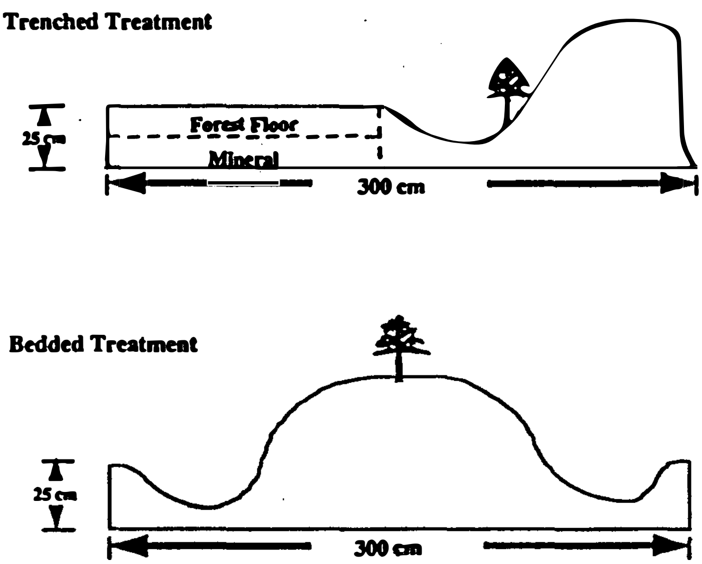

Figure 2 Cross-section profile of the trenched and bedded site preparation treatments. The planting line is indicated by the tree in the figure. (Figure is not to scale.)

surements were provided by Trettin (1992). Subsequent recovery studies were described by McLaughlin et al. (1994, 1996). Studies on the initial seedling survival were described by Cho (1990), and subsequent studies of seedling productivity and plant community response have been developed by Gale et al. (submitted). Table 4 provides a summary of the methods used in the results discussed here. These results are based on sampling designed to assess treatment response on a whole-soil basis. In the first 2 years after the timber harvest treatments, all site preparation treatments were monitored. However, by this time the trench treatment was not considered a viable silvicultural treatment on these sites, and only the WTH and the bed treatments were further sampled.

RESULTS AND DISCUSSION

Organic Matter Decomposition

Organic matter decomposition is an important process that affects ecosystem functions in many northern wetlands. The cotton strip assay, which measures cotton tensile strength loss (CTSL), provides an effective index of organic matter

Table 4 Variables and Methods for Estimating Soil, Water, and Vegetation Parameters

Measurement	Method	Sample location	Sample period	Reference
		Soil characteristics		
Chemical properties:				
Nitrogen	Kjeldahl	0–25 cm	year 1, 2	Bremner and Mulvaney, 1982
Ca, Mg, K	NH_4O AC ext.	0–25 cm	year 1, 2	Thomas, 1982
Ext. Acid and Al	KCl ext.	0–25 cm	year 1, 2	Bamhisel and Bertsch, 1982
pH	direct, buffered	0–25 cm	annual	McLean, 1982
Redox	rod	0–75 cm	year 1, 2	Camell and Anderson, 1986
	electrode	15 cm	year 3, 4	Faulkner et al., 1989
Physical properties:				
Texture	hydrometer	O, A, B, C	pretreatment	Gee and Bauder, 1986
Bulk density	core	O, A, B, C	year 1	Blake and Hartge, 1986
Soil temp.	probe	7.5, 0.5, 25 cm	year 1, 2	Taylor and Jackson, 1986
		Hydrological properties		
Water table depth	well	2 m	monthly	Faulkner et al., 1989
Soil water	lysimeters	15, 30 cm	monthly	
		Vegetation		
Seedling production	inventory direct meas.	veg. strata	year 1, 3, 4	Chatarpawl et al., 1985
Vascular species composition	density plots	veg. strata	year 4	Chatarpawl et al., 1985

Note: Soils and water were sampled 1988–1993; other parameters as noted.

decomposition by employing a uniform substrate (cellulose) whose degradation is related to environmental factors and soil conditions (French, 1988; Hill et al., 1988). CTSL was significantly different among the silvicultural treatments (Figure 3). Both the harvesting and site preparation treatments exhibited greater cellulose decay as compared to the uncut plots, with the greatest CTSL occurring after bedding. This pattern of organic matter decomposition persisted through the first growing season following disturbance (Trettin and Jurgensen, 1992).

The most common site factors attributed to the increase in cellulose decay are altered temperature and moisture regimes (Bridgham et al., 1991; Mader, 1990). The silvicultural treatments in this study caused a significant increase in soil temperature that corresponded to the degree of soil disturbance and vegetation removal. Mean soil temperature in June to July decreased with soil depth in order of bedding > WTH > uncut (Figure 4). The cellulose decomposition response was correlated with changes in soil temperature. Because the rate of decomposition is strongly controlled by temperature, higher rates of organic matter decay are expected to continue on harvested and regenerated sites until canopy closure reduces soil temperature.

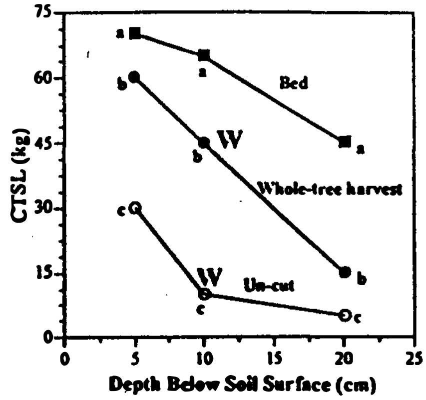

Figure 3 Organic matter decomposition as measured by cotton tensile strength loss (CTSL) for the bed, harvest-only, and uncut reference sites 1 year after harvest. Lower case letters denote a statistically significant (p = 0.05) difference at each sampling depth. The letter "W" denotes the location of the water table during the incubation. (Adapted from Trettin, C. C. and Jurgensen, M. F., *Int. Peat J.*, II, 392–399, 1992. With permission.)

Soil moisture and aeration also influenced cellulose decomposition (Lahde, 1969). Water table and aerated soil depth were nearly the same on all treatments, except when the water table was near the surface (<15 cm) or deeper than 50 cm. Consequently, the CTSL response for the trench, harvest-only, and uncut treatments at the 20 cm soil depth during late spring and early summer was tempered by saturated soil conditions over what would be expected with aerated conditions (Figure 3). In contrast, the incubation zone in the bed treatment was above the water table in the late spring-early summer sampling period, thereby providing an aerobic decomposition environment. Later in the summer, the water table was below the cotton strip for all the treatments, thereby minimizing or negating the effect of saturation on the measured cellulose decomposition.

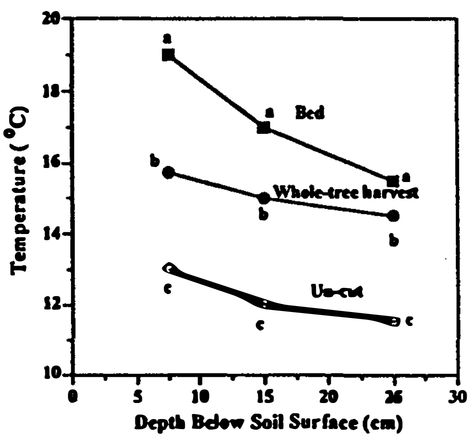

Figure 4 Average soil temperature during June to July in the first year following harvest for the whole-tree harvest, bed, and uncut treatments. Lower case letters denote a statistically significant (p = 0.05) difference at each sampling depth. (Adapted from Trettin, C. C. and Jurgensen, M. F., *Int. Peat J.*, II, 392–399, 1992. With permission.)

Bridgham et al. (1991) also reported that soil moisture was a controlling factor on CTSL in wetlands in North Carolina, particularly when sites had been drained.

Soil Chemical Properties

The following discussion considers the changes in C, Ca, N, Al, acidity, and redox potential following WTH and site preparation. These are considered critical parameters affecting the long-term site productivity potential of forested wetlands.

Carbon

The most significant effect of WTH and site preparation on soil properties was on soil C. Whole-tree harvesting alone caused a 30 percent reduction in soil C 12 months after harvesting, while bedding caused an increase (130 percent) in soil C in the planting line but a net reduction (32 percent) when the entire surface area of the treatment was considered (Trettin et al., 1992). Five years after harvesting, the C content surface soil in the planting line of the bedded treatment was 35 percent lower than in the uncut stand, while soil C losses in the WTH had increased to 47 percent (Table 5). These results indicated differences in organic matter decomposition rates between the harvesting and site preparation practices in the 4 years following disturbance. Accelerated decomposition apparently had been sustained in the bed, oxidizing the organic matter that had been concentrated there by the treatment. In contrast, the net loss in the WTH between the first and fifth years was only an additional 17 percent.

Other studies have also reported reductions in soil carbon or organic matter content as a result of intensive site preparation (Morris and Pritchett, 1983; Pye and Vitousek, 1985; Tew et al., 1986). Burger and Pritchett (1988) found that the level of organic matter reduction corresponded to the degree of site preparation. In a review of silvicultural impacts on soil C, Trettin et al. (1995) reported that change in temperature and soil moisture are largely responsible for reductions in soil C. Others (Tuttle et al., 1985; Trettin et al., 1992) have reported an increase in organic matter content following bedding, but those results were from measurements in the center of the bed, which does not represent the whole soil area (Attiwill et al., 1985; Sutton, 1993).

Table 5 Soil Carbon Content After Harvesting and Site Preparation Compared to the Uncut Reference Stand

	Uncut	Whole-tree harvest		Bedded	
	Carbon (mg/ha)	Carbon (mg/ha)	% loss	Carbon (mg/ha)	% loss
Forest floor	31.4	8.9	72	12.7	60
Mineral soil[a]	35.0	18.9	46	32.8	5
Total	66.4	35.2	47	43.2	35

Note: The trench treatment was not resampled in 1993.

[a] Measured to a mineral soil depth of 30 cm.

From McLaughlin, J. W., unpublished data. With permission.

Table 6 Average Extractable Ca, K, Al, Exchangeable Acidity (AC) in the Surface 25 cm of Soil (Including Forest Floor) 1 Year After Treatments Were Established

	Treatment			
Property	Uncut	WTH	Trenched	Bedded
Ca (meq)	0.27[a]	0.24[a]	0.32[a]	0.31[a]
K (meq)	0.08[a]	0.05[b]	0.06[c]	0.05[b]
Al (meq)	0.98[a]	0.94[a]	1.23[a,b]	1.37[b]
AC (meq)	5.39[a,b]	3.70[a]	7.50[b]	7.41[b]
Total N (g)	0.084[b]	0.069[a]	0.083[a,b]	0.072[b]

Note: Values expressed on the basis of 100 cm^{-3}. Different lower case letters ([a], [b], [c]) indicate a statistically significant difference within rows ($p = 0.05$).

From Trettin, C. C., Silvicultural Effects on Functional Processes of a Boreal Wetland, Ph.D. Thesis, College of Forest Resources, North Carolina State University, 1992, 153 pp. With permission.

Nutrients (Ca, K, N)

Harvesting and site preparation treatments changed the quantity and distribution of nutrients in the surface 25 cm of the soil 1 year following disturbance (Table 6). Although the trenched and bedded treatments had higher Ca levels than the uncut reference site, the difference was not statistically significant. Among silvicultural treatments, the bedded and WTH treatments had the lowest K levels, reflecting the mobility and sensitivity of K to leaching loss following disturbance. The loss of K on the WTH and trench treatments was due primarily to reductions in the forest floor, since there was no difference in extractable K among those treatments in the mineral soil. Morris and Pritchett (1983) reported a similar K response on a flatwood site where there was little change in extractable K and Ca in the mineral soil, but had significant reductions in the forest floor. However, the reduction of K in the forest floor in that study and others (Tew et al., 1986; Pye and Vitousek, 1985) was a result of displacement of the forest floor into windrows. Windrowing of the forest floor is in contrast to the treatments in this study, where the forest floor remained on the site. Other studies on several southeastern United States sites (Miller and Edwards, 1985; Tuttle et al., 1985) have not measured statistically significant reductions in extractable bases within 2 to 4 years following harvesting and site preparation.

There were no significant differences in total N among the WTH, bedded, and trenched treatments (Table 6). Similarly, there was no difference between total N levels in the trenched and bedded treatments as compared to the uncut stand. The C:N ratio of the uncut reference site was approximately 30; in contrast, it was 23 on the bedded treatment and 27 on the trenched and WTH treatments. The reduction in C:N and relatively constant total N levels suggest that immobilization was occurring. The reduction in total N on the WTH treatment was primarily a result of lower N levels in the mineral horizon. Burger and Pritchett (1988) reported that total N was reduced as a result of intensive site preparation, but the ratio of organic matter to total N remained relatively constant due to reductions in organic matter content.

Acidity and Aluminum

The soil conditions imposed by the silvicultural treatments were conducive to increased acidification. The acidification effect is subject to both spatial (Nykvist and Skyllberg, 1989) and temporal (Johnson, 1987; Skyllberg, 1991) variation. In our study, soil Al content increased as a result of site preparation treatments (Table 6). Extractable Al in the bedded treatment was measurably greater than the WTH treatment and the uncut reference site. Although the trenched treatment had higher extractable Al than the WTH treatment, the difference was not statistically significant. Similar to Al, the total acidity on the bedded and trenched treatments was greater than both the uncut reference site and WTH treatment; however, only the difference among the site preparation treatments and the WTH treatment was statistically significant. The direction of change in the soil environment measured in this study was toward a more acidified soil with lower levels of available base cations. Potentially, continued acidification is likely due to vegetation removal during harvesting and vegetation control (Binkley and Richter, 1987), as well as the recolonization of *Sphagnum* spp. (Clymo, 1984).

Mechanisms controlling soil acidification on northern wetlands include organic acid production, ferrolysis, and biomass removal. Organic acid production is considered the dominant acidification process in northern peatlands (Hemond, 1983; Urban et al., 1987). The measured increase in cellulose decomposition in this study (Trettin and Jurgensen, 1992) reflects increased microbial activity and probably increased decomposition of the native organic matter. The accelerated decomposition could cause the increased acidity. Oxidation of ferrous iron is also a likely contributor to the acidity pool (Bouma, 1983). Both the bedded and trenched treatments effectively increased the aerated soil volume, thereby increasing the time available for iron oxidation. The implications of increased acidity following disturbance has important ramifications with respect to Al and dissolved organic C transport from the wetland to adjacent waters. Aluminum moves from the forest floor as organic Al compounds and is immobilized in the B horizon. Most Al leaving the solum is inorganic Al derived from the mineral soil (Driscoll et al., 1989).

Redox Potential

In the first year after the site preparation treatments were installed, the anaerobic soil zone (based on the steel rod oxidation depth) exhibited a complex response pattern that was affected by the silvicultural treatment, position within the wetland, and measurement period (Trettin, 1992). As expected, the bedded treatment had the greatest oxidized soil depth, in the center of the beds, at each measurement date throughout the summer. The trenched and WTH treatments were not significantly different at any of the measurement dates. Subsequent measurements using electrodes in the fifth growing season showed that reducing conditions were predominant at 15 and 30 cm regardless of treatment; however, there was considerable variation in soil redox potentials, ranging from –220 to +500 mv, and no significance differences were found among treatments. Average redox potentials were higher at 15 cm than at 30 cm, which would be expected because of higher oxygen diffusion rates in surface soil horizons (Vepraskas, 1992).

Water Quality

Assessment of water quality from the vadose zone and shallow groundwater was an effective approach for determining post-treatment response to the silvicultural treatments and in confirming the changes in soil nutrients. In the first year following harvesting and site preparation, water quality results corroborated the increase in organic matter decomposition, as measured by the increase in electrical conductivity in both the vadose zone and groundwater under each treatment (Trettin, 1992). Similarly, soil K leaching was evident in both vadose and groundwater samples for the two site preparation treatments and the WTH. The water samples were particularly effective for assessing the N response to disturbance, because changes in N cycling processes (ammonification and nitrification) were evident in the vadose zone.

Five years after timber harvesting, there was still some difference in water quality among treatments, but there was no evidence of water quality degradation (Table 7). Dissolved organic carbon (DOC), pH, and conductivity were similar between the silvicultural treatments and the uncut site. In fact, soil water DOC, pH, and conductivity were highly correlated with one another. These results were similar to Moore (1987), who reported no significant differences in DOC con-

Table 7 Average Water Chemistry 5 Years after Harvesting and Site Preparation

Depth (cm)	pH	Conductivity (µ mhos cm^{-1})	DOC (mg L^{-1})	µg L NH_4^+	NO_3^-	PO_4^{-3}	TKN	TP
			Uncut stand					
15	4.1	48	48	97	39	20	777	329
30	4.3	46	44	78	31	9	664	115
Water table	5.2	65	21	22	14	4	201	95
			Whole-tree harvest					
15	4.5	42	44	104	56	5	759	151
30	4.7	36	36	82	36	4	740	95
Water table	5.4	54	22	26	15	6	247	57
			Bedded treatment					
15	4.4	42	51	198	58	4	704	205
30	4.5	38	42	175	62	7	798	94
Water table	5.3	59	25	102	49	2	345	91

Note: Samples were collected monthly at 15 and 30 cm soil depths and from the water table in 1993.

centration for three of four peatlands in the subarctic region of Quebec after drainage and harvesting. DOC concentrations were positively related to water table depth and forest floor pH (Table 7), but only to a soil depth of 17 cm. This was likely due to increased aeration as the water table lowered and the soil shifted from predominantly anaerobic to aerobic microbial respiration, causing greater organic matter degradation, and higher soluble C (Schlesinger, 1991). This inverse relationship has also been found in other spodosols in the northeastern United States and eastern Canada (McDowell and Wood, 1984; Moore et al., 1992). Increased soil sorption of DOC in the Bs horizon was the likely cause. The Bs horizon has the strongest DOC sorption potential of all mineral soil horizons (McLaughlin et al., 1994). There were, however, differences in the hydrophobic and hydrophilic acid composition of DOC and its carboxyl acidity. The WTH treatment had a lower hydrophobic acid composition than the uncut stand and lower hydrophilic acid carboxyl acidity (McLaughlin et al., 1996).

Inorganic N (NO_3 + NH_4) in the WTH and bedded treatments still exhibited higher concentrations 5 years following disturbance (Table 7). However, ammonium concentrations were approximately one-half and NO_3 levels were one-seventh the uncut level 12 months after harvest on all treatments. Ammonium concentrations were lower in the soil water of the uncut stand than those reported for a poorly drained spruce/fir forest in Maine (Lawrence and Fernandez, 1991). The higher concentration of NH_4 than NO_3 is consistent with what has generally been reported for poorly drained soils (Lawrence and Fernandez, 1991; Schlesinger, 1991). The range of TKN concentrations in the lysimeter samples for the uncut stand and both silvicultural treatments were similar (Table 7), although the partitioning between organic and inorganic N was different. Ammonium and NO_3 accounted for approximately 35 percent of the soil water N in the bedded treatment, 20 percent in the WTH treatment, and only 18 percent in the uncut stand. Among all treatments, 60 to 85 percent of the N in the soil water occurred in organic forms. Organic N is transported through soils in conjunction with DOC (Qualls et al., 1991). Correspondingly, in this study there was a strong positive correlation between soil water TKN and DOC concentrations (McLaughlin, unpublished data).

Phosphorus levels were not measured in the first year after harvest; however, after 5 years, the uncut reference stand had higher soil water P concentrations than harvested and site-prepared plots (Table 7). The general decrease in P concentrations with increasing soil depth indicated that P sorption may be an important soil process at this wetland site. Phosphate has been found to be strongly adsorbed in soils of many different forest ecosystems (Wood et al., 1984; Richardson, 1985; Walbridge et al., 1991). However, McLaughlin et al. (1994) showed that DOC sorption potential of the mineral soil at this site is low due to high sand content and low extractable iron and aluminum. A similar situation may also occur for P sorption (Walbridge et al., 1991). Phosphorus is generally deficient in wetland soils (Richardson, 1985; McLaughlin et al., 1994) and would be used immediately by either plants or microorganisms when released during organic matter decomposition. Such P immobilization would lower P in the soil solution (Richardson, 1985). Total P concentrations in soil water of the uncut reference site were higher than in the site preparation treatment (Table 7). Organic P concentrations (the difference between PO_4 and total P) accounted for greater than 90 percent of the soluble P in all treatments at both 15 and 30 cm depths. Phosphorus predominantly moves through the soil bound to DOC (Moore, 1987; Schoenau and Bettany, 1987; Qualls et al., 1991; Walbridge et al., 1991).

Plant Community Response

Four years after planting, jack pine seedlings growing on the bedded treatments had significantly greater heights and root collar diameters than those on the WTH and trenched treatments (Table 8). As previously discussed, bedding increased the aerated rooting zone and increased rates of organic matter decomposition and nutrient availability. In contrast, the trench treatment resulted in the seedlings being planted in the mineral soil, effectively below the original surface elevation. That planting position resulted in the largest rate of first-year mortality (Cho, 1990). After 4 years those seedlings were larger than those flat-planted in the WTH treatment, although the difference was not statistically significant.

Plant diversity, however, responded differently to the harvesting and site preparation treatments than did seedling development. Species numbers on the WTH areas were significantly greater than the trenched and uncut reference areas, yet similar to bedded areas (Table 8). Total plant coverage on the WTH areas had significantly greater coverage than all the other site preparation treatments and the uncut areas. Low total plant cover on the uncut area is probably due to complete cover of bryophytes, while bryophyte cover was minimal on the harvested and site-prepared sites.

Table 8 Seedling Height and Diameter, Number of Species, and Plant Coverage 4 Years After Planting

	Uncut	Whole-tree harvest	Trenched	Bedded
		Seedling		
Height (cm)	—	55.3[a]	64.0[a]	88.8[b]
Diameter (cm)	—	35.6[a]	46.8[a]	69.6[b]
		Plant community		
No. of plant species	8.1[b]	10.0[a]	8.7[b]	9.1[a,b]
Total plant coverage (%)	17.0[c]	38.0[a]	29.0[b]	28.0[b]
		Relative coverage		
Herbaceous (%)	39.0[b]	5.0[a]	9.0[a]	8.0[a]
Grass/sedge (%)	4.0[b]	22.0[a]	31.0[a]	30.0[a]

Note: Different lower case letters (a, b, c) indicate a statistically significant difference (p = 0.05).

From Gale et al., submitted. With permission.

Relative plant coverage of woody species was not significantly different among site preparation treatments and the uncut reference. Significant differences in relative cover of herbaceous and grass/sedge species among treatments and reference site were determined (Table 8). However, relative coverage of herbaceous species on the uncut area was approximately four to seven times greater than coverage on site preparation areas. Relative cover of grass/sedge species was approximately four to eight times greater on site preparation areas than the uncut area. No significant differences in relative coverage of herbaceous and grass/sedge species among the three silvicultural treatments were detected. Relative cover indicates a shift in the community composition of planted sites from a tree–herbaceous dominated system to a tree–grass/sedge system when compared with the uncut stand 4 years after timber harvesting.

CONCLUSIONS AND PERSPECTIVES

The site in this study was characterized by a histic-mineral soil, a nascent C-accumulating wetland soil (Trettin et al., 1995). Accelerated organic matter decomposition and C losses were expected after harvest because of increased soil temperature, aeration, and substrate availability associated with these treatments. Measurements after timber harvesting and site preparation demonstrated that the site became a net source of C, either as CO_2 to the atmosphere or as DOC to the soil water. Both of these pathways have implications for global carbon cycling and possible climate change (Schlesinger, 1991). Accelerated organic matter decomposition can also contribute to soil acidification, loss of soil fertility, and a change in soil hydrological properties. Carbon loss has occurred during the first 5 years following disturbance. However, loss as DOC was not evident after 5 years. It is likely that the harvested and site-prepared lands will exhibit higher decomposition rates until canopy closure results in a reduction in soil temperature. At that point, this system may revert to a soil C-accumulating ecosystem.

Maintenance of soil nutrient levels is an important factor for sustaining the integrity of forested wetlands, particularly on oligotrophic sites. The whole-tree harvesting system used in this study removed all woody and leaf biomass, thereby eliminating much of this nutrient pool. Water quality information was important in evaluating wetland nutrient status because it provided an integrated picture of disturbance impacts. In the first year following harvest, cation and N leaching were evident, but the concentrations were low and never approached any regulatory or best management practice standard. Five years after timber harvesting, the bedding treatment was still causing a release of inorganic N into the soil water. However, the fluxes were not determined in this study; hence, the impacts of leaching on total nutrient pools could not be assessed.

Site preparation significantly increased seedling growth on harvested areas. This was especially evident in the bedding treatment, which created raised planting mounds and improved soil aeration and nutrient availability. Harvesting and site preparation also decreased coverage of the understory community. This was expected due to physical soil disturbance and loss of the forest floor. Whether these plant community differences will continue, as successional changes proceed, remains to be determined. Critical components for assessing future productivity, whether it is measured as tree growth, understory plant cover, or as overall community structure, are climate and hydrology.

These results have demonstrated that timber harvesting and associated site preparation practices can change soil, vegetation, and to a lesser degree hydrological properties of a northern wetland. The silvicultural challenge is to develop and apply forest management prescriptions that minimize site disturbance and preserve the integrity of the structural components of the wetland system. This may involve less intensive utilization and harvesting regimes that leave more branch and top material on site and reduce soil disturbance. A site preparation treatment that provides a planting site while minimizing or avoiding disturbance to the remainder of the site is desirable. Examples of such treatments include spot-mounding (Sutton, 1993) or flat-planting with spot vegetation control, both of which cause minimal site disturbance. The cost of bedding, in terms of soil C, long-term site productivity, and vegetation composition, must be considered with respect to gains in fiber crop production. It should not be assumed that future fiber production is commensurate with the degree of cultivation, particularly on infertile soils, although recent work in Finland has shown that ameliorative practices of water management and fertilization may offset soil C losses through increased tree productiviy (Laine et al., 1992).

The basis for this synthesis was relatively short-term results (5 years). It is very difficult to interpolate these results to long-term ecosystem function or fiber crop production. However, whether the observed short-term responses will reflect long-term changes in soil or water processes or vegetation dynamics must be determined in subsequent work. Additional research on silvicultural effects on boreal wetlands is also needed, both to establish the long-term effects of disturbance and to consider alternative prescriptions for accomplishing management objectives. Such studies should include (a) the effect of landscape-position on wetland function and how the impact of disturbance changes with landscape position and (b) cumulative impact assessment of forest management in upland and wetland ecosystems within a landscape. Regeneration studies are needed to (a) consider regeneration response to the current treatments, (b) consider alternative mechanical and chemical site preparation prescriptions, and (c) consider the use of natural regeneration, including the use of fire.

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