SCARIFICATION TRIALS FOR DIRECT SEEDING ON UPLAND BLACK SPRUCE SITES IN NORTHWESTERN ONTARIO

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ABSTRACT

Seven operational or prototype scarifiers were examined in small pilot-scale trials to determine their capabilities for producing black spruce (*Picea mariana* [Mill.] B.S.P.) seedbed on upland sites. Relationships between site conditions, productivity and seedbed production were investigated for each machine. None of the scarifiers tested consistently met the target requirements for black spruce seedbed exposure for subsequent aerial seeding on upland sandy tills. Best results were obtained with a substantially modified Cazes and Heppner (C&H) plow. Intensive treatment with implements such as disc trenchers, which provide continuous tillage but do not create large windrows, offer potential for improved seedbed distribution. Soils and topographic conditions generally had a greater impact on seedbed exposure than on machine productivity.

RÉSUMÉ

Sept scarificateurs fonctionnels ou expérimentaux ont été testés à l'échelle pilote pour déterminer leur capacité à produire des lits de germination d'Épinettes noires (*Picea mariana* [Mill.] B.S.P.) sur les hautes-terres. Les rapports entre les conditions de terrain, la productivité et la production des lits de germination ont été étudiés pour chaque appareil. Aucun des scarificateurs testés n'atteignait régulièrement les exigences fixées en ce qui a trait à l'exposition des lits de germination d'Epinettes noires préparés pour l'ensemencement aérienne dans les terrains sablonneux des hautes-terres. Les meilleurs résultats ont été obtenus avec une charrue Cazes and Heppner (C & H) fortement modifiée. Les traitements intensifs avec des appareils comme les trancheuses à disques, qui labourent continuellement mais ne font pas de gros andains, peuvent conduire à une distribution améliorée des lits de germination. Les sols et la topographie ont eu généralement plus d'effet sur l'exposition des lits de germination que sur la productivité des appareils.

ACKNOWLEDGMENTS

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INTRODUCTION

Upland black spruce *(Picea mariana* [Mill.] B.S.P.)-dominated forests occupy approximately 22% of Ontario's productive forest land (Ketcheson and Jeglum 1972) and, of this area, roughly 40,000 ha are harvested each year (Anon. 1983). The majority of these spruce forests are clear cut and require treatment to ensure prompt regeneration. While many sites should be planted, extensive areas must be regenerated by other means because of poor access, limited site productivity, and lack of planting stock or labor.

Aerial seeding is potentially an economical alternative for reforesting large areas of black spruce cutover. However, most seeding trials with black spruce on upland sites have failed to produce adequately stocked stands (Waldron 1974, Fraser 1981a, 1981b). To improve results, Richardson (1974) concluded that better site preparation was crucial. He pointed out that this would require seedbed-microsite work to define the conditions required for optimum germination and establishment, and then the development of site preparation techniques to obtain these conditions. Fraser (1981b) concurred with Richardson and recognized three major factors as militating against seeding success with black spruce: inadequate site preparation, microclimatic extremes associated with excessive seedbed exposure, and the traditional "one-shot" application of seed.

From 1978 to 1981, the Ontario Ministry of Natural Resources (OMNR) and the Great Lakes Forestry Centre (GLFC) cooperatively undertook a series of operational trials to determine whether several existing scarification implements and techniques could be used effectively to create suitable quantities of receptive seedbed for black spruce. OMNR supplied the sites, carried out the scarification, and provided logistical support and operational expertise, while GLFC designed the experiments and conducted the assessments. Members of the Liaison, Development and Technical Services Unit at GLFC laid out the plots and collected ergonomic data. Members of the Black Spruce Project at GLFC assessed site-preparation quality and undertook followup studies on seedbed suitability and direct seeding (Fleming and Groot 1984).

METHODS

Study Areas

All trials were conducted in the Black Sturgeon Management Unit of OMNR's Thunder Bay District, within the present Abitibi-Price Inc. Spruce River Forest. The areas are located 60 to 135 km north of Thunder Bay (lat. 48°25', long. 89°15'), within the Superior or Central Plateau sections of the Boreal Forest Region (Rowe 1972).

The locations were chosen to represent upland sandy tills (containing less than 40 cm of organic matter over mineral soil) which, before clearcutting, supported black spruce or black spruce-jack pine *(Pinus banksiana* Lamb.) stands. Sites that were predominantly very shallow (less than 30 cm of mineral soil over bedrock) were not selected because such areas should be either strip cut or left as protection forest (Robinson 1974). The soils of the study sites were largely noncalcareous, silty to loamy, very fine sands, although some sandy loams were also found. Moisture regimes varied from moderately fresh to moderately wet (*sensu* Bates et al. 1982). The areas were characterized by gently to moderately rolling, thin ground moraine till over granitic Archaean bedrock. In addition, parts of the 1980 and 1981 study sites had overlying deposits of sandy outwash more than 1 m deep (Zoltai 1965a,b). Stones constituted as much as 20% of the till volume (and a much greater proportion in boulder pavement areas), and large surface boulders were present (Zoltai 1965a). Numerous combinations of physiographic site type, soil texture, soil depth, stone and boulder content and soil moisture regime were present, creating a mosaic of sites within individual scarification chances.

The previous forests on the four trial sites were composed largely of mature to overmature black spruce-jack pine stands. Some pure black spruce and jack pine-black spruce types were also present. The 1978, 1979, and half of the 1980 study sites were logged conventionally; trees were delimbed and topped at the stump and then skidded tree-length to roadside. The 1981 site and the other half of the 1980 site were full-tree logged, with delimbing and topping taking place at roadside. Additional details on characteristics of the previous stands, logging methods and the time of scarification are given in Appendix B.

Seedbed Prescription

The black spruce seedbed prescription used for these trials was based on interim results from continuing experiments, as well as on the findings of several researchers (i.e., LeBarron 1944, Place 1955, Winston 1975, Fraser 1981a, Jeglum 1984). It pertains only to sites with: 1) moderately fresh to very moist moisture regimes, and sandy to loamy soil textures; 2) predominantly at least 30 cm of mineral soil over bedrock (cf. Jeglum 1980); and 3) on a 4-m^2 basis, at least 40% of the area with less than 15% of the ground surface covered by a combination of *Sphagnum*, *Polytrichum* and pioneer mosses (i.e., *Ceratadon purpureus* (Hedw.) Brid. and *Pohla nutans* (Hedw.) Lindb.).

Sites that do not meet the first two criteria likely require different, or at least modified, site preparation techniques. In contrast, treatment is unnecessary on areas with sufficient quantities of *Sphagnum*, *Polytrichum* and/or pioneer mosses, which are excellent natural seedbeds (Jeglum 1984).

The objective of scarification was to expose as much of the H, Hi and/or Ah soil horizons as possible. These horizons are found at the mineral soil-humus interface. Upland seedbeds judged to be acceptable for black spruce (i.e., receptive seedbed) included the H, Hi, Ah, F, Ae and B horizons, or any mixture thereof, found not more than 5 cm above or 10 cm below the mineral soil-humus interface (Fleming and Groot 1984). Well decomposed wood directly overlying H, Hi or mineral soil horizons was considered acceptable as well.

Scarification results were assessed also in terms of seedbed preparation for jack pine. The definition of receptive seedbed used for this species followed that of Riley (1980): "exposed mineral soil with a firm base, a thin duff/mineral soil mix which would readily settle to a firm base, or firm mineral soil with a very thin duff cover." This prescription is somewhat broader than that for black spruce. It includes both a thin litter layer over mineral soil and deeper mineral soil horizons.

Machinery

The scarifiers used in each trial from 1978 to 1981 are listed in Table 1.

Table 1. Scarifiers examined in each trial, and number of sample plots treated

Trial	Scarifier	Number of 0.2-ha plots
1978	CFS Row Scarifier	7
	Mini-barrels and chains	8
1979	CFS Row Scarifier	4
	Atkinson Backscratcher	4
	Broyeur A.M.	4
1980 full-tree	CFS Row Scarifier	9
	TTS Disc Trencher	7
	modified C&H plow	6
1980 tree-length	CFS Row Scarifier	4
	TTS Disc Trencher	6
	modified C&H plow	8
1981	CFS Row Scarifier	11

1978 trial: In 1978 three different scarifiers were tested: (a) the CFS Row Scarifier; (b) flanged mini-barrels and chains; and (c) a Model 300 and then a Model 500 National Hydro-Ax chain flail with delimber head. Only the results of the first two tests are reported here. The Hydro-Ax was examined solely on a conceptual basis, to determine whether suitable seedbeds could be created by thoroughly mulching the organic horizons and mixing them lightly with the mineral soil beneath. The machine, as currently conceived, is not designed for scarification.

The CFS Row Scarifier (a modified SIECO Heavy Duty Fire Suppression Plow), and the Michigan Floating Hitch used to attach the plow to the prime mover, are described by Mattice and McPhee (1979) and Smith (1980). In 1978 this unit (Fig. 1) was pulled by a John Deere 450C crawler tractor, with a locally constructed V-blade attached to the front to part slash.

The mini-barrels unit (Fig. 2) consisted of six 36-cm-diameter flanged barrels (Smith 1980) attached to a 2.4-m-long drawbar in two rows of three barrels each, with spiked anchor chains trailing behind each row. The unit was pulled by a C7D Tree Farmer grapple skidder (130 hp), with a Nipigon Slash Eliminator[1] (Fig. 3) attached to the front to clear logging debris.

1979 trial: In 1979 three scarifiers were tested: (a) the CFS Row Scarifier; (b) the Atkinson Backscratcher; and (c) the Broyeur A.M. The row scarifier was pulled by a John Deere 450C crawler tractor equipped with a front-mounted CFS V-blade (Cameron 1978).

The Atkinson Backscratcher is a prototype tool developed by G.T. Atkinson and V.F. Haavisto of GLFC, in conjunction with staff of several OMNR districts. It consists of three small middle buster plows, each drawn by its own free-floating trailing arm attached to a modified logging arch (Fig. 4). During these trials, depth of scarification was controlled solely by the shape of the plows and their angles of draft. The winch cable of the prime mover is attached to a hinged horizontal bar beneath the trailing arms, allowing the plows to be lifted and cleared if they become clogged with slash.

The Broyeur A.M. consists of a 1.8-m-diameter x 4.3-m-wide cylinder (Fig. 5). The cylinder has thirty-five barbed steel teeth, each 61 cm long, welded to it in five rows, and is attached to the prime mover by a metal frame that allows it to rotate freely as it is pulled along. Five trailing 3-m-long spiked chains are dragged behind the drum. The weight of the cylinder can be increased by filling the reservoir with water. In these trials a Cat D8H crawler tractor was used to pull the Broyeur. The prime mover was unable to tow the scarifier effectively when the reservoir was filled, and therefore weight (water) was not added for the trial.

1980 trial: Three scarifiers were tested in 1980: (a) the CFS Row Scarifier, pulled by a John Deere 450B crawler tractor with a front-mounted CFS V-blade; (b) a TTS model 35 Disc Trencher (Smith et al. 1985) pulled by a Clark 667 skidder equipped with a Bräcke hitch and a front-mounted Nipigon Slash Eliminator (Fig. 6); and (c) a substantially modified C&H scarification plow (Clarke 1977, Smith 1980) attached to a Cat D7F crawler tractor. The last-named plow was modified by welding moldboards to the outer side-arm assembly (Fig. 7) to create, in effect, a large V-plow. As a result, the outer plow did virtually all of the scarification.

1981 trial: Only one machine was tested in 1981, the CFS Row Scarifier. It was pulled by a Cat D4 equipped with a front-mounted CFS V-blade that parts slash.

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[1] designed and constructed by staff of OMNR's Nipigon district

Figure 1. CFS Row Scarifier

Figure 2. Mini-barrels

Figure 3. Nipigon Slash Eliminator

Figure 4. Atkinson Backscratcher

Figure 5. Broyeur A.M.

Figure 6. TTS Disc Trencher

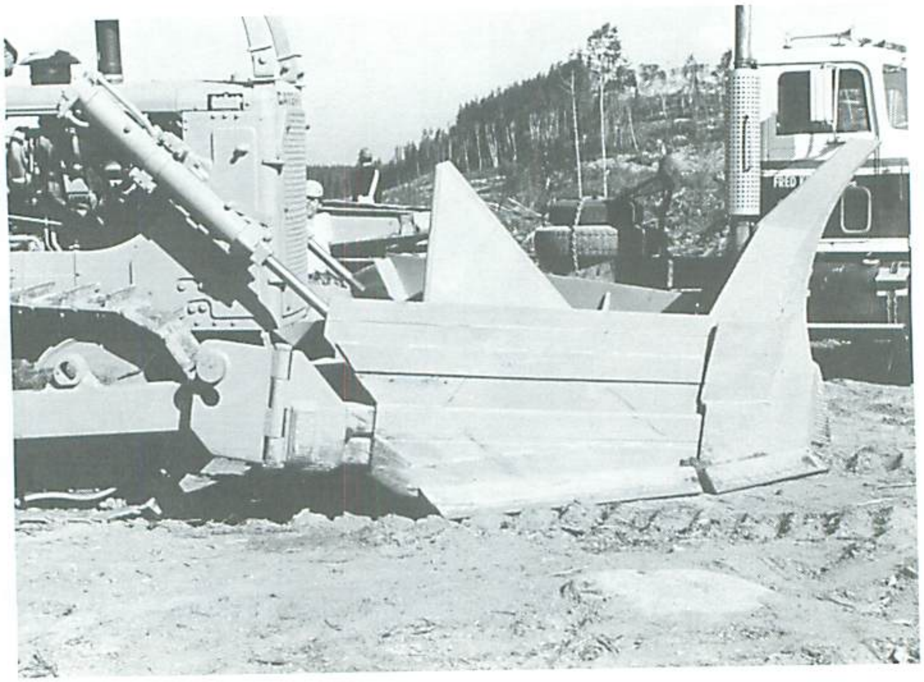

Figure 7. Modified C&H scarification plow

Equipment Evaluation

Field studies undertaken during each trial consisted of an evaluation of site conditions before treatment, continuous and plot-related work studies during scarification, and a post-treatment assessment of seedbed exposure for both black spruce and jack pine (see **Seedbed Prescription**).

Pretreatment assessment: Before scarification, a series of 0.2-ha sample plots, each divided into five 0.04-ha subplots (Riley 1975, Smith et al. 1985), was located on representative sections in each treatment block (Table 1). All pretreatment and post-treatment assessments, as well as the detailed time studies, were carried out in these plots.

In the 1978 and 1979 trials, pretreatment assessment procedures and sampling intensities for stumps, slash (according to the line-intersect method as outlined by Van Wagner [1968]), residual trees (more than 6 m high or 5 cm in diameter) and slope followed those of Riley (1975). To determine slash volume for pieces 1-6 cm in diameter at the point of intersection (for which only a total frequency tally was made) a quadratic mean diameter of 2.4 cm was used[2]. The following parameters were recorded at four regularly spaced intervals across each subplot: LFH (duff) depth; soil depth, measured from the top of the

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2 based on information from slash tallies on black spruce cutovers in northeastern Ontario (D.J. McRae, unpublished data)

mineral soil to a maximum of 60 cm; and stoniness frequency, i.e., the number of times (%) a stone or boulder obstruction was encountered in the top 30 cm of mineral soil when it was probed 10 times per interval with a 1-cm-diameter rod (cf. Viro 1952, 1958). The surface coverage of exposed bedrock and boulders was estimated visually. In addition, a soil pit was dug near the middle of each subplot after treatment to determine soil texture, moisture regime and depth. In 1979 ground roughness (Anon. 1969) was assessed on two 5-m x 20-m sections per subplot (2.5 m on either side of the lines used for slash assessment).

Procedures used in 1980 were similar to those used in 1979, with the exception that the line-intercept slash tally was increased from 40 to 100 m per subplot, and stump density was assessed by species on an additional 80 m^2 (two 2-m x 20-m lengths) per subplot.

To quantify differences in slash loadings after full-tree as opposed to tree-length logging, supplementary line-intersect sampling was conducted. Three sites were selected, each of which previously supported a single stand that was harvested with both logging systems (i.e., parts of each stand were harvested with each system). These represented a jack pine-black spruce type on a moderately fresh sandy outwash, an upland black spruce type on a very fresh to moderately moist sandy till, and a black spruce lowland type on shallow peatland in a small depression. On each site 40-m-long sampling lines were established. Tallies were conducted as above, but the species and condition at the time of harvest (alive or dead) were also recorded for all pieces $\geqslant$7 cm in diameter.

In 1981 the plots and subplots were sampled more intensively to allow for an analysis of sampling procedures and intensity. Slash was tallied along 60 contiguous 2-m sections per subplot (six equally spaced 20-m lines, three running the length of the subplot and three running the width [Fig. 8]). Slash depth (Smith et al. 1985) was measured at the midpoint of each 2-m section (60 measurements per subplot), as was stoniness frequency. Exposed rock (aerial coverage), ground roughness, residual trees, and stumps (by species, diameter [30 cm above ground or at the face, whichever was lower], and height) were tallied on 30 contiguous 4-m^2 quadrats located along the three sampling lines running the width of each subplot. Data on slope and soil moisture regime, texture and depth were obtained by means of the same procedures as in earlier trials. LFH depth was measured at 12 equally spaced locations within each subplot.

Work studies: Work studies were conducted at two levels. Continuous time studies were carried out for each machine throughout each trial to document overall capability in relation to productivity, performance and operational characteristics. To determine average travel speed and to examine how site factors influenced productivity, the time taken for the equipment to traverse each subplot during each pass, as well as the types and lengths of delays, were also recorded. Machine time elements were broken into several classes, as defined by Folkema et al. (1981). The continuous time studies were assessed by means of procedures similar to those employed by Smith et al. (1985). Only passes with no long-term or short-term delays other than obstacle delays were used to calculate travel speeds within each subplot.

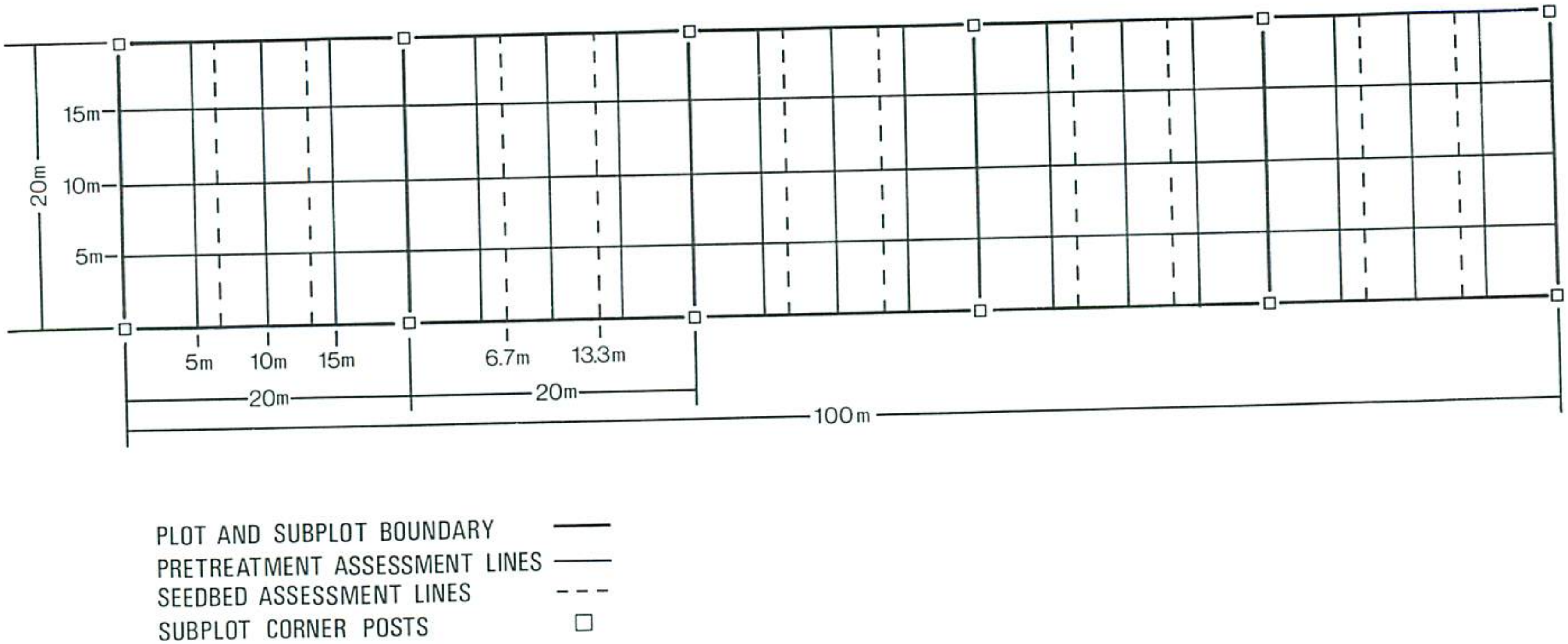

Figure 8. Plot layout for pretreatment and post-treatment assessments (after Smith et al. 1985).

Post-treatment assessment: After treatment, a series of 4-m^2 quadrats was established randomly along lines running across each subplot, perpendicular to the direction of machine travel. Each quadrat was assessed for aerial coverage of receptive black spruce seedbed, receptive jack pine seedbed, lowland seedbed (Sphagnum moss, peat and lowland muck) and net scarification (the percentage of the quadrat which the scarifying implement passed over and attempted to treat). Seedbed production was then examined in terms of gross and net seedbed exposure (GSE and NSE). GSE refers to the amount of seedbed created as a percentage of the total area treated (% aerial coverage). NSE is the amount of seedbed produced within the scarified path created by the implement, i.e., within the confines of the furrow (Anon. 1979).

In the 1978 and 1980 trials one sampling line with six quadrats[3] bisected each subplot. In 1979 and 1981 two sampling lines of six quadrats each were run across each subplot at the 6.7 and 13.3 m marks (Fig. 8).

Site conditions, seedbed exposure and machine productivity for different machine-trial combinations were compared by analysis of variance. Transformations were performed when applicable to ensure adherence to test assumptions. Individual differences were established with Tukey's multiple comparison test. Relationships between site conditions and machine performance were examined by means of correlation analysis and least-squares multiple linear regression. Best-fit equations were selected on the basis of t-statistics, Mallows Cp statistic and R^2 values. Scatter plots of residuals and of each independent variable versus each dependent variable were used to identify outliers and determine whether transformations would improve relationships. Where extreme outliers were present, a maximum of one outlier was removed for a given independent variable.

Significance in all tests was determined at the P=0.05 level.

RESULTS

Prescarification Assessment

Tables 2 and 3 summarize pretreatment site conditions for the areas treated by individual machines in different years. Ideally, all site conditions on the different blocks should be similar if good comparisons among machines are to be made; however, this is rarely the case. In these trials significant differences in slash and stump conditions among the various blocks were evident (Table 2). The 1978 row scarifier and mini-barrel blocks and the 1980 TTS tree-length block had the most small slash (<7 cm), while the 1980 row scarifier tree-length block had the least. With larger slash (≥7 cm), the most notable differences were the high values for slash frequency and volume in the C&H plow full-tree block. The 1979 and 1980 tree-length row scarifier blocks had significantly smaller total slash volumes than several others.

[3] In 1978 one of the mini-barrel plots and two of the CFS Row Scarifier plots had two lines of six quadrats each per subplot.

Table 2. Mean slash and stump conditions, before scarification, for different blocks

Condition	Block (trial and machine)					
	1978		1979	1980 Full-tree		
	Row scarifier	Mini-barrels	Row scarifier	Row scarifier	C&H plow	TTS
Slash frequency/m, pieces <7 cm diam [a]	2.73e (0.12) [b]	2.68e (0.12)	1.81bcd (0.12)	1.26a (0.05)	1.47ab (0.06)	1.63abc (0.14)
Slash frequency/m, pieces $\geq$7 cm diam [a]	0.51abc (0.03)	0.50abc (0.03)	0.50abc (0.03)	0.40a (0.02)	0.52bc (0.03)	0.40ab (0.03)
Slash volume (m^3/ha) pieces <7 cm diam [a]	19.4e (0.87)	19.1e (0.84)	12.9bc (0.84)	9.0a (0.36)	10.4ab (0.44)	11.6abc (0.99)
Slash volume (m^3/ha) pieces $\geq$7 cm diam [a]	87.2ab (5.7)	87.7ab (5.8)	69.9a (6.0)	78.1ab (5.3)	104.4b (5.1)	88.9ab (10.1)
Total slash volume (m^3/ha)	106.6a (5.8)	106.8a (6.3)	82.9a (6.6)	87.1a (5.5)	114.9a (5.2)	100.6a (10.6)
Stump frequency/ha	1011ab (46)	1184ab (78)	1998d (163)	1301abc (106)	1018ab (73)	1474bcd (194)
Mean stump cross-sectional area (m^2)	0.042c (.001)	0.039c (.002)	0.029ab (.002)	0.037bc (.003)	0.040c (.002)	0.041c (.004)
Mean stump height (cm)	31.5a (.76)	30.3a (.70)	36.3b (1.32)	31.7a (.62)	33.0ab (.83)	33.5ab (.82)
Residuals/ha	41.7ab (10.2)	46.3b (11.5)	30.0ab (11.7)	12.2ab (5.3)	11.7ab (5.7)	24.0ab (12.6)

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Table 2. Mean slash and stump conditions, before scarification, for different blocks (concl.)

	1980 Tree-length			1981
	Row scarifier	C&H plow	TTS	Row scarifier
Slash frequency/m, pieces <7 cm diam [a]	1.77bc (0.09)	2.30de (0.07)	2.65e (0.10)	1.99cd (0.08)
Slash frequency/m, pieces ≥7 cm diam [a]	0.47abc (0.02)	0.43abc (0.02)	0.45abc (0.03)	0.52c (0.02)
Slash volume (m^3/ha) pieces <7 cm diam [a]	12.6bc (0.65)	16.5de (0.53)	18.8e (0.74)	14.2cd (0.60)
Slash volume (m^3/ha) pieces ≥7 cm diam [a]	68.7a (5.6)	90.6ab (5.1)	92.3ab (7.0)	95.9ab (4.5)
Total Slash volume (m^3/ha)	81.3a (5.7)	107.1a (5.1)	111.1a (7.2)	110.1a (4.8)
Stump frequency/ha	1728cd (169)	840a (74)	1090ab (67)	1148ab (63)
Mean stump cross-sectional area (m^2)	0.028a (.002)	0.042c (.002)	0.041c (.002)	0.037bc (.001)
Mean stump height (cm)	32.9ab (.43)	30.1a (.40)	31.8a (.32)	32.2a (.77)
Residuals/ha	0.00a (0.0)	37.5ab (20.8)	5.0ab (3.4)	10.6ab (4.4)

[a] At the point of intersection
[b] Standard errors

There is no significant difference (P = 0.05) between values followed by the same letter(s) in any given row.

Table 3. Mean physiographic characteristics and soil conditions, before scarification, for different treatment blocks.

	Block (trial and machine)					
	1978		1979	1980 Full-tree		
Condition	Row scarifier	Mini-barrels	Row scarifier	Row scarifier	C&H plow	TTS
Exposed bedrock (% coverage)	0.5a (0.50) [a]	0.3a (0.21)	0.0a (0.0)	0.0a (0.0)	0.0a (0.0)	0.0a (0.0)
Soil depth (cm) [b]	40a (3.1)	33a (1.4)	85bc (6.7)	101d (0.0)	100d (0.8)	100cd (0.4)
Effective soil depth (cm) [c]	42.2b (2.0)	34.4a (1.3)	56.3c (2.5)	60.0c (0.0)	60.0c (0.0)	60.0c (0.0)
LFH depth (cm)	13.4de (0.61)	13.1cde (0.58)	14.3e (0.93)	8.0a (0.42)	10.1ab (0.91)	10.1ab (0.57)
Moisture regime	3.8c (0.16)	3.2bc (0.15)	3.9c (0.19)	2.6ab (0.14)	3.7bc (0.19)	3.5bc (0.16)
Stoniness frequency (%)	53.4cd (3.1)	58.3d (2.7)	40.0bc (4.2)	39.4bc (3.2)	45.2bcd (4.2)	41.6bc (3.6)
Average slope (%)	2.7b (0.38)	4.8c (0.46)	2.0ab (0.44)	1.6ab (0.16)	1.2ab (0.22)	0.9a (0.24))
Maximum slope (%)	3.4ab (0.45)	5.7b (0.61)	3.0a (0.70)	2.0a (0.18)	1.7a (0.27)	1.5a (0.31)
Ground roughness class	n/a	n/a	2.6c (0.13)	1.9ab (0.06)	2.0ab (0.08)	2.1ab (0.08)
Ground roughness obstacle occurrence/100 m^2	n/a	n/a	23.3d (1.5)	15.1bc (1.2)	13.0ab (0.8)	17.5bcd (2.1)
Total ground roughness obstacle volume/100 m^2	n/a	n/a	1.19c (0.17)	0.53a (0.03)	0.60ab (0.05)	0.66ab (0.06)

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Table 3. Mean physiographic characteristics and soil conditions, before scarification, for different treatment blocks (concl.).

Condition	Block (trial and machine)			
	1980 Tree-length			1981
	Row scarifier	C&H plow	TTS	Row scarifier
Exposed bedrock (% coverage)	0.0a (0.0)	0.0a (0.0)	0.0a (0.0)	0.0a (0.0)
Soil depth (cm) [b]	86bc (3.5)	90bc (3.6)	77b (4.4)	94cd (2.2)
Effective soil depth (cm) [c]	60.0c (0.0)	57.8c (0.9)	57.6c (1.1)	54.0c (1.3)
LFH depth (cm)	10.2abc (0.76)	7.7a (0.42)	11.1bcd (0.77)	10.4bc (0.39)
Moisture regime	3.7bc (0.16)	2.2a (0.13)	3.4bc (0.17)	3.2bc (0.11)
Stoniness frequency (%)	30.5ab (5.0)	21.4a (3.8)	34.9ab (3.7)	51.4cd (2.9)
Average slope (%)	1.2ab (0.20)	1.2ab (0.29)	1.8ab (0.30)	2.1ab (0.21)
Maximum slope (%)	2.0a (0.27)	2.2a (0.45)	2.6a (0.37)	2.8a (0.27)
Ground roughness class	2.2abc (0.13)	1.8a (0.10)	2.1ab (0.07)	2.2bc (0.09)
Ground roughness obstacle occurrence/100 m^2	19.4cd (1.4)	9.3a (0.7)	12.7ab (0.8)	13.5ab (0.8)
Total ground roughness obstacle volume/100 m^2	0.78abc (0.07)	0.37a (0.04)	0.56ab (0.05)	0.82bc (0.10)

[a] Standard error
[b] To a maximum of 100 cm
[c] To a maximum of 60 cm

There is no significant difference (P = 0.05) between values followed by the same letter(s) in any given row.

Stumps were significantly more numerous in the 1979 and 1980 tree-length row scarifier blocks than on most others. The fewest stumps were found on the tree-length C&H plow block. There was relatively little variation in mean stump cross-sectional area between scarification chances. Most notable were the low values associated with the 1979 and 1980 tree-length row scarifier blocks. There was even less variation in mean stump heights. The only significant differences were associated with the high values for the 1979 row scarifier block.

Differences in some physiographic and soil conditions among treatment blocks were also evident (Table 3). Although there was little exposed bedrock on any of the sites, the 1978 row scarifier and mini-barrel blocks had the shallowest soils. The tree-length C&H plow block had significantly drier moisture regimes and shallower LFH depths, on average, than most others. The wettest moisture regimes and deepest LFH depths were found in the 1978 and 1979 row scarifier blocks.

The stoniest soils were found in the two 1978 blocks, whereas the least stony sites were in the 1980 tree-length blocks. Slopes were quite gentle throughout, although greater slopes (both average and maximum) were recorded in the mini-barrel block. The greatest degree of ground roughness was found in the 1979 row scarifier block, although none of the blocks possessed particularly difficult conditions. The lowest values for ground roughness were recorded for the tree-length C&H plow block.

Over all, conditions appeared to be the most severe in the 1979 row scarifier block.

Effect of Logging System on Slash Conditions

Comparisons of the effects of harvesting systems are easily confounded by differences in the age, density, species composition or tree size of the stands logged. Consequently, while an examination of slash loadings on the 1980 full-tree and tree-length logged plots may provide some idea of the effects of the two systems, differences in stand characteristics obscure the results.

To obtain a more precise indication of effects on slash loading, the impact of full-tree and tree-length logging was examined in three different stands (separate from those examined during the main study), each representing a particular stand type (Fig. 9, Tables A1 and A2). Full-tree logging significantly reduced slash $\leqslant 10$ cm in diameter on all three sites (Fig. 9), but had no consistent effect on quantities of larger slash. As a result, the overall impact depended largely on the relative proportion of larger to smaller slash. In the jack pine-black spruce type, where small slash (<10 cm in diameter) comprised only 30% of the total slash volume (i.e., on the tree-length harvested area), variations in cull and utilization completely overshadowed the effects of full-tree logging on total slash loadings. However, for both the upland and the lowland black spruce types, small slash comprised 50-55% of the total slash volume, and full-tree logging resulted in significant reductions in total loadings.

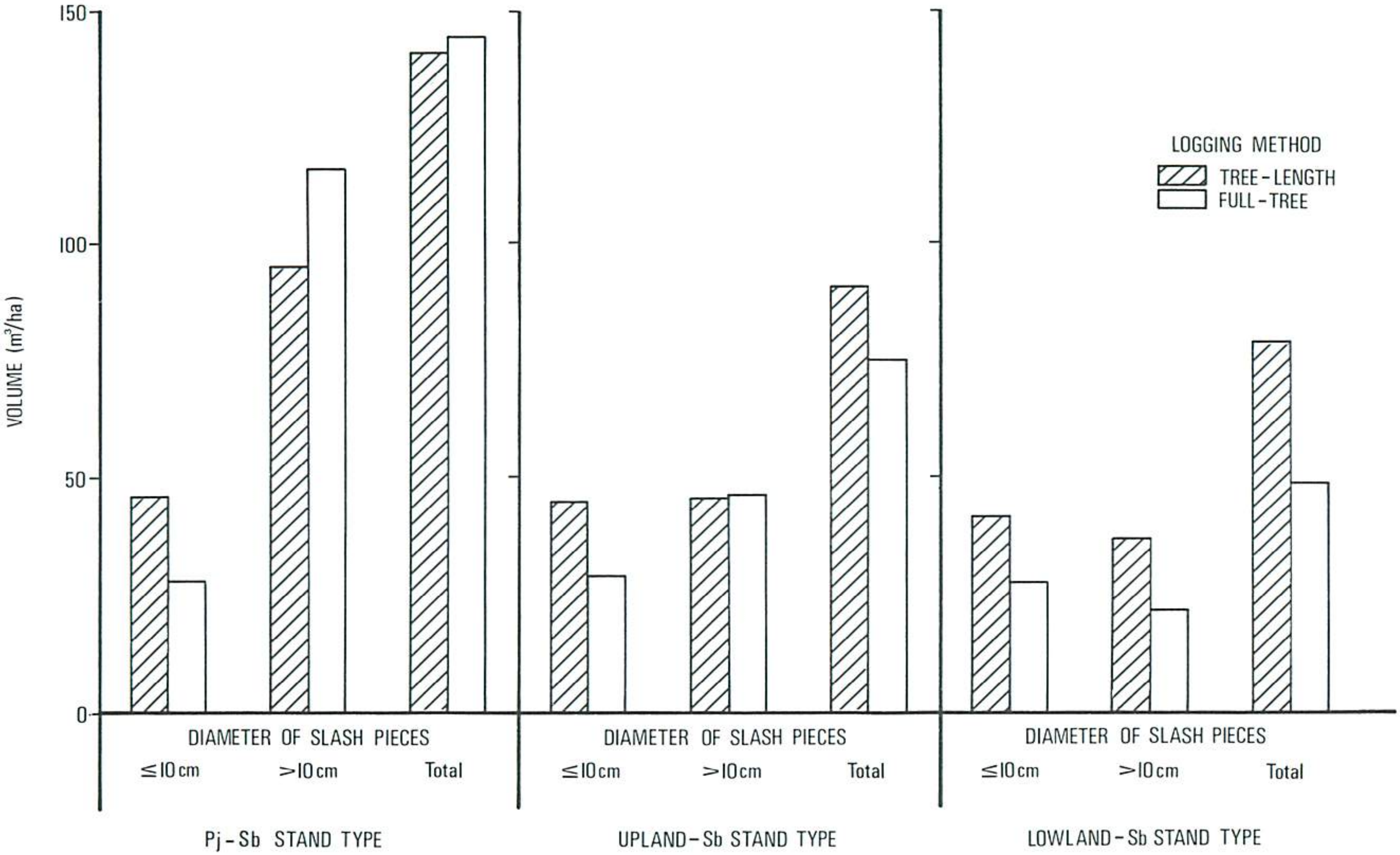

Figure 9. Slash volumes after full-tree and tree-length logging on different site types, Madden Lake Road, 1980.

Slash volumes (for pieces ≥ 7 cm) of the two major species, jack pine and black spruce, were also compared (Table A2). On each site, full-tree logging led to significant reductions (40-65%) in the frequency and volume of black spruce slash. However, similar trends were not apparent for jack pine slash.

These differences in relative slash loadings with the two species are largely a reflection of successional trends and stand age. At the time of harvest, the stands were at least 100 years old, and the jack pine component was decadent. At least 85% of the jack pine slash left after logging (i.e., on the tree-length sites) was dead at the time of harvest (Fig. 10). Under such conditions, post-harvest slash loadings will be high, regardless of the logging system employed. In contrast, only 35-50% of the black spruce slash volume was dead at the time of harvest. The black spruce lowland stand had the smallest component of 'dead' black spruce slash of any of the stands.

Time Studies

Results of the continuous time studies were broken down by machine time elements for each equipment combination in each trial. Productivity was examined in terms of the major time elements comprising total machine time (TMT) (Table 4), as well as through a more detailed breakdown of productive machine time (PMT) (Table 5) and short-term delays (Table A3). Definitions of machine time elements and formulas, and both short-term and plot study time elements, are given in Appendix C.

There were large variations among machines and trials in the proportion of TMT consisting of PMT (Table 4). The 1978 row scarifier and the mini-barrels had the best PMTs (93.0 and 85.7%, respectively), while the row scarifier in 1979 and 1980 had the poorest. In most cases, the majority of downtime was a result of repairs to the prime mover. Major repairs to the scarifiers were required in three of the machine-trial combinations as follows: to fix the nose, moldboards and rolling drum of the outer portion of the modified C&H plow; to repair the Bräcke hitch assembly used with the TTS, as well as to replace the bearings and repair the bolts on one of the discs; and, in 1981, to weld one of the moldboards and repair the hitch and hydraulic hosing on the row scarifier. Much of the miscellaneous delay time was a result of being stuck.

Effective productive time (EPT) comprised from 46 to 72% of PMT (Table 5). EPT was greatest with the 1978 and 1981 row scarifiers, and least with the 1980 row scarifier. The TTS and the modified C&H plow took considerably less time on average to turn around at the end of a pass (maneuver) than either the row scarifier or the mini-barrels. The prime mover for the row scarifier tended to have greater difficulty with obstacles than did the other prime movers, as was evident from the greater PMT attributed to obstacle-prime mover. Over all, when one considers both the implement and prime mover in terms of PMT, the modified C&H plow and the TTS were least affected by obstacles.

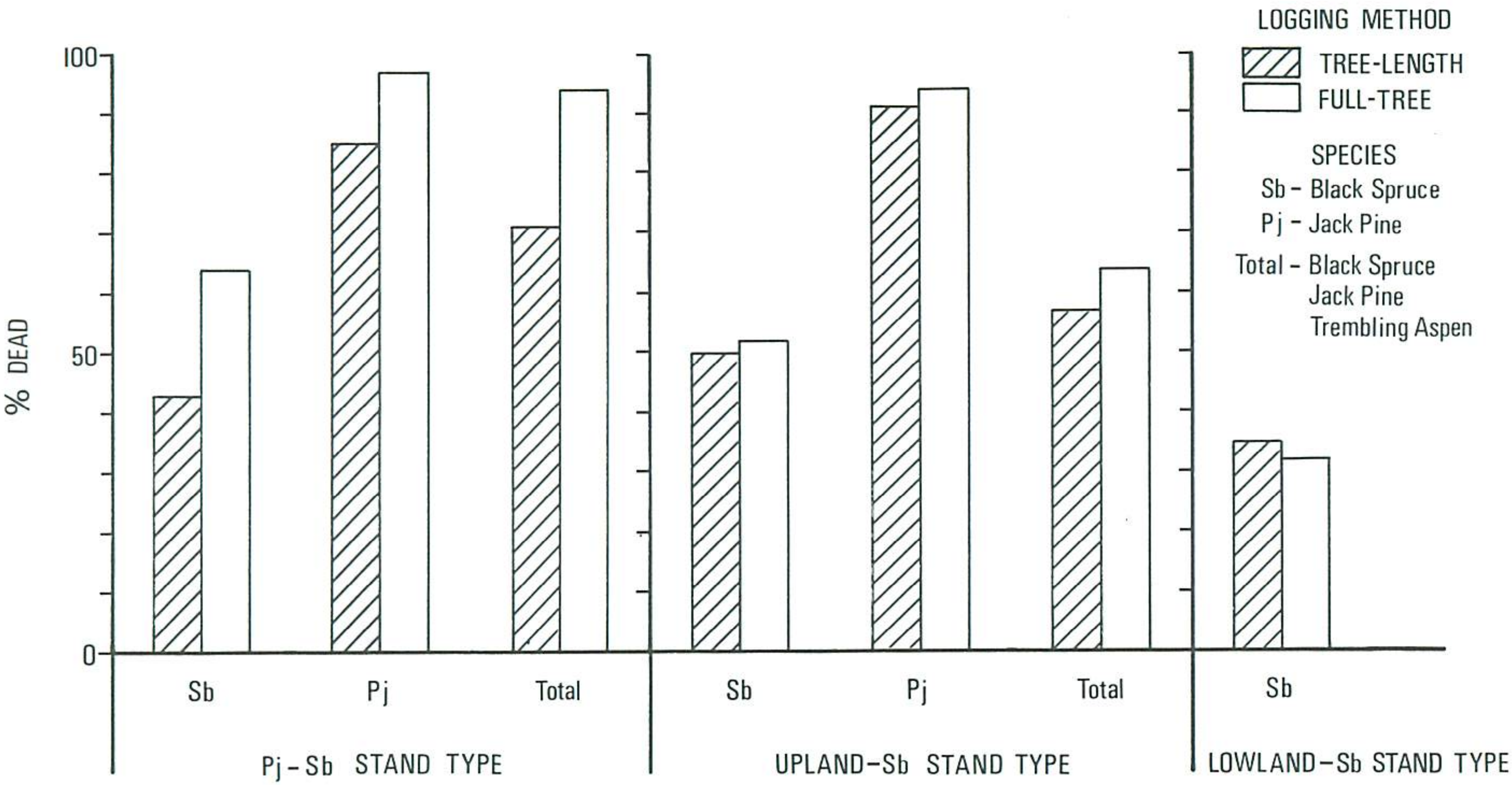

Figure 10. Estimated proportion of slash volume >7 cm diameter on tree-length and full-tree logged sites that was dead at the time of harvest, for three stand types.

Table 4. Summary of major time elements (continuous time study) comprising total machine time

		Time elements (%)				
		Machine and operation	Downtime for active repair and service (>15 min)			
			Repair		Service	
Machine	Trial year	Productive machine time (%)	Implement (%)	Prime mover (%)	Implement (%)	Prime mover (%)
Row scarifier	1978	93.0	1.0	1.4	-	-
Row scarifier	1979	46.7	-	21.2	-	-
Row scarifier	1980	36.4	2.6	40.3	-	-
Row scarifier	1981	67.9	8.9	8.4	0.3	0.9
Mini-barrels	1978	85.7	-	6.6	-	0.7
Modified C&H plow	1980	69.0	18.3	1.0	-	0.4
TTS	1980	62.0	11.8	14.6	1.0	2.5

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Table 4. Summary of major time elements (continuous time study) comprising total machine time (concl.)

Machine	Trial year	Time elements (%) — Downtime attributable to other delays (>15 min) — Awaiting parts: Implement (%)	Awaiting parts: Prime mover (%)	Awaiting mechanic: Implement (%)	Awaiting mechanic: Prime mover (%)	Miscellaneous delay and major component (%)
Row scarifier	1978	-	-	-	-	4.6 (stuck 2.7)
Row scarifier	1979	-	13.6	-	-	18.5 (stuck 8.8)
Row scarifier	1980	-	1.5	-	16.8	2.3 (stuck 1.0)
Row scarifier	1981	5.6	1.2	3.7	-	3.1 (stuck 1.7)
Mini-barrels	1978	-	5.7	-	-	1.3
Modified C&H plow	1980	-	-	-	-	11.3 (stuck 10.0)
TTS	1980	-	1.2	-	-	6.9 (stuck 1.3)

Table 5. Summary of time elements comprising productive machine time

Scarifier	Year	Productive machine time								
				Maneuver		Obstacle				
		Effective productive time (%)	Travel (%)	(%)	Mean time per turn (min)	Implement (%)	Prime mover (%)	Sub-total (%)	Short-term delays[a] (%)	Total (%)
Row scarifier	1978	71.7	3.6	9.0	0.72	0.5	5.0	89.8	10.2	100.0
Row scarifier	1979	59.0	2.9	7.8	0.74	1.0	13.2	83.9	16.1	100.0
Row scarifier	1980	45.8	3.0	10.1	0.94	1.4	17.9	78.2	21.8	100.0
Row scarifier	1981	70.3	2.7	12.3	1.48	1.3	6.3	92.9	7.1	100.0
Mini-barrels	1978	63.3	0.3	11.8	1.00	2.1	5.0	82.5	17.5	100.0
Modified C&H plow	1980	66.0	6.9	7.4	0.57	1.2	2.9	84.4	15.6	100.0
TTS	1980	59.7	5.1	4.8	0.36	2.9	1.3	73.8	26.2	100.0

[a] Less than 15 minutes

Short-term delays constituted 7-26% of PMT. The highest percentages were associated with the TTS and the 1980 row scarifier. A breakdown of these delays (Table A3) revealed that, for these two machines, 47-78% of this time was spent on the prime mover, mostly in repairs and service. In contrast, 65% of the short-term delays with the 1978 row scarifier and 67% of those with the modified C&H plow were "personal" or "unattributed".

Utilization, mechanical availability and CPPA availability were calculated for each machine-trial combination (Fig. 11), in accordance with formulas presented by Folkema et al. (1981) (Appendix C). CPPA availability varied from 38 to 93%, and utilization ranged from 36 to 93%. The highest values were associated with the 1978 row scarifier and the mini-barrels. The lowest values were obtained with the row scarifier in 1979 and 1980. Mechanical availability varied from 46 to 97%, and again, the 1978 row scarifier and the mini-barrels demonstrated the best availability, while the 1980 row scarifier demonstrated the poorest.

An examination of mean functioning time (MFT) and mean productive time (MPT) per pass within the subplots (Table 6) revealed that the TTS was by far the fastest machine. Its rate of travel was at least twice that of any of the others. Most of the machines were operated at approximately 2 km/hr, the only other notable exceptions being the slow functioning times for the 1978 and 1981 row scarifier (1.4 and 1.2 km/hr, respectively). MPTs were usually less than 0.5 km/hr slower than MFTs. A comparison of MFT and MPT for repeat and initial passes with the TTS[4] revealed no significant differences in either case.

Total functioning time (TFT) and total productive time (TPT) were calculated on an area basis, i.e., for all passes within each subplot (Table 7). The highest productivity (about 1.1 ha/hr TFT and 1.0 ha/hr TPT) was achieved with the TTS, followed by the modified C&H plow (approximately 0.9 ha/hr for both TFT and TPT). The 1981 row scarifier had the poorest productivity, while that of the 1978 row scarifier was also quite low.

There were a number of significant correlations between site conditions and both productive and functioning time (Tables A4-A7). The majority of these were positive (62% for MPT, 68% for TPT, 73% for MFT and 78% for TFT), but there were also several inverse relationships. Undoubtedly some significant correlations arose merely by chance, in view of the large number of correlation coefficients examined. The largest number of significant correlations, for both functioning and productive time, were found with the row scarifier in 1981 and for all years combined. Very few significant correlations were evident with either the 1979 row scarifier or the mini-barrels.

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[4] Repeat passes refer to the final pass in what amounted to a triple pass system with the TTS. This system was used to make a second pass by straddling the furrows created with the first pass. The next pass was then made on untreated ground, but as close as possible to the outside furrow created by the previous pass, and the pattern (double passing) was repeated. Once all initial (first and second) passes had been made, the area was 'retreated' with a third pass at normal 2-m spacing.

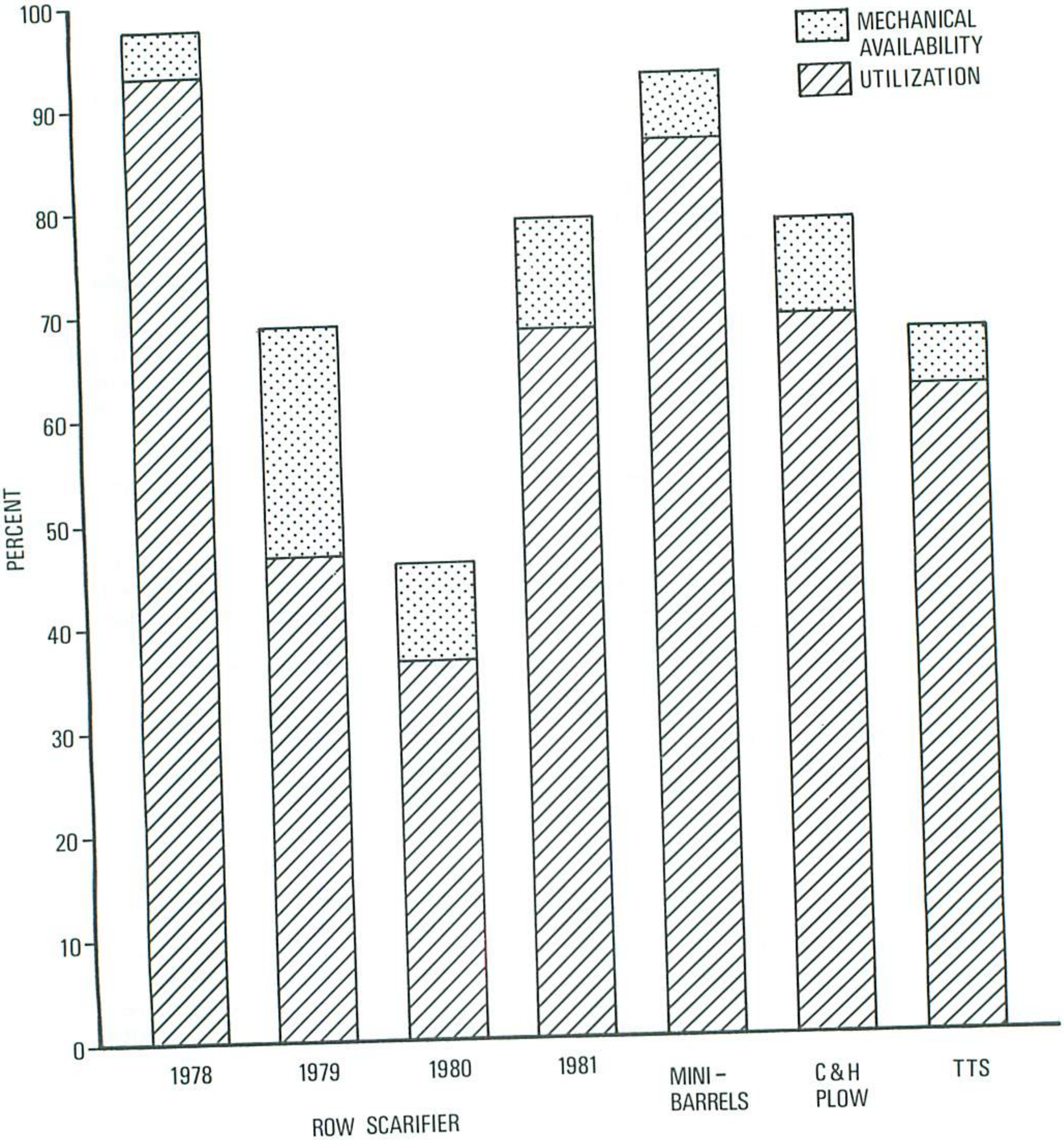

Figure 11. Utilization and mechanical availability (%)[a] based on continuous time studies.

a CPPA availability was virtually identical to utilization for all machine-trial combinations, with the exception of the 1981 row scarifier (67.9% utilization versus 78.6% CPPA availability).

Table 6. Comparison of mean functioning time and mean productive time per pass in each subplot, all machines and trials

Machine	Trial	Mean functioning time [a] (km/hr)	Mean productive time [b] (km/hr)
Row scarifier	1978	1.4b (.090) [c]	1.3a (.080)
Row scarifier	1979	1.8c (.034)	1.6bc (.040)
Row scarifier	1980 F [d]	2.2d (.027)	1.8bc (.034)
Row scarifier	1980 T [d]	2.0cd (.049)	1.5b (.051)
Row scarifier	1981	1.2a (.011)	1.2a (.013)
Mini-barrels	1978	2.1d (.050)	1.9cd (.053)
Modified C&H plow	1980 F	2.2d (.027)	2.0cd (.030)
Modified C&H plow	1980 T	2.3d (.026)	2.1d (.034)
TTS	1980 F	4.6e (.062)	4.4e (.068)
TTS	1980 T	4.5e (.078)	3.9e (.092)

[a] Based only on passes with no machine delays
[b] Based only on passes with no machine delays other than obstacle delays
[c] Standard error
[d] F = full-tree logged, T = tree-length logged
There is no significant difference (P = 0.05) between values followed by the letter(s) in any given column.

The relationships between MPT, TPT and MFT and individual site conditions were never particularly strong (R > 0.80), but higher correlations were evident with TFT. Site conditions which were correlated most frequently in a consistent manner (i.e., positively or negatively, but not both) with functioning time included average slope and several measures of slash loading, largely of slash volume. Those most frequently and consistently correlated with productive time were various measures of slash loading and the frequency of ground roughness obstacles (negative correlation).

Isolation of those site conditions that have the greatest impact on proproductivity, and the determination of cause and effect relationships, are complicated by numerous correlations between the different independent variables (Table A8). Stepwise linear regression was used to identify some of the more important variables affecting productivity, and to determine the relative contribution of each (Tables A9-A12). Equations are not presented because of the relatively small sample sizes, the lack of independence of some of the predictors, the imprecise nature of estimates for some of the independent variables, and the absence of consistently strong, well fitted relationships.

Table 7. Comparison of mean total functioning and productive times per subplot, all machines and trials

Machine	Trial	Total functioning time [a] (ha/hr)	Total productive time [b] (ha/hr)
Row scarifier	1978	0.48b (.011) [c]	0.43b (.013)
Row scarifier	1979	0.77cd (.033)	0.65d (.025)
Row scarifier	1980 F [d]	0.73c (.019)	0.63cd (.022)
Row scarifier	1980 T [d]	0.78cde (.052)	0.51c (.030)
Row scarifier	1981	0.31a (.008)	0.29a (.007)
Mini-barrels	1978	0.79c (.042)	0.70cd (.038)
Modified C&H plow	1980 F	0.88de (.011)	0.87e (.011)
Modified C&H plow	1980 T	0.91de (.010)	0.88e (.017)
TTS	1980 F	1.16e (.042)	1.06e (.044)
TTS	1980 T	1.11e (.039)	0.93e (.054)

[a] Based only on subplots with no machine delays

[b] Based only on subplots with no machine delays other than obstacle delays

[c] Standard error

[d] F = full-tree logged, T = tree-length logged

There is no significant difference (P = 0.05) between values followed by the same letter(s) in any given column.

In almost all cases, less than half the variability in MFT, MPT and TPT was accounted for by the site conditions examined. In several instances, relatively high R^2 values were obtained with TFT, but sample sizes were very small and, on the basis of Mallow's statistic, the equations usually did not fit the data well. Multiple linear relationships were usually stronger for functioning time than for productive time.

Site conditions most frequently found in the best-fit linear equations for productivity (MFT, MPT, TFT and TPT) were slash frequency of pieces < 7 cm, maximum slope, and slash volume of pieces 11-20 cm. However, in half of the equations involving maximum slope, the coefficient for this parameter was negative (the relationship was inverse). Over all, one third of the independent variables in the best-fit equations for productivity had negative coefficients.

Seedbed Exposure

The modified C&H plow created the greatest overall (gross) quantities of both black spruce and jack pine seedbed (Table 8). There was considerable variation in gross seedbed exposure (GSE) from year to year with the row scarifier but, with the exception of the C&H plow, it produced more seedbed on a given site than did any of the other machines tested (although differences often were not significant). The Broyeur and the TTS provided the smallest quantities of GSE in 1979 and 1980, respectively.

The C&H plow, on the tree-length logged site, also produced the largest net seedbed exposure (NSE), followed by the mini-barrels, and the row scarifier and the C&H plow on the 1980 full-tree logged site. Again, there was considerable variation in NSE with the row scarifier from year to year and between sites. The Broyeur produced the lowest values for NSE. Differences in the relative rankings of the machines for NSE as compared with GSE are a result of net scarification. The highest values for net scarification (i.e., the most complete coverage of the scarification chance by the actual scarifying implement) were achieved by the Broyeur and the 1981 row scarifier. The lowest values were associated with the Atkinson Backscratcher and the mini-barrels. Again, there was considerable variation among sites with the row scarifier.

A comparison of triple-pass coverage on the one hand with double-pass coverage with the TTS on the other revealed no consistent differences in either black spruce or jack pine GSE.

GSE was also examined from the perspective of seedbed distribution, i.e., the attainment of threshold or minimum values per 4-m^2 quadrat (Fig. 12). The row scarifier in 1978 and 1980 and the mini-barrels did the best job of producing at least some black spruce seedbed ($\geq$5%) in each quadrat. However, even with the best machine, the 1978 row scarifier, 35% of the area, when considered on a 4-m^2 quadrat basis, had <5% receptive seedbed. The poorest seedbed distribution in this respect was found on the Broyeur and TTS blocks. Likewise, the poorest jack pine seedbed distribution from this perspective was associated with the 1981 row scarifier and the Broyeur.

Examination of black spruce stocking probability curves for different levels of GSE at seeding rates of 100,000 and 150,000 viable seed/ha (*sensu* Riley 1980) revealed that an inflection point often occurred near 15% GSE.[5] That is, as the amount of GSE per 4-m^2 quadrat increased, up to about 15%, there was a substantial rise in stocking. However, once this level was surpassed, returns diminished; further increases in GSE did not produce commensurate increases in stocking. There was little increase in stocking probability at black spruce GSE levels in excess of 25%.

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[5] based on preliminary results from aerial seeding trials carried out on the areas scarified during these trials (R.L. Fleming, unpublished data)

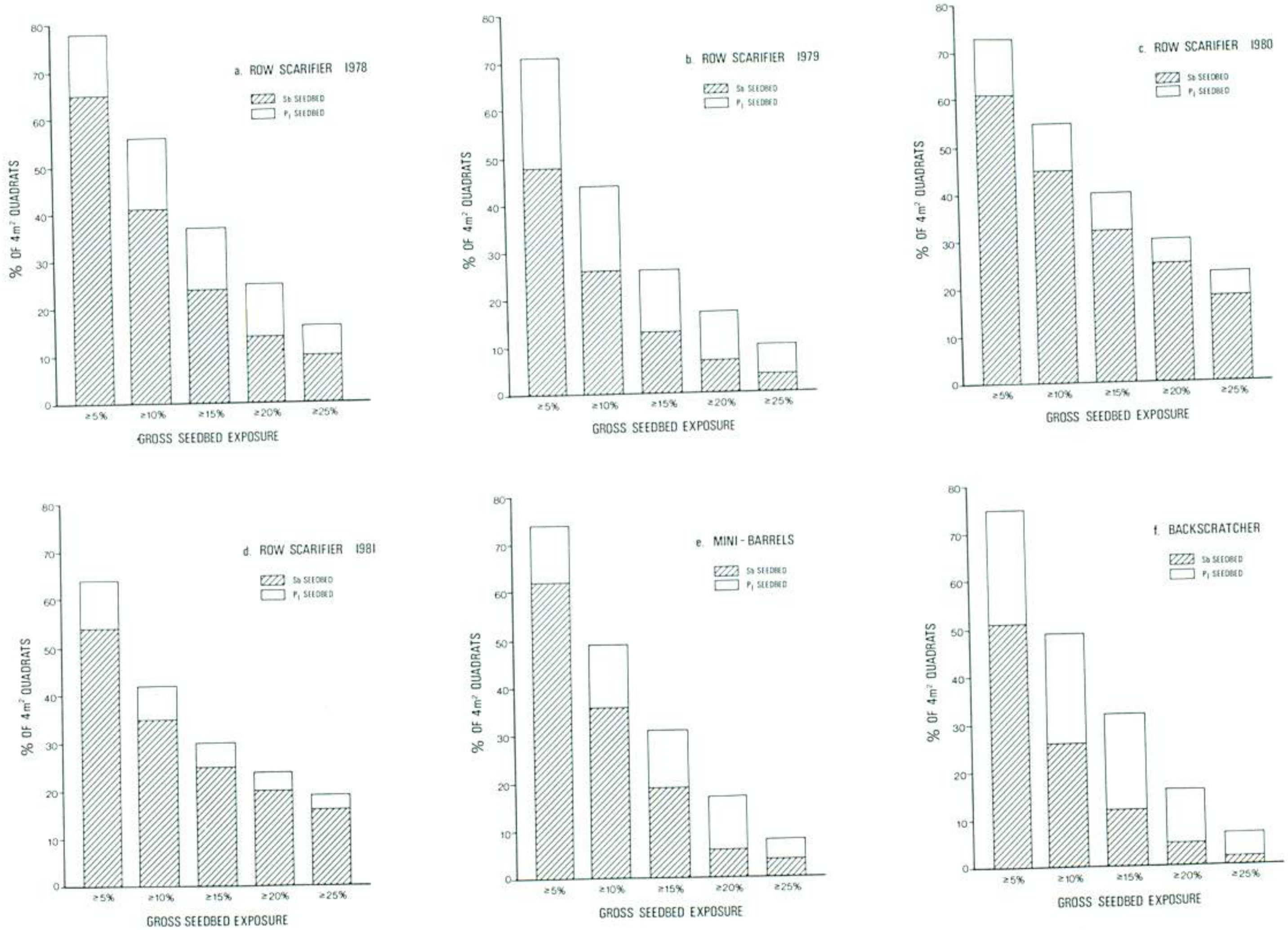

Figure 12. Seedbed distribution with machines examined in scarification trials, 1979-1981.

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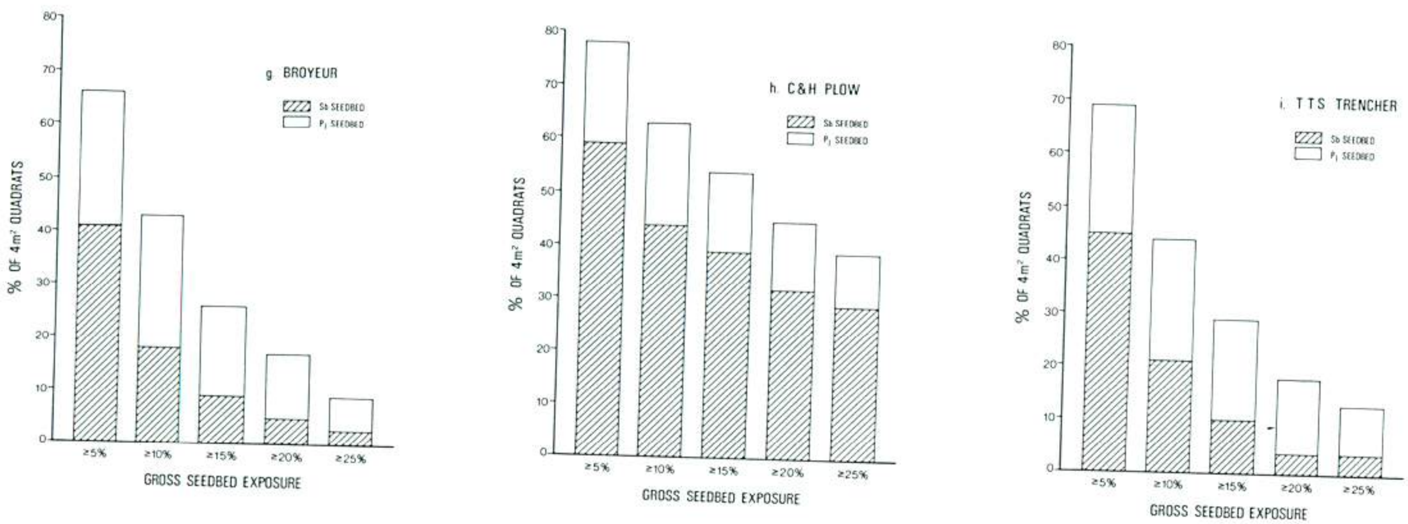

Figure 12. Seedbed distribution with machines examined in scarification trials, 1979-1981.

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Table 8. Comparisons of gross and net seedbed exposure [a], all machines and trials

Machine	Year	Gross black spruce seedbed (%)	Gross jack pine seedbed (%)	Net scarification (%)	Net black spruce seedbed (%)	Net jack pine seedbed (%)
Row scarifier	1978	9.8ab (0.62) [b]	13.3ab (0.70)	57.1	17.1bc (0.96)	23.3bc (1.08)
Row scarifier	1979	7.0a (0.64)	11.0a (0.74)	47.7	14.7bc (1.33)	23.1bc (1.71)
Row scarifier	1980 F [c]	14.8c (0.98)	17.6bc (1.01)	59.9	24.7d (1.51)	29.4c (1.60)
Row scarifier	1980 T [c]	8.2ab (0.98)	11.9ab (1.15)	63.3	13.0b (1.56)	18.8b (1.83)
Row scarifier	1981	10.9b (0.55)	13.4ab (0.60)	76.7	14.2bc (0.65)	17.4ab (0.70)
Mini-barrels	1979	8.0ab (0.44)	10.9a (0.55)	33.1	24.5d (1.24)	32.9cd (1.85)
Atkinson Backscratcher	1979	6.6a (0.50)	10.9a (0.63)	37.2	17.7bcd (1.12)	29.3c (1.86)
Broyeur	1979	5.8a (0.59)	10.7a (0.78)	89.9	6.4a (0.88)	11.9a (1.15)
Modified C&H plow	1980 F	12.4bc (1.43)	19.1c (1.67)	58.7	21.1cd (2.00)	32.5cd (3.59)
Modified C&H plow	1980 T	22.3f (1.55)	31.3d (1.76)	61.5	36.3e (2.21)	50.9e (3.06)
TTS	1980 F	6.8a (0.60)	13.7abc (0.93)	46.2	14.7bc (1.19)	29.6c (2.44)
TTS	1980 T	5.6a (0.53)	9.9a (0.72)	44.3	12.6b (1.50)	22.3bc (2.66)

a For all quadrats with <10% lowland seedbed
b Standard error
c F = full-tree logged, T = tree-length logged

There is no significant difference (P = 0.05) between values followed by the same letter(s) in any given column.

At a threshold value of 15% GSE for black spruce, the modified C&H plow, followed by the 1980 row scarifier, produced the best seedbed distribution (with 39% and 32% of the quadrats sampled in the respective areas meeting or exceeding the threshold value). In contrast, by the same standard, the Broyeur, TTS, Backscratcher and 1979 row scarifier performed poorly. However, the C&H plow and the 1980 row scarifier also produced the greatest amount of 'excessive' GSE (the largest percentage of quadrats with >25% seedbed exposure).

A threshold value of 15% GSE (per 4-m^2 quadrat) is also recommended for jack pine seedbed distribution for subsequent aerial seeding (Riley 1980). On the basis of this value, the modified C&H plow and the 1980 row scarifier again provided the best seedbed distribution (with 54% and 40%, respectively, of the quadrats assessed meeting or exceeding the threshold value). The poorest results were obtained with the Broyeur and the 1979 row scarifier.

An examination of correlations among GSE[6] and various site conditions revealed a number of significant relationships (Tables 9 and 10). For each machine-trial combination there were at least two, and usually six or more, site variables that were correlated significantly with GSE. In the vast majority of cases (93% for black spruce GSE and 91% for jack pine GSE) these involved inverse relationships, i.e., as site constraints increased, GSE decreased. Stump height was the most consistent exception; in three cases stump height was correlated positively with black spruce and jack pine GSE. Although high stumps are usually an obstacle to scarification equipment, on three treatment blocks higher stumps served as an index for areas that could be treated more effectively. Mean stump height per trial rarely exceeded 35 cm; therefore, somewhat higher stumps than average were unlikely to constitute a major impediment. However, the reason for improved site preparation on areas with higher stumps is unclear.

Individual site variables significantly correlated with GSE changed from machine to machine and from trial to trial. Those displaying strong linear or curvilinear relationships in some instances often exhibited little correlation in others. Those site conditions that most frequently demonstrated significant relationships with GSE were stump frequency, total stump cross-sectional area, total stump volume, slash volume of pieces 7-10 cm in diameter, LFH depth, soil texture, moisture regime and ground roughness obstacle occurrence. In all cases, these correlations were negative. Hence, as moisture regimes got wetter and soil textures became finer, GSE decreased.

The combined effects of various site conditions on GSE were investigated through multiple linear regression (Tables A13 and A14). The R^2 values for the best-fit equations ranged from 0.19 to 0.67, and in only half of the trials did the site conditions examined account for more than 50% of the variation in seedbed exposure ($R^2 > 0.50$). Further evidence of the rather crude nature of these relationships is provided by the values for Mallow's statistic. The importance

[6] GSE rather than NSE was chosen as the dependent variable because site conditions affect inter-row spacing as well as seedbed preparation within the furrow.

Table 9. Significant correlations (P = 0.05) between gross black spruce seedbed exposure and site conditions, all machines and trials

Site condition	Machine: Row scarifier 1978	Row scarifier 1979	Row scarifier 1980	Row scarifier 1981	Row scarifier Combined	C&H plow	TTS	Mini-barrels	No. of significant correlations
Slash frequency/m, <7 cm		-0.50			0.42				2
Slash frequency/m, ≥7 cm			-0.47		-0.33	-0.34			3
Slash volume, 7-10 cm			-0.43	-0.33	-0.39	-0.30	-0.47		5
Slash volume, 11-20 cm									0
Slash volume, ≥7 cm						-0.40 [a]			1
Total slash volume		-0.45				-0.37 [a]			2
Stump frequency			-0.36	-0.44	-0.34	-0.40 [a]		-0.57 [a]	5
Stump height	0.52	0.50						0.46	3
Total stump cross-sectional area	-0.39		-0.31	-0.37	-0.39		-0.39		5
Total stump volume			-0.31	-0.38	-0.34		-0.30	-0.46 [a]	5
Residuals/ha					-0.18				1
LFH depth			-0.36	-0.53	-0.41	-0.49 [a]		-0.48	5
Stoniness frequency				-0.51	-0.26	-0.66 [a]	-0.45	-0.54	5
Surface stones				-0.58 [b]	-0.20				2
Boulder coverage						-0.51	-0.53		2
Soil texture		-0.48	-0.36	-0.51	-0.19	-0.47			5
Moisture regime			-0.47	-0.40	-0.36	-0.53 [a]			4
Average slope		-0.54 [a]							1
Maximum slope		-0.53 [a]					0.34		2
Ground roughness					-0.23	-0.48			2
Ground roughness height class			-0.36	-0.51	-0.44	-0.53			4
Total ground roughness obstacle volume			-0.31		-0.27	-0.50	-0.35		4
Number of significant correlation	2	6	10	10	15	13	7	5	68

[a] lny = x
[b] -1/y = x

Table 10. Significant correlations (P = 0.05) between gross jack pine seedbed exposure and site conditions, all machines and trials

Site condition	Machine: Row scarifier 1978	Row scarifier 1979	Row scarifier 1980	Row scarifier 1981	Row scarifier Combined	C&H plow	TTS	Mini-barrels	No. of significant correlations
Slash frequency/m, <7 cm						0.41		0.46	2
Slash frequency/m, ⩾7 cm			-0.36		-0.21	-0.35	-0.35		4
Slash volume, 7-10 cm			-0.34	-0.36 [b]	-0.30	-0.32	-0.59 [b]		5
Slash volume, 11-20 cm		-0.50							1
Slash volume, ⩾7 cm						-0.31			1
Total slash volume		-0.52 [a]				-0.29 [b]			2
Stump frequency			-0.28	-0.57 [a]	-0.31	-0.33	-0.40 [b]	-0.42	6
Stump height	0.44				0.17		0.31		3
Total stump cross-sectional area				-0.47	-0.38		-0.38		3
Total stump volume			-0.28	-0.54 [b]	-0.31		-0.47 [b]		4
Residuals/ha									0
LFH depth			-0.36	-0.61 [a]	-0.36	-0.59		-0.57 [a]	5
Stoniness frequency	-0.37			-0.55 [a]	-0.31	-0.72 [b]	-0.56	-0.49	6
Surface stones				-0.43	-0.18				2
Boulder coverage						-0.56	-0.54		2
Soil texture		-0.48	-0.33	-0.59	-0.25	-0.57			5
Moisture regime			-0.44	-0.47	-0.36	-0.63		-0.35	5
Average slope		-0.69							1
Maximum slope		-0.66					0.34		2
Ground roughness						-0.25			1
Ground roughness height class			-0.30	-0.59	-0.39	-0.50	-0.48 [b]		5
Total ground roughness obstacle volume					-0.23	-0.37	-0.45 [b]		3
Number of significant correlations	2	5	8	10	13	14	11	5	68

[a] y = log x
[b] lny = x

of particular site conditions varied greatly from machine to machine and from trial to trial for the row scarifier. When all machines and trials were considered, 16 different site factors were found in the best-fit equations for black spruce and/or jack pine GSE. Those which occurred most frequently were, in descending order, LFH depth , soil texture, stoniness frequency, slash volume of pieces 7-10 cm, maximum slope and slash frequency of pieces ≥7 cm.

The relationships between functioning time and productive time on the one hand, and gross seedbed exposure on the other, were also investigated. There were few significant correlations, and those that were significant were not particularly strong. In addition, scatter plots did not disclose any strong curvilinear trends.

DISCUSSION

Full-tree Logging

Full-tree logging holds considerable promise as a technique for reducing slash-related regeneration problems. Tops and limbs of the harvested trees are concentrated at roadside landings, rather than being distributed over the cutover. This reduces slash coverage of favorable seedbeds, and may also facilitate subsequent scarification treatment (Haavisto 1979, Saltarelli 1980, Puttock 1984, Smith et al. 1985).[7]

The extent to which scarification is facilitated depends upon the importance of slash as a limiting factor and the magnitude of the reductions that can be achieved. Some scarifiers are more severely hampered than others by slash (cf. Smith et al. 1985). As well, the size and distribution (aggregation) of slash may be of greater concern than total slash loading. In both the present study and that of Smith et al. (1985), the volume of branch-sized slash appeared to have a greater impact on seedbed production than did total slash volume. However, we found that the volume of large-diameter slash and total slash volume were the most important slash characteristics affecting productivity.

The quantity of residue on the cutover after logging is a reflection of the species composition and the age of the stand, the level of utilization, and the method of harvest (Puttock 1984). Our data indicate that scarification results, in terms of seedbed exposure, can be improved by full-tree logging (if indeed slash loading is a major limiting factor) because the volume of branch-sized slash left on the cutover is reduced. However, stand age, stand composition and utilization often have a much greater impact on total slash volumes, and therefore on machine productivity, than full-tree logging. In stands with a large proportion of unmerchantable or dead material or on sites with poor utilization, full-tree logging is unlikely to reduce total slash volumes substantially.

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7 The serious negative impacts of full-tree logging on nutrient-poor sites (Morrison 1980, Gordon 1981) are not considered in this study. Full-tree logging also removes most seed-bearing cones to roadside and thus eliminates an important supplementary seed source (Morrison 1980).

Time Studies

The wide variation in PMT (from 36 to 93%) among the different machine combinations resulted from differences in the suitability and state of repair of the units as well as in the severity of site conditions and operator performance. PMTs for scarification trials generally range from 70 to 85% (Haarlaa 1973, Tynkkynen 1974, Seppala 1975, Smith et al. 1985, Puttock and Smith 1986). Excellent PMTs were obtained in 1978 because site conditions were not particularly demanding, and both scarification units were in good repair. The 1980 and 1981 sites were somewhat more difficult and this largely accounted for the lower PMTs associated with the modified C&H plow and the 1981 row scarifier. Initially, lengthy delays were encountered with the TTS when it was necessary to repair one of the discs; however, once this problem was overcome, the unit functioned effectively. The extremely low PMT value for the 1980 row scarifier reflected the decrepit condition of the prime mover. Numerous lengthy delays were incurred while parts were obtained and repairs were made. Delays were also experienced when it was necessary to repair the 1979 row scarifier unit, but these were primarily a result of the severe site conditions.

In some cases (e.g., the 1979 row scarifier and the modified C&H plow) lengthy delays were incurred while additional machinery was brought in to free the unit after it became stuck. These delays would have been much shorter if the units had been operating in pairs (two machines per block), as is often the case in operational situations.

Effective productive times, except in the case of the 1980 row scarifier, were well within the range reported in other scarification trials (Ryans 1982, Hedin 1985, Smith et al. 1985, Puttock and Smith 1986). The much lower EPT for the 1980 row scarifier was the result of numerous obstacle delays (although site conditions were not particularly severe), and short-term delays to repair the prime mover. In both cases these delays were largely a result of the disrepair of the tractor. While the time study methodology separates delays from productive time, operators of machinery that is in poor condition are likely to be more cautious. As a result, EPT travel speed, and, to some degree, scarification results will also be affected.

As is often the case when scarification trials are conducted on relatively small blocks, maneuvering accounted for a sizable portion (5-12%) of PMT. The percentage of time spent maneuvering could be reduced considerably in larger treatment blocks, particularly if the machinery was operated in a lands or square pattern, rather than on a run-by-run basis (Bäcke et al. 1978).

On the basis of productivity (time study), the TTS and the modified C&H plow units gave the best results. They could be maneuvered readily (mean time consumption per turn compared favorably with those of other machines and trials [Ryans 1982, Hedin 1985, Smith et al. 1985]), they were not unduly hampered by surface obstacles or site conditions, and they (particularly the TTS) produced the highest MFTs and MPTs within the plots. The values for MPT (km/hr) for these two units were comparable with the production rates reported by Coates and Haeussler (1984) for similar units in north central British Columbia. The travel speed of the TTS was significantly greater than that of any of the other machines, and although it was within the range reported by Hedin (1985) for a variety of trenchers, it was also 0.6-0.9 km/hr greater than those reported by Smith et al. (1985) for a similar skidder-pulled unit. However, neither the TTS nor the modified C&H plow was particularly reliable or effectively used when judged by mechanical availability and utilization.

Travel speeds with the mini-barrels (MFT of 2.1 km/hr, MPT of 1.9 km/hr) were lower and obstacle-prime mover delays were more numerous than might be expected with a skidder-pulled unit. However, unbeknownst to the operator, the brake of the prime mover was partially locked throughout much of the trial. Nevertheless, utilization and mechanical availability were quite good. Under normal operating conditions, productivity with this unit should fall somewhere between that obtained with the TTS and that obtained with the modified C&H plow.

In contrast, the row scarifier was considerably less productive. Even when the 1979 and 1980 results are ignored (because of severe site conditions [1979] and a dilapidated prime mover [1980]), it is evident that the unit was slower, treated less area per unit of time, took longer to maneuver and had greater difficulty with obstacles than did any of the others. In 1978, the combination of a reliable prime mover and a knowledgeable and experienced operator resulted in excellent availability and utilization. However, in 1981, with a different operator and prime mover, values for these two indices fell considerably. In defense of this unit, the small prime mover required is likely to be relatively inexpensive to purchase and operate.

The site parameters that most consistently demonstrated significant correlations with productivity and occurred most frequently in the best-fit multiple linear regressions were related to slash, stump and slope conditions. As such, these conditions (and, in particular, slash) constituted the major impediments to the movement of the machinery. However, in other circumstances (e.g., where slash loadings are not as high), differences in conditions such as soil moisture, stoniness and soil texture can have a greater impact on productivity than slash characteristics (Haarlaa 1973, Tynkkynen 1974, Seppala 1975).

It is not surprising that better relationships (more significant and consistent correlations and stronger regressions) were generally found between site conditions and functioning time as opposed to productive time. Values for productive time are confounded by a variety of short-term delays that obscure the effects of site to some extent.

As indicated by the best-fit linear regressions, site differences usually accounted for more of the variation in GSE than in productivity. Cutover sites such as these do not hinder the progress of large crawler tractors and skidders to the same extent as they reduce the effectiveness of scarification. The best relationships between productivity and site conditions were obtained with the row scarifier units, which consisted of small crawler tractors not designed to cope with rugged cutovers.

Site conditions such as slash loadings, stumps, boulders and slope can have a major impact on productivity, but to determine their effects, the machines must be operated on a greater range of conditions than was available in these trials. Small changes in a particular site attribute are unlikely to have much effect on the productivity of machines designed for logging work.

Seedbed Exposure

Of the machines examined, only the modified C&H plow and, at times, the row scarifier came close to providing the quantity and distribution of seedbed required for black spruce or jack pine aerial seeding. The most important results, in terms of the potential for seeding success, are those related to seedbed distribution. Riley (1980) suggested that, for jack pine aerial seeding, no more than 20% of the seeding chance (when considered on the basis of 4-m^2 units) should have $\leqslant$5% receptive seedbed, and furthermore, no more than 20% of the area should contain 6-15% receptive seedbed. The only machine able to approach these target requirements was the modified C&H plow; 22% of the quadrats sampled on the areas it treated had $\leqslant$5% receptive seedbed, and 24% had 5-14% receptive seedbed (Fig. 12). Seedbed production with the row scarifier in 1980 was also quite good. If the same target requirements were applied to black spruce seedbed distribution, the best results were again obtained with the modified C&H plow. However, in this case, 61% of the quadrats sampled had <15% receptive seedbed (Fig. 12). The poorest results were obtained with the Broyeur and the TTS.

The amount of seedbed required to achieve a high probability of stocking success is governed by the timing and rate of seeding, the number of applications of seed, the presence of supplementary seed sources (i.e., nearby stands and seed-bearing cones in the slash) and microsite conditions. Hence, seedbed requirements will vary somewhat, depending on the seeding prescription and the site (e.g., moisture regime). In alternate strip clearcuts, large quantities of seed are provided on a continuous basis, and the microclimate is moderated by the adjacent uncut strips (Jeglum 1984). As a result, a lower threshold value for black spruce seedbed distribution would be appropriate. On the basis of a threshold value of 10% receptive seedbed, the 1978 and 1980 row scarifier and the modified C&H plow produced the best results, although even in these cases, at least 55% of the areas treated contained inadequate quantities of seedbed.

Significant relationships among seedbed exposure and a variety of site conditions were found in all machine-trial combinations (Tables 9-10). The large number of correlations and the results of regression analysis suggest that site conditions can and do play a major role in determining the effectiveness of scarification. The importance of different conditions varies with the machinery involved and the particular site in question; in these trials, as in several others (e.g., Jahnke and Nilsson 1975, Skraamo 1976), no single condition or group of conditions stood out consistently as the dominant factor governing seedbed production. Slash loadings, stump characteristics, slope, LFH depth, stoniness, soil texture and moisture regime each explained a significant portion of the variation in seedbed exposure in several trials. While slash loadings can limit scarification performance (Berg et al. 1981, Smith et al. 1985), other site variables can play an equally important role.

In most scarification experiments relatively weak relationships (low R^2 values) have been found between site conditions and seedbed exposure (Berg et al. 1981, Stockermans 1984, Smith et al. 1985), and the present trials are no exception. Stronger relationships could likely be obtained if performance was investigated on a wider variety of sites and sample sizes for both pretreatment site conditions and seedbed exposure were increased. There may be additional site variables, such as soil bearing capacity, age of cutover and stoniness index, that were not considered, but that have a substantial impact on scarification.

Finally, a word of caution with regard to the seedbed prescription: although we are confident that the prescription is well suited to the conditions specified (see **Seedbed Prescription**), excessively wide furrows may result in poorer growth if the organic horizons have been removed. Narrower, more numerous furrows would avoid such problems and would also give better seedbed distribution for the same total quantity of seedbed produced.

Comments on Machine Suitability

In the evaluation of results, it should be noted that these trials represented short-term, pilot-scale experiments. Adjustments were made from time to time throughout each trial to improve seedbed exposure and performance. As a result, productivity suffered to some extent. However, general impressions of machine suitability and ideas for modifications to improve performance formed an important part of the evaluations.

TTS Model 35 Disc Trencher

The TTS has perhaps the greatest potential of any of the scarifiers tested for improved performance over that demonstrated in these trials. Seedbed exposure with this machine in 1980 fell well short of what had been expected, or achieved in the region (Stockermans 1984). It was our opinion that better results could be obtained by operating the machine at a lower speed (cf. Tykkynen 1974) and adjusting the discs differently.

In 1983 and 1984 we employed a TTS 35 Disc Trencher on similar, though full-tree logged, sites to prepare blocks for black spruce aerial seeding. In both years a large prime mover was used (a 180 hp Clark 668) and operated at a lower speed in double pass fashion (see footnote 4), extra weight was added to the bunk to aid penetration, and the discs were set at a greater angle to the direction of travel to provide wider but shallower furrows. Results, in terms of seedbed exposure (Table 11 and Fig. 13), were much improved. Mean seedbed exposure values were similar to those produced with the row scarifier. Jack pine seedbed distribution was equal or superior to that obtained in any of the previous trials, while that for black spruce was also considerably improved. As well, in both years, the proportion of quadrats with at least 5% receptive seedbed exceeded that found with all other machines. However, productivity was undoubtedly lower than in 1980.

Table 11. Gross seedbed exposure [a] with the TTS in 1983 and 1984, Black Sturgeon Management Unit

	Seedbed type				
	Black spruce seedbed exposure		Jack pine seedbed exposure		
Year of trial	Mean (%)	Standard error	Mean (%)	Standard error	N [b]
1983	9.4	0.25	15.4	0.34	1061
1984	11.4	0.52	19.8	0.86	399

[a] For all quadrats with < 10% lowland seedbed
[b] Sample size (number of 4-m^2 quadrats)

It is unlikely that results with the TTS 35 Disc Trencher, in terms of seedbed exposure, can be substantially improved over those obtained in 1984. The TTS throws slash and debris to the side, rather than aligning it in narrow windrows. As a result, increases in seedbed production from more intensive treatment (i.e., reduced inter-pass spacing) quickly diminish after a certain point because seedbed exposed in previous passes is covered up as new seedbed is being created. However, trenchers with hydraulic downpressure and/or powered disc rotation have the potential to enhance seedbed production further through increased net seedbed exposure (completeness of the furrow).

Atkinson Backscratcher

In theory, a hydraulic system could be added to this implement to govern plow angle and down-pressure, thereby giving greater control of scarification depth. If developed as an operational tool, the Atkinson Backscratcher would likely produce quantities of seedbed similar to those produced by the TTS 35 or various other passive or powered disc trenchers.

CFS Row Scarifier

It is also unlikely that seedbed production or distribution with the row scarifier can be improved substantially without major equipment modifications. In most trials, this plow was operated by competent, experienced personnel. Net seedbed exposure was as good as could be expected and inter-row spacing was usually kept as close as possible. Indeed, inter-row spacing in 1981 was too close and seedbed production was reduced because of spillover into the adjacent furrow. (This spacing also contributed to exceptionally low productivity because machine passage was obstructed by the windrow created in the previous pass, and because more passes were used per unit area.)

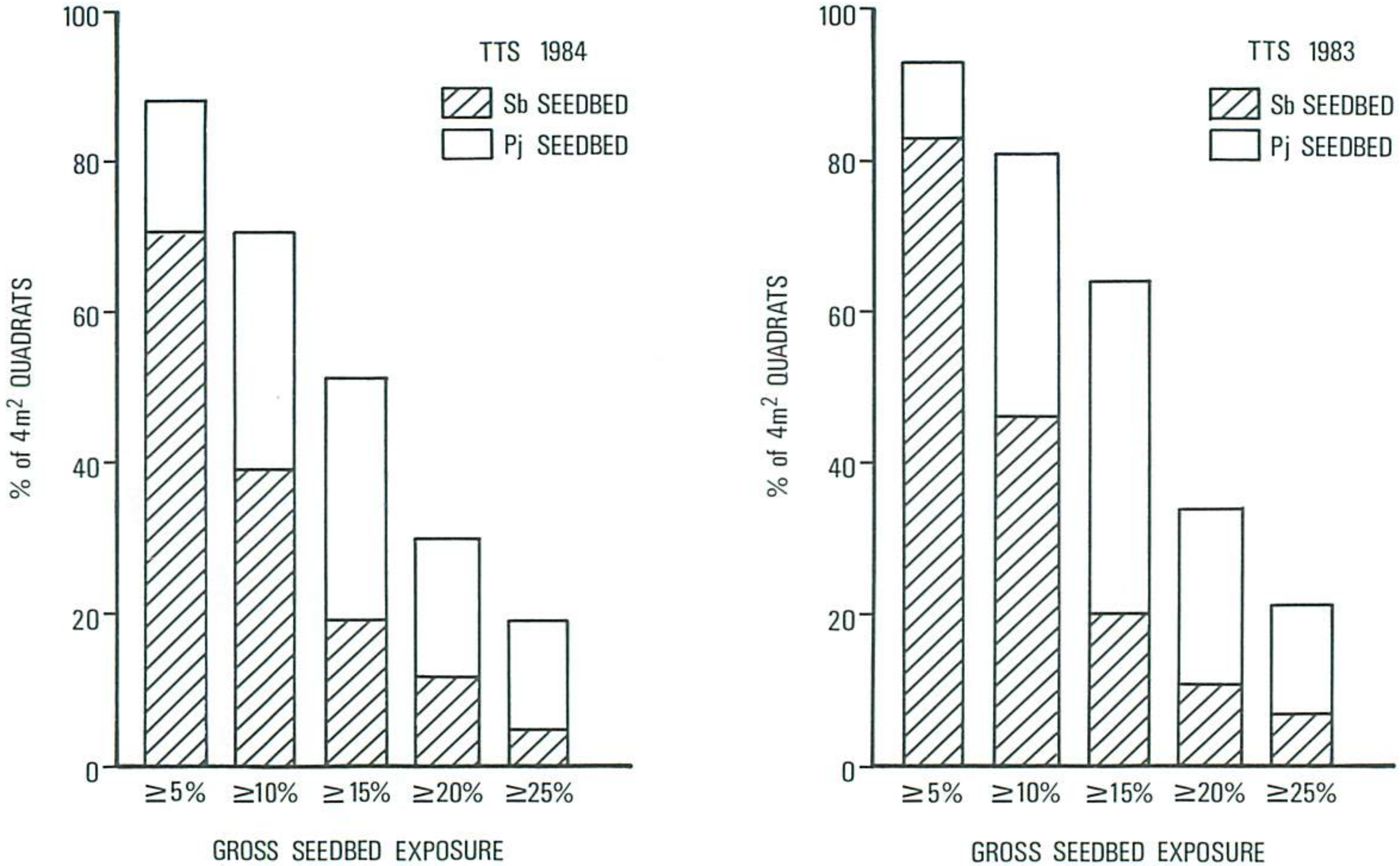

Figure 13. Seedbed distribution with the TTS in 1983 and 1984, black spruce aerial seeding trials, Black Sturgeon Management Unit.

The row scarifier unit, as conceived at the present time, is underpowered for cutovers with heavy slash loadings or numerous large stumps. As well, crawler tractors within the specified horsepower range for this implement (60-70 hp) have limited clearance, and easily get hung up on high stumps, slash or boulders. On more difficult sites (e.g., the 1979 block), the limited power supply and clearance necessitate an increase in mean inter-row spacing to avoid impediments. Under these conditions, the tractor is also constantly climbing over or avoiding obstacles too big to move. On soils with reduced bearing capacities, the combined weight of the V-blade and row scarifier increase the probability of getting stuck, and it is more difficult to free the machine because the plow is close-coupled.

It may be possible to adapt the row scarifier to a tractor in the 120- to 160-hp range. However, this would require substantial modifications to both the plow and the floating hitch attachment, and should be approached with caution. For instance, if the plow were widened it might be too large to shift laterally around large obstacles or to contour the micro-relief effectively. There are also several large front-mounted plows available, such as the C&H plow and various FESCO reforestation plows[8], which, after minor modifications, may be just as suitable.

Cazes and Heppner Scarification Plow

The C&H plow is highly operator sensitive, and the skill and technique of the driver have a large bearing on scarification results (Clarke 1977). The results we obtained with the modified version were procured by a skilled operator who was able to control the depth of scarification and keep inter-row spacing to a minimum. Further modifications should be made to reduce operator dependance as well as to improve net seedbed exposure and increase productivity. Removal of the inner plow in this modified version would decrease the total weight considerably, thereby improving productivity and reducing the likelihood of getting stuck. When combined with a larger rolling drum or a skid plate to support the plow, removal of the inner plow would also prevent excessively deep scarification, a common problem with the machine at present. In any event, if the development of a modified C&H plow is to be pursued, a thorough design analysis is needed to ensure that the plow is structurally sound and able to withstand the rigors of scarification. In the current modified version, the outer plow is performing different functions than those for which it was designed.

Excessive churning with this unit is a problem because the front-mounted plow removes the supporting organic horizons and root mat, and thus the tractor pads pass directly over the newly created seedbed. The likelihood of getting stuck increases greatly as the bearing capacity of the soil decreases, although the tractor winch (rear-mounted) is free to help in extricating the machine. Operation on very rocky or bouldery sites causes excessive wear on both the tractor and the plow, and increases the likelihood of structural damage.

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8 FESCO Forestry Equipment Specialists, Starkville, Miss.

Broyeur A.M.

In retrospect, the Broyeur was a poor choice of equipment for these trials because the machine was not designed to produce sizable quantities of the seedbed we required. The teeth gouge deep, narrow holes in the ground, and the soil removed thereby is spread over the organic horizons by the trailing anchor chains. While this does result in 'mineral soil exposure', the soil so exposed is a poor seedbed because of the intervening organic layers that separate it from the mineral soil beneath. The holes themselves are inhospitable microsites for seedling establishment because of slumping and flooding.

Mini-barrels and Chains

Seedbed results with the mini-barrels and chains were comparable with those obtained with several other machines, and both the productivity and the cost of such skidder-pulled units are usually quite reasonable. Unfortunately, there is little room for improvement. The rows of drags cannot be spaced more closely to enhance net scarification without increasing the danger of becoming entangled. Heavier drags could improve penetration of slash, but would also produce deeper trenches and, therefore, poorer seedbed exposure (i.e., mineral soil > 10 cm below the interface). Because the depth of scarification cannot be readily controlled or quickly changed to accommodate frequent variations in site conditions, drag scarification will remain a somewhat hit-or-miss operation. As a result, it is unlikely that units such as the mini-barrels will be able to produce the quantities of black spruce seedbed required for direct seeding on a consistent basis.

CONCLUSIONS

In view of the small, pilot-scale nature of these trials, definitive conclusions cannot be reached with respect to machine performance, productivity or suitability. Nevertheless, a brief summary of major findings, observations and inferences is given below.

1) The best results, in terms of machine productivity (functioning and productive time), were obtained with the TTS, followed in consecutive order by the modified C&H plow, the mini-barrels and the row scarifier. However, neither the TTS nor the modified C&H plow was particularly reliable or effectively used, when judged in terms of utilization and availability. Under normal operating conditions the productivity with skidder-pulled mini-barrels should approach that with the TTS. The small crawler tractors for which the row scarifier is currently designed are not well suited to rugged cutover conditions, and productivity is much lower.

2) Of the site factors examined, slash, stump and slope characteristics appeared to have the greatest impact on productivity. However, in most cases site conditions accounted for < 50% of the variability in productive and functioning time. A greater range of site conditions must be tested if stronger relationships are to be developed.

3) The best seedbed exposure (both in quantity and in distribution) was achieved with the modified C&H plow, followed by the row scarifier. However, while the modified C&H plow more or less met the seedbed distribution standard for jack pine aerial seeding (Riley 1980), it fell short of the proposed requirements for black spruce aerial seeding. If the threshold value for black spruce seedbed exposure per 4-m^2 quadrat could be reduced from 15% (e.g., by improving the rates and timing of seedfall through multiple seeding or strip cutting), scarification machinery such as the TTS, when used in a double pass operation with wide disc settings, would have considerable potential because of the superior seedbed distribution afforded. The use of trenchers with hydraulic downpressure and/or powered disc rotation to increase seedbed exposure should be investigated.

4) The results of correlation and regression analysis suggest that site conditions play a major role in determining the effectiveness of scarification in terms of seedbed production. The importance of different conditions varies with the machinery involved and the site in question. Slash loadings, stump characteristics, slope, LFH depth, stoniness, soil texture and moisture regime each explained a significant portion of the variation in seedbed exposure on several occasions. Better relationships could probably be developed if a wider variety of sites was treated and sampling procedures were improved.

5) In most situations, full-tree logging can lead to improved seedbed production by scarification machinery through reductions in the amount of branch-sized slash left on the cutover. However, stand characteristics and utilization often have a greater impact on total slash loadings and productivity than does the logging method.

6) While major modifications to machinery may produce substantial improvements in performance, a thorough analysis is required to ensure that the redesigned equipment will withstand the rigors of scarification. Although the modified C&H plow produced the best results over all, the structural soundness and durability of the redesigned scarifier remains to be demonstrated.

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APPENDIX A

SUPPLEMENTARY TABLES

Table A1. Comparison of slash conditions after full-tree and tree-length logging on similar sites, Madden Lake Road, 1980

Stand and site type	Logging method	Frequency/m of pieces	
		< 7 cm [a]	≥ 7 cm [a]
Jack pine-black spruce, sandy outwash (Pj 6, Sb 4) [b]	tree-length	2.99a (.23) [c]	0.60a (.03)
	full-tree	2.16b (.11)	0.43b (.04)
Black spruce, upland sandy till (Sb 9, Pj 1)	tree-length	2.76a (.11)	0.47a (.03)
	full-tree	1.53b (.10)	0.40a (.05)
Black spruce, shallow peatland	tree-length	2.47a (.14)	0.44a (.03)
	full-tree	1.79b (.16)	0.28b (.06)

...cont'd

Table A1. Comparison of slash conditions after full-tree and tree-length logging on similar sites, Madden Lake Road, 1980 (concl.)

Stand and site type	Logging method	Slash volume (m^3/ha), pieces					
		<7 cm [a]	7-10 cm [a]	11-20 cm [a]	≥21 cm [a]	≥7 cm [a]	All
Jack pine-black spruce, sandy outwash (Pj 6, Sb 4) [b]	tree-length	21.4a (1.7)	24.3a (1.4)	80.2a (8.0)	15.0b (3.8)	119.6a (9.2)	141.0a (9.1)
	full-tree	15.4b (0.8)	12.7b (1.6)	57.0b (6.2)	59.3a (7.6)	129.0a (13.4)	144.4a (13.7)
Black spruce, upland sandy till (Sb 9, Pj 1)	tree-length	19.7a (0.8)	25.2a (1.9)	37.7a (3.7)	8.1a (3.7)	71.1a (5.8)	90.8a (6.0)
	full-tree	10.9b (0.7)	18.1b (2.2)	42.2a (6.6)	3.9a (2.0)	64.2a (8.0)	75.1b (8.5)
Black spruce, shallow peatland	tree-length	17.6a (1.0)	24.0a (1.6)	32.2a (2.7)	4.6a (2.3)	60.8a (4.4)	78.4a (4.4)
	full-tree	12.8b (1.1)	14.6b (3.4)	21.2a (7.3)	0.0a (0.0)	35.8b (9.5)	48.6b (9.7)

[a] In diameter, at the point of intersection
[b] Based on FRI stand composition data. Species abbreviations: Sb - black spruce, Pj - jack pine.
[c] Standard error

There is no significant difference (P = 0.05) between values followed by the same letter in any given column, for a particular stand type.

Table A2. Comparison of slash values, by species, after full-tree and tree-length logging on similar sites, Madden Lake Road, 1980

Stand type	Species [a]	Logging method	Frequency/m of pieces ⩾7 cm [b]	Slash volume (m^3/ha) of pieces 7–10 cm [b]	11–20 cm [b]	⩾21 cm [b]	⩾ 7 cm [b]
Jack pine-black spruce	Sb	tree-length	0.20a (0.02) [c]	10.4a (1.1)	17.7a (2.8)	6.5a (2.7)	34.6a (4.2)
		full-tree	0.08b (0.01)	4.5b (0.8)	5.0b (1.2)	1.7a (1.7)	11.1b (2.2)
	Pj	tree-length	0.30a (0.03)	9.1a (1.2)	53.0a (6.6)	8.5b (2.8)	70.7b (7.5)
		full-tree	0.26a (0.03)	4.2b (0.8)	41.9a (5.6)	56.8a (6.6)	102.9a (11.1)
Black spruce upland	Sb	tree-length	0.33a (0.03)	19.2a (1.9)	21.2a (3.2)	5.2a (2.6)	45.7a (5.3)
		full-tree	0.20b (0.03)	10.1b (1.6)	18.5a (4.2)	0.7a (0.7)	29.4b (5.6)
	Pj	tree-length	0.04a (0.01)	0.8a (0.3)	8.1a (1.7)	0.7a (0.7)	9.6a (2.1)
		full-tree	0.06a (0.01)	1.2a (0.5)	9.5a (2.5)	1.5a (1.0)	12.2a (2.9)
Black spruce peatland	Sb	tree-length	0.30a (0.02)	17.3a (1.2)	18.2a (2.8)	4.6a (2.3)	40.1a (3.4)
		full-tree	0.18b (0.03)	9.6b (2.2)	11.3a (3.3)	0.0a (0.0)	20.9b (4.4)

[a] Species abbreviations follow those outlined in Table A1.
[b] In diameter, at the point of intersection
[c] Standard error

There is no significant difference ($P = 0.05$) between values followed by the same letter in any given column, for a particular stand type-species combination.

Table A3. Breakdown of minor (<15 min) delays within productive machine time

Machine	Year	Clean (%)	Personal (%)	Super-vision (%)	Delays: Repair: Implement (%)	Repair: Prime mover (%)	Service: Implement (%)	Service: Prime mover (%)	Adjust implement (%)	Wait for mechanic/parts (%)	Other: Implement (%)	Other: Prime mover (%)	Other: Neither (%)
Row scarifier	1978	0.0	32.2	0.0	0.0	4.9	11.8	18.8	0.0	0.0	0.0	0.0	32.3
Row scarifier	1979	0.0	19.8	7.0	0.0	30.6	0.0	0.0	0.0	0.0	0.0	19.5	23.1
Row scarifier	1980	2.2	4.7	3.0	0.0	41.5	2.4	18.0	0.0	0.0	0.0	17.8	10.4
Row scarifier	1981	1.0	17.6	2.8	9.7	14.9	20.2	23.0	0.0	0.0	0.0	1.2	9.6
Mini-barrels	1978	0.0	22.1	3.7	17.3	8.8	0.5	23.7	0.0	4.1	0.0	4.1	15.7
Modified C&H plow	1980	0.0	46.8	5.5	0.5	0.0	2.6	15.1	0.0	0.0	0.0	9.2	20.3
TTS	1980	0.0	9.5	4.4	4.6	19.4	3.1	21.0	0.0	0.0	9.8	7.0	21.2

Table A4. Significant correlations (P = 0.05) between mean functioning time per pass and site conditions, all machines and trials

Site condition	Machine								No. of significant correlations
	Row scarifier					C&H plow	TTS	Mini-barrels	
	1978	1979	1980	1981	Combined				
Slash frequency/m, <7 cm		0.56		0.34	0.49	−0.33			4
Slash frequency/m, ≥7 cm			0.41		0.37				2
Slash volume, 7-10 cm			0.34						1
Slash volume, 11-20 cm				0.47	0.46		0.46		3
Slash volume, ≥7 cm				0.43	0.43		0.41		3
Total slash volume			0.30	0.45	0.47		0.42		4
Stump frequency			0.39	−0.34	−0.24				3
Stump height	−0.57			0.38					2
Total stump cross-sectional area			0.57	−0.40					2
Total stump volume			0.50	−0.36					2
Residuals/ha	0.58			0.40					2
LFH depth						0.30			1
Stoniness frequency					0.34	0.38			2
Surface stones					0.20				1
Boulder coverage						0.36			1
Soil texture				−0.40					1
Moisture regime	−0.39			−0.38					2
Average slope	0.34			0.39	0.26			0.34	4
Maximum slope				0.37	0.23		−0.31		3
Ground roughness class									0
Ground roughness obstacle occurrence/100 m^2			0.31	−0.35	−0.26				3
Total ground roughness obstacle volume/100 m^2			0.37						1
Soil depth					−0.66				1
Number of significant correlations	4	1	8	14	12	4	4	1	48

Table A5. Significant correlations (P = 0.05) between total functioning time per subplot and site conditions, all machines and trials

Site condition	Machine: Row scarifier 1978	Row scarifier 1979	Row scarifier 1980	Row scarifier 1981	Row scarifier Combined	C&H plow	TTS	Mini-barrels	No. of significant correlations
Slash frequency/m, <7 cm		0.87		0.62	0.37		0.51		4
Slash frequency/m, ≥7 cm				0.55	0.36		0.39		3
Slash volume, 7-10 cm									0
Slash volume, 11-20 cm				0.70	0.47		0.55		3
Slash volume, ≥7 cm		0.84		0.66	0.39		0.57		4
Total slash volume		0.88		0.69	0.41		0.60		4
Stump frequency			0.47	-0.47			-0.41		3
Stump height									0
Total stump cross-sectional area			0.73						1
Total stump volume			0.66	-0.62					2
Residuals/ha	0.70								1
LFH depth				-0.47		0.29			2
Stoniness frequency					0.42	0.32			2
Surface stones									0
Boulder coverage						0.35			1
Soil texture									0
Moisture regime				-0.63					1
Average slope	0.64								1
Maximum slope	0.83						-0.38		2
Ground roughness class									0
Ground roughness obstable occurrence/100 m^2									0
Total ground roughness obstacle volume/100 m^2					-0.40				1
Soil depth					-0.76				1
Number of significant correlations	3	3	3	9	8	3	7	0	36

Table A5. Significant correlations (P = 0.05) between total functioning time per subplot and site conditions, all machines and trials

Site condition	Machine: Row scarifier 1978	1979	1980	1981	Combined	C&H plow	TTS	Mini-barrels	No. of significant correlations
Slash frequency/m, <7 cm		0.87		0.62	0.37		0.51		4
Slash frequency/m, ≥7 cm				0.55	0.36		0.39		3
Slash volume, 7-10 cm									0
Slash volume, 11-20 cm				0.70	0.47		0.55		3
Slash volume, ≥7 cm		0.84		0.66	0.39		0.57		4
Total slash volume		0.88		0.69	0.41		0.60		4
Stump frequency			0.47	−0.47			−0.41		3
Stump height									0
Total stump cross-sectional area			0.73						1
Total stump volume			0.66	−0.62					2
Residuals/ha	0.70								1
LFH depth				−0.47		0.29			2
Stoniness frequency					0.42	0.32			2
Surface stones									0
Boulder coverage						0.35			1
Soil texture									0
Moisture regime				−0.63					1
Average slope	0.64								1
Maximum slope	0.83						−0.38		2
Ground roughness class									0
Ground roughness obstable occurrence/100 m^2									0
Total ground roughness obstacle volume/100 m^2					−0.40				1
Soil depth					−0.76				1
Number of significant correlations	3	3	3	9	8	3	7	0	36

Table A6. Significant correlations (P = 0.05) between mean productive time per pass and site conditions, all machines and trials

Site condition	Machine: Row scarifier 1978	Row scarifier 1979	Row scarifier 1980	Row scarifier 1981	Row scarifier Combined	C&H plow	TTS	Mini-barrels	No. of significant correlations
Slash frequency/m, < 7 cm			0.34 [a]		0.37				2
Slash frequency/m, ⩾ 7 cm			0.27 [a]		0.33				2
Slash volume, 7-10 cm									0
Slash volume, 11-20 cm				0.47	0.32		0.28		3
Slash volume, ⩾ 7 cm			0.34 [a]	0.43	0.36				3
Total slash volume			0.36 [a]	0.44	0.40				3
Stump frequency	0.37						-0.37		2
Stump height	-0.50		0.50 [a]	0.41					3
Total stump cross-sectional area	0.37			-0.33					2
Total stump volume	0.42			-0.32			-0.30		3
Residuals/ha									0
LFH depth									0
Stoniness frequency			-0.25					-0.45	2
Surface stones									0
Boulder coverage									0
Soil texture									0
Moisture regime				-0.39					1
Average slope				0.35				0.34	2
Maximum slope				0.36			-0.31		2
Ground roughness class									0
Ground roughness obstacle occurrence/100 m^2				-0.35	-0.23		-0.30		3
Total ground roughness obstacle volume/100 m^2									0
Soil depth					-0.23				1
Number of significant correlations	4	0	6	10	7	0	5	2	34

[a] lny = x

Table A6. Significant correlations (P = 0.05) between mean productive time per pass and site conditions, all machines and trials

Site condition	Machine: Row scarifier 1978	Row scarifier 1979	Row scarifier 1980	Row scarifier 1981	Row scarifier Combined	C&H plow	TTS	Mini-barrels	No. of significant correlations
Slash frequency/m, < 7 cm			0.34 [a]		0.37				2
Slash frequency/m, ≥ 7 cm			0.27 [a]		0.33				2
Slash volume, 7-10 cm									0
Slash volume, 11-20 cm				0.47	0.32		0.28		3
Slash volume, ≥ 7 cm			0.34 [a]	0.43	0.36				3
Total slash volume			0.36 [a]	0.44	0.40				3
Stump frequency	0.37						-0.37		2
Stump height	-0.50		0.50 [a]	0.41					3
Total stump cross-sectional area	0.37			-0.33					2
Total stump volume	0.42			-0.32			-0.30		3
Residuals/ha									0
LFH depth									0
Stoniness frequency			-0.25					-0.45	2
Surface stones									0
Boulder coverage									0
Soil texture									0
Moisture regime				-0.39					1
Average slope				0.35				0.34	2
Maximum slope				0.36			-0.31		2
Ground roughness class									0
Ground roughness obstacle occurrence/100 m^2				-0.35	-0.23		-0.30		3
Total ground roughness obstacle volume/100 m^2									0
Soil depth					-0.23				1
Number of significant correlations	4	0	6	10	7	0	5	2	34

[a] lny = x

Table A7. Significant correlations (P = 0.05) between total productive time per subplot and site conditions, all machines and trials

Site condition	Machine: Row scarifier 1978	Row scarifier 1979	Row scarifier 1980	Row scarifier 1981	Row scarifier Combined	C&H plow	TTS	Mini-barrels	No. of significant correlations
Slash frequency/m, < 7 cm			0.42 [a]		0.30				2
Slash frequency/m, ⩾7 cm			0.39		0.33				2
Slash volume, 7-10 cm			0.32						1
Slash volume, 11-20 cm				0.64 [a]	0.40		0.42		3
Slash volume, ⩾7 cm			0.29 [a]	0.58 [a]	0.35		0.41		4
Total slash volume			0.32 [a]	0.45	0.35		0.41		4
Stump frequency					-0.20 [a]		-0.47 [a]		2
Stump height	-0.63		0.42 [a]	0.44	-0.23		0.35		5
Total stump cross-sectional area	0.40								1
Total stump volume	0.41						-0.37		2
Residuals/ha									0
LFH depth				-0.43					1
Stoniness frequency					0.24			-0.46	2
Surface stones									0
Boulder coverage									0
Soil texture									0
Moisture regime				-0.42					1
Average slope						0.34		0.36	2
Maximum slope						0.39	-0.38 [a]	0.47	3
Ground roughness class									0
Ground roughness obstacle occurrence/100 m^2					-0.28		-0.37		2
Total ground roughness obstacle volume/100 m^2									0
Soil depth					-0.26				1
Number of significant correlations	3	0	6	6	10	2	8	3	38

[a] lny = x

Table A8. Correlation matrix of site conditions, all trials combined

Factor	Factors						
	Slash frequency/m < 7 cm	Slash frequency/m ⩾ 7 cm	Slash volume, ⩾ 7 cm	Total slash volume	Stump frequency	Stump height	Total stump x-sectional area
Slash frequency/m, ⩾7 cm	0.30 [a]						
Slash volume, ⩾ 7 cm	0.31 [a]	0.76 [a]					
Total slash volume	0.45 [a]	0.76 [a]	0.99 [a]				
Stump frequency	-0.24 [a]	-0.04	-0.44 [a]	-0.45 [a]			
Stump height	-0.01	-0.05	0.12	0.11	-0.12		
Total stump cross-sectional area	0.03	0.06	0.18	-0.16	0.71 [a]	-0.15	
Total stump volume	-0.18	-0.01	-0.35 [a]	-0.36 [a]	0.95 [a]	-0.11	0.84 [a]
Moisture regime	-0.11	-0.13	-0.30 [a]	-0.30 [a]	0.30 [a]	-0.09	0.09
Soil texture	0.02	0.00	-0.01	-0.01	0.04	-0.21 [a]	0.07
LFH depth	0.11	0.11	-0.14	-0.11	0.27 [a]	-0.17	0.19
Stoniness frequency	0.06	0.22 [a]	-0.03	-0.02	0.21 [a]	-0.25 [a]	0.15
Average slope	-0.42 [a]	-0.21 [a]	-0.13	-0.18	0.03	-0.03	-0.13
Maximum slope	-0.40 [a]	-0.19	-0.10	-0.16	0.02	-0.06	-0.14
Ground roughness class	-0.02	0.06	-0.17	-0.17	0.52 [a]	0.26 [a]	0.40 [a]
Ground roughness obstacle occurrence	-0.20	0.00	-0.46 [a]	-0.46 [a]	0.93 [a]	-0.11	0.66 [a]
Total ground roughness obstacle volume	-0.03	0.07	0.16	-0.16	0.51 [a]	0.27 [a]	0.38 [a]

[a] Significant linear association at the P = 0.01 level

...cont'd

Table A8. Correlation matrix of site conditions, all trials combined

	Factors						
Factor	Slash frequency/m < 7 cm	Slash frequency/m ≥ 7 cm	Slash volume, ≥ 7 cm	Total slash volume	Stump frequency	Stump height	Total stump x-sectional area
Slash frequency/m, ≥7 cm	0.30 [a]						
Slash volume, ≥7 cm	0.31 [a]	0.76 [a]					
Total slash volume	0.45 [a]	0.76 [a]	0.99 [a]				
Stump frequency	-0.24 [a]	-0.04	-0.44 [a]	-0.45 [a]			
Stump height	-0.01	-0.05	0.12	0.11	-0.12		
Total stump cross-sectional area	0.03	0.06	0.18	-0.16	0.71 [a]	-0.15	
Total stump volume	-0.18	-0.01	-0.35 [a]	-0.36 [a]	0.95 [a]	-0.11	0.84 [a]
Moisture regime	-0.11	-0.13	-0.30 [a]	-0.30 [a]	0.30 [a]	-0.09	0.09
Soil texture	0.02	0.00	-0.01	-0.01	0.04	-0.21 [a]	0.07
LFH depth	0.11	0.11	-0.14	-0.11	0.27 [a]	-0.17	0.19
Stoniness frequency	0.06	0.22 [a]	-0.03	-0.02	0.21 [a]	-0.25 [a]	0.15
Average slope	-0.42 [a]	-0.21 [a]	-0.13	-0.18	0.03	-0.03	-0.13
Maximum slope	-0.40 [a]	-0.19	-0.10	-0.16	0.02	-0.06	-0.14
Ground roughness class	-0.02	0.06	-0.17	-0.17	0.52 [a]	0.26 [a]	0.40 [a]
Ground roughness obstacle occurrence	-0.20	0.00	-0.46 [a]	-0.46 [a]	0.93 [a]	-0.11	0.66 [a]
Total ground roughness obstacle volume	-0.03	0.07	0.16	-0.16	0.51 [a]	0.27 [a]	0.38 [a]

[a] Significant linear association at the P = 0.01 level

...cont'd

Table A8. Correlation matrix of site conditions, all trials combined (concl.)

Factor	Factors: Total stump volume	Moisture regime	Soil texture	LFH layer	Stoniness frequency	Average slope	Maximum slope	Ground roughness class	Ground roughness obstacle occurrence
Slash frequency/m, ⩾7 cm									
Slash volume, ⩾7 cm									
Total slash volume									
Stump frequency									
Stump height									
Total stump cross-sectional area									
Total stump volume									
Moisture regime	0.22 [a]								
Soil texture	0.00	0.36 [a]							
LFH depth	0.24 [a]	0.49 [a]	0.22 [a]						
Stoniness frequency	0.19	0.32 [a]	0.35 [a]	0.45 [a]					
Average slope	-0.02	-0.02	-0.14	-0.24 [a]	-0.24 [a]				
Maximum slope	-0.04	-0.03	-0.10	-0.21 [a]	-0.23 [a]	0.97 [a]			
Ground roughness class	0.48 [a]	0.13	-0.08	0.28 [a]	0.11	-0.15	-0.17		
Ground roughness obstacle occurrence	0.87 [a]	0.40 [a]	0.09	0.35 [a]	0.33 [a]	-0.01	-0.03	0.46 [a]	
Total ground roughness obstacle volume	0.49 [a]	0.13	-0.06	0.30 [a]	0.17	-0.17	-0.19	0.77 [a]	0.97

[a] Significant linear association at the P = 0.01 level

Table A9. Characteristics of best-fit multiple linear regressions relating site conditions to mean functioning time per pass, all machines and trials

Machine	Significant independent variables	Regression coefficients	T-statistics	R^2	Mallow's Cp statistic	N [a]
Row scarifier 1978	stump height	-0.891	-3.42	0.55	1.35	27
	residuals/ha	0.062	3.49			
Row scarifier 1979	slash frequency, <7 cm	5.560	2.63	0.32	9.02	17
Row scarifier 1980	total stump cross-sectional area	0.297	4.59	0.32	-2.46	46
Row scarifier 1981	residuals/ha	0.211	3.00	0.46	1.55	35
	slash frequency, < 7 cm	3.875	2.02			
	total stump cross-sectional area	-0.301	-3.33			
Row scarifier, all years combined	slash frequency, < 7 cm	13.386	4.59	0.55	6.38	81
	slash volume, 11-20 cm	0.193	2.29			
	stump frequency	0.021	2.91			
	stoniness frequency	0.380	4.53			
	maximum slope	2.855	2.56			
	ground roughness obstacle occurrence/100 m^2	-1.893	-3.00			
Modified C&H plow	stoniness frequency	0.068	3.27	0.18	4.83	50
TTS	slash volume, 11-20 cm	0.042	3.13	0.27	5.09	43
	maximum slope	-0.542	-2.06			
Mini-barrels	average slope	1.854	2.10	0.11	4.81	36

[a] Sample size (number of passes)

Table A10. Characteristics of best-fit multiple linear regressions relating site conditions to total functioning time per subplot, all machines and trials

Machine	Significant independent variables	Regression coefficients	T-statistics	R^2	Mallow's Cp statistic	N [a]
Row scarifier 1978	residuals/ha	0.370	4.63	0.92	6.45	10
	maximum slope	15.090	6.23			
Row scarifier 1979	total slash volume	1.822	6.64	0.94	6.63	6
	LFH depth	2.846	2.77			
Row scarifier 1980	total stump cross-sectional area	1.631	4.31	0.54	0.49	18
Row scarifier 1981	slash frequency, <7 cm	45.504	3.10	0.78	0.51	18
	stump frequency	-0.095	-3.21			
	moisture regime	-35.258	-3.25			
	LFH depth	33.930	3.20			
Row scarifier, all years combined	slash frequency, < 7 cm	68.514	4.51	0.81	4.50	33
	slash volume, 11-20 cm	2.659	2.96			
	total slash volume	-1.709	-2.30			
	soil depth	-4.043	-4.74			
Modified C&H plow	stoniness frequency	0.268	2.54	0.14	0.82	40
TTS	slash frequency, < 7 cm	19.809	4.21	0.48	2.59	30
	maximum slope	-8.094	-3.05			
Mini-barrels	no significant relationships					

[a] Sample size (number of subplots). Most subplots are not represented because functioning times were confounded by machine delays.

Table A11. Characteristics of best-fit multiple linear regressions relating site conditions to mean productive time per pass, all machines and trials

Machine	Significant independent variables	Regression coefficients	T-statistics	R^2	Mallow's Cp statistic	N [a]
Row scarifier 1978	stump height	-2.179	-3.01	0.25	0.61	29
Row scarifier 1979	no significant relationships					
Row scarifier 1980	stump height	0.034	4.49	0.45	3.37	63
	total ground roughness obstacle volume/100 m^2	0.408	4.12			
	total slash volume	0.003	3.16			
Row scarifier 1981 [b]	slash volume, 11-20 cm	0.177	2.27	0.25	-0.82	35
	maximum slope	2.419	2.22			
Row scarifier, all years combined	slash frequency, < 7 cm	12.426	3.58	0.29	3.50	123
	total slash volume	0.136	2.06			
	stump frequency	0.022	3.32			
	ground roughness obstacle occurrence/100 m^2	-2.210	-3.62			
Modified C&H plow	no significant relationships					
TTS	total stump cross-sectional area	-0.891	2.67	0.23	1.15	45
	maximum slope		-2.03			
Mini-barrels	stoniness frequency	-0.630	-3.01	0.20	3.41	38

[a] Sample size (number of passes)
[b] y = lny

Table A12. Characteristics of best-fit multiple linear regressions relating site conditions to total productive time per subplot, all machines and trials

Machine	Significant independent variables	Regression coefficients	T-statistics	R^2	Mallow's Cp statistic	N [a]
Row scarifier 1978	stump frequency	-1.197	-2.98	0.61	5.00	25
	stump height	-11.433	-3.39			
	total stump cross-sectional area	-20.747	-2.31			
	total stump volume	0.024	2.86			
Row scarifier 1979	no significant relationships					
Row scarifier 1980 [b]	slash frequency, < 7 cm	0.145	2.18	0.37	3.16	55
	slash frequency, ≥ 7 cm	0.536	2.32			
	stump height	0.025	3.29			
Row scarifier 1981	slash volume, 11-20 cm	2.804	5.37	0.47	-1.46	34
Row scarifier, all years combined	slash frequency, < 7 cm	114.547	3.71	0.39	6.21	112
	slash volume, 11-20 cm	1.733	2.14			
	stump frequency	0.270	4.00			
	stoniness frequency	3.592	4.28			
	ground roughness obstacle occurrence/100 m^2	-28.003	-4.59			
Modified C&H plow	maximum slope	6.634	2.83	0.15	0.40	46
TTS	stump frequency	-0.038	-3.62	0.34	-0.92	45
	maximum slope	-12.744	-2.99			
Mini-barrels	stoniness frequency	-3.040	-2.47	0.34	2.32	35
	maximum slope	18.731	2.58			

[a] Sample size (number of subplots)
[b] y = lny

Table A13. Characteristics of best-fit multiple linear regressions relating site conditions to black spruce GSE, all machines and trials

Machine	Significant independent variables	Regression coefficients	T-statistics	R^2	Mallow's Cp statistic	N [a]
Row scarifier 1978	stump height	0.603	3.09	0.27	1.61	28
Row scarifier 1979	slash frequency, <7 cm	-3.531	-3.19	0.52	2.05	19
	maximum slope	-0.559	-2.97			
Row scarifier 1980	slash frequency, ≥7 cm	-31.420	-3.71	0.39	0.92	54
	soil texture	-0.843	-2.71			
	LFH depth	-0.857	-2.19			
Row scarifier 1981 [b]	slash volume, 7-10 cm	-0.030	-2.32	0.58	2.98	39
	surface stones	-0.391	-2.03			
	soil texture	-0.085	-3.70			
	stoniness frequency	-0.014	-2.40			
Row scarifier, all years combined	slash frequency, ≥7 cm	-19.278	-5.00	0.45	4.21	112
	soil texture	-0.445	-3.11			
	LFH depth	-0.506	-2.63			
	moisture regime	-1.180	-2.10			
	stump frequency	-0.002	-2.18			
Modified C&H plow [c]	total slash volume	-0.010	-3.20	0.64	5.00	43
	LFH depth	-0.085	-3.39			
	stoniness frequency	-0.050	-4.22			
	boulder coverage	0.029	2.87			
TTS	slash volume, 7-10 cm	-0.140	-3.17	0.62	1.01	41
	stoniness frequency	-0.064	-2.94			
	LFH depth	0.909	4.08			
Mini-barrels	stump frequency	-0.003	-2.40	0.34	1.96	36
	LFH depth	-0.396	-2.09			

[a] Sample size (number of subplots)
[b] $y = \sqrt{y}$
[c] $y = \ln y$

Table A14. Characteristics of best-fit multiple linear regressions relating site conditions to jack pine GSE, all machines and trials

Machine	Significant independent variables	Regression coefficients	T-statistics	R^2	Mallow's Cp statistic	N [a]
Row scarifier 1978	stump height	0.511	2.50	0.19	3.23	28
Row scarifier 1979	soil texture	-0.626	-2.59	0.65	5.32	18
	maximum slope	-1.405	-3.33			
Row scarifier 1980	slash frequency, ≥7 cm	-24.561	-2.69	0.31	-1.10	53
	soil texture	-0.774	-2.46			
	LFH depth	-0.866	-2.21			
Row scarifier 1981	slash volume, 7-10 cm	-0.197	-2.02	0.67	1.87	39
	soil texture	-0.701	-3.63			
	stoniness frequency	-0.144	-3.59			
	total stump volume [c]	-5.834	-2.68			
Row scarifier, all years combined	slash frequency, ≥7 cm	-15.602	-3.78	0.42	2.13	111
	moisture regime	-1.618	-2.99			
	soil texture	-0.531	-3.62			
	LFH depth	-0.419	-2.08			
	total stump cross-sectional area	-0.099	-2.37			
Modified C&H plow	total slash volume	-0.110	-2.03	0.58	1.78	47
	moisture regime	-2.411	-2.07			
	LFH depth	-1.499	-3.33			
	ground roughness height class	-1.105	-2.95			
TTS [b]	slash volume, 7-10 cm	-0.020	-2.92	0.67	1.78	37
	stoniness frequency	-0.012	-3.31			
	maximum slope	0.106	3.02			
	total stump cross-sectional area	-0.011	-2.55			
Mini-barrels	LFH depth [c]	-27.278	-4.05	0.33	0.38	36

[a] Sample size (number of subplots)
[b] y = lny
[c] x = log x

APPENDIX B

STAND CHARACTERISTICS AND LOGGING METHODS FOR THE TRIAL SITES

1978 Trial, Banksian Lake Road (100 km north of Thunder Bay)

The previous forest on this 47-ha site consisted of well stocked (80-100%) 70-year-old stands with 70% black spruce, 20-30% jack pine and 0-10% balsam fir *(Abies balsamea* [L.] Mill.)[9], and was placed in site classes 1-2. Logging was done in the late winter and early spring of 1977 by cut-and-skid crews with wheeled skidders. Trees were delimbed and topped at the stump and then skidded tree-length to the roadside. Scarification was conducted in August, 1978.

1979 Trial, McGaughey Lake Road (60 km north of Thunder Bay)

Three different stands occupied this 28-ha site before logging: a 130-year-old pure black spruce stand with 60% stocking, classified as site class 2; a 90-year-old pure black spruce stand with 70% stocking, classified as site class 1; and an 80-year-old stand composed of 50% jack pine, 40% black spruce and 10% white birch *(Betula papyrifera* Marsh.) with 80% stocking, classified as site class 2. The harvesting system was similar to that employed in the 1978 trial, and was carried out during the late winter and spring of 1978. Scarification was conducted in October, 1979.

1980 Trial, Madden Lake Road (135 km north northwest of Thunder Bay)

This was the largest of the trials, covering an area of 140 ha. A number of 100- to 110-year-old black spruce, black spruce-jack pine and jack pine-black spruce stands comprised the previous forest. Stocking ranged from 60% to 100%. Three of the five stands in the black spruce working group were placed in site class X, while the other two were placed in site class 1. The one stand in the jack pine working group was placed in site class 1. The area was logged in the spring of 1980 by cut-and-skid crews with wheeled skidders. On roughly half the area, full-tree logging was conducted, with delimbing and topping at roadside, while the other half was harvested by conventional tree-length logging at the stump. Scarification was carried out in August, 1980.

1981 Trial, Road 600, Stonehouse Lake area (130 km north of Thunder Bay)

Three 90- to 100-year-old stands (site class 1) comprised the previous forest on this 52-ha site. The stands ranged in composition from 100% black spruce to 80% black spruce and 20% jack pine, and in stocking from 50 to 90%. The area was harvested in the summer of 1980 by cut-and-skid crews with wheeled skidders, largely by means of a tree-length logging system in which the trees were delimbed and topped at the stump. (Small portions were full-tree logged.) Scarification began in mid-July and was completed by early August, 1981.

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[9] Data on stand composition were taken from OMNR Forest Resources Inventory (FRI) stand maps, compiled in 1962. Stand ages have been adjusted to reflect age at the time of logging. Species composition is by basal area, to the nearest 10%. Stocking is an expression of the relationship between actual basal area and normal basal area obtained from normal yield tables. Site class is an expression of stand age-height relationships, and is also obtained from normal yield tables (Anon. 1973).

APPENDIX C

TIME STUDY DEFINITIONS

Machine Time Elements

Productive Machine Time (PMT): that part of total machine time (TMT) during which the machine is performing its primary function

Active Repair: that part of TMT during which parts are being fixed or replaced as a result of failure or malfunction (it also includes modifications or improvements to the machine)

Service: that part of TMT devoted to routine and preventive maintenance to maintain the machine in satisfactory operating condition

Delay: that portion of TMT during which the machine is not performing its primary function, is not undergoing active repair, and is not in service

Machine Time Formulas

$$\text{Utilization} = \frac{\text{PMT}}{\text{TMT}} \times 100$$

$$\text{Mechanical availability} = \frac{\text{PMT}}{\text{PMT + repairs + service}} \times 100$$

$$\text{CPPA availability} = \frac{\text{TMT - (repair + service + wait [parts \& mechanic])}}{\text{TMT}} \times 100$$

Short-term Study Time Elements

PMTs were broken down into the following elements:

Effective Productive Time (EPT): proportion of time spent scarifying (starts when the implement is in the soil and the prime mover begins forward travel, and includes winching of the implement if the implement is equipped with a quick disconnect hitch and there is effective scarification during winching)

Maneuvering (turning): time spent turning the implement and prime mover between passes

Obstacle: time spent between stopping because of an obstacle, and the resumption of scarification (depending on the cause, obstacle time is attributed to the implement or the prime mover)

Short-term Delays: delays between 0.05 min and 15 min (delays over 15 min were not considered part of productive time; delay is any downtime or non-productive operating time)

Plot Study Time Elements

Mean Functioning Time (MFT): average time taken to complete a pass in which there were no machine delays (includes just EPT)

Mean Productive Time (MPT): average time taken to complete a pass in which there were no machine delays other than obstacle delays (includes EPT and obstacle delays, but not maneuvering or short-term delays)

Total Functioning Time (TFT): total time taken to scarify a subplot (400 m^2) in which there were no machine delays (includes just EPT, but number of passes may vary slightly)

Total Productive Time (TPT): total time taken to scarify a subplot (400 m^2) in which there were no machine delays other than obstacle delays (includes EPT and obstacle delays, but no maneuvering or short-term delays)