

A Five-year Scenario of Vegetation management in a mixedwood cutover in Alberta

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The environmental impact of vegetation management methods was carried out from 1985 to 1991 in a 3-year-old aspen cutover within the mixedwood section of the boreal forest region. The vegetation management treatments for site preparation included broadcast application of 2 (LH) and 4 (HH) kg of hexazinone ha⁻¹ as PRONONE 10G, disc trenching (DT) and double disking (DD) and their combination. Lodgepole pine and white spruce were planted in spring 1987 following the 1986 fall herbicide application and 1987 spring mechanical treatments. We evaluated impacts and briefly present results for changes in vegetation composition, structure and dynamics; herbicide residue in soils, water and vegetation; and nutrient dynamics in leaves and soil. Impacts on vegetation were assessed as changes in stem density of woody species, and cover by vegetation strata and species (only in herbicide and control plots). The efficacy of treatments in controlling woody vegetation density peaked by the second to third growing seasons following the treatments and was in the order: DD > HH+DT > HH > DT+LH > LH > control. There was no loss of plant species as a result of the herbicide, however, the species abundance and cover were reduced at least for two years. There are indications that successional trends followed different pathways in control and herbicide treated plots. Environmental distribution, movement, and persistence of hexazinone were examined in soil leachate, permanent and ephemeral streams, at various soils depths and in vegetation. Amounts of hexazinone residues in soil leachate, surface water and sediment in pools near the application site were extremely small or non-detectable. In the HH-treatment, residues of hexazinone and its two major metabolites A and B in soils accounted for 5%, 1%, and 2% respectively of the applied amount at 767 days after application. Residues leached to soil depths of 10-20, 20-30, 30-35, and 35-40 cm within 8, 37, 37, and 365 days respectively in both 2 and 4 kg/ha hexazinone treatments. The foliage of several plant species accumulated hexazinone and its metabolites. By the end of second growing season, hexazinone residues were not detected in most species. Detected concentrations were well below the acute and chronic toxicity levels in various organisms. Nutrient dynamics in foliage and soil were altered for at least two years following the hexazinone application. Both total S, and total N concentrations in the soil organic horizons increased. Extractable NH₄⁺-N and NO₃⁻-N concentrations were also higher in the organic soil horizons of the herbicide-treated plots compared to the control. Normal seasonal dynamics of Ca, Mg, K, P, S and N in foliage were disrupted.

Introduction

Management of competing vegetation is critical for site preparation and crop release measures on thousands of hectares of productive forest sites in Alberta and other parts of Canada. These sites are either inadequately stocked to conifers or have regenerated to less valued hardwoods. Vegetation management problems exist both at stand establishment and later at stand tending stages on sites where *Populus tremuloides* (Michx.) (trembling aspen) and *Calamagrostis canadensis* (Michx.) Nutt. (marsh reed grass) out compete the desirable softwood species.

Herbicide and mechanical treatments are two practices forest managers have used to control competing vegetation until the crop species reach a free-to-grow stage. Recently, new emphasis on sustainable development in forestry has called into question many site preparation practices and raised

concerns about the long-term environmental impacts of these practices. The concerns include long-term changes in vegetation composition and structure, persistence of toxic residues of herbicides in the forest environment, loss of wildlife habitats, increase in soil erosion, depletion of nutrient availability by slowing the nutrient cycling, adverse effects on microorganisms and non-fibre use of the forest.

The majority of vegetation management studies have been designed to assess the control of specific species before planting or release of the crop species sometime after planting (Eis 1981; Drouin 1989). Information is lacking on vegetation changes particularly in boreal species other than the crop and target species (Kimmins 1975). Boyd *et al.* (1985) reviewed the current literature and summarized the efficacy of several herbicides including hexazinone to control a number of forest weed species in the Inland Northwest United States. A number of species and genera (*Amelanchier alnifolia* Nutt., Saskatoon berry; *Arctostaphylos uva-ursi* (L.) Spreng., common

bearberry; *Lonicera* spp.; *Prunus* spp.; *Ribes* spp.; *Rosa* spp.; *Rubus* spp., (raspberry); *Salix* spp.; *Spiraea betulifolia* Dougl., Meadowsweet; *Symphoricarpos* spp.; *Vaccinium* spp.; *Carex* spp.; *Calamagrostis* spp.) described in Boyd *et al.* (1985) are also common to our study. In the Lake States, hexazinone (Velpar[®] L) provided control of trembling aspen, cherry (*Prunus* spp.), raspberry, serviceberry (*Amelanchier* spp.) and various grasses (Alm and Wherton 1988). Sutton (1986) reported a good control of trembling aspen, *Acer spicatum* Lam. (mountain maple), *Prunus pensylvanica* L.f. (pin cherry) with hexazinone at 4.2 a.i. ha⁻¹ rate. Cover of non-target species such as *Cornus canadensis* L. (bunchberry), *Solidago* L. spp. (golden rod), *Galeopsis* spp. (hemp nettle) and mosses was reduced for 2 years with a pre-treatment recovery by the end of 3 years after application with hexazinone (Anonymous 1989). One species, *Corylus cornuta* Marsh. (hazel), was unaffected by hexazinone (Wile 1981).

The behaviour and fate of herbicides in forest ecosystems are also important environmental concerns. The solubility of hexazinone in water is 3.3% (w/w) which makes it mobile in soil. Its mobility varies with soil texture, soil moisture and slope (e.g., Roy *et al.* 1989; Feng and Navratil 1990). Down-slope movement of 2-3 m has been reported on slopes of 7-22° (Barry and Torstensson 1983; Harrington *et al.* 1982; Roy *et al.* 1990). Low concentrations of hexazinone appeared in stormflow and baseflow but dissipated rapidly in streams treated directly with hexazinone (Neary *et al.* 1983; 1986; Miller and Bace 1980). Feng and Feng (1988) reported 1 to 31 µg L⁻¹ of hexazinone in ephemeral and permanent streams at various post-treatment times and downstream distances from the treated plots. Hexazinone is readily absorbed by vegetation, and residues of hexazinone and its metabolites A and B persist in foliage and litter at concentrations exceeding 0.02, 0.17 and 0.13 µg g⁻¹ respectively, for two growing seasons following application (Sidhu and Feng 1993, Bouchard *et al.* 1985, Lavy *et al.* 1989; USDA 1984). The concentrations observed pose no known toxicological threat to wildlife. The toxicity of hexazinone to fish and aquatic biota and mammals is low (WSSA 1989). For example, acute oral LD₅₀ level in rats is 1690 mg kg⁻¹ for hexazinone. Rhodes and Jewell (1980) in their laboratory study found complete excretion of hexazinone residues in rats. Extremely small residues of hexazinone (<0.17 µg kg⁻¹ and its metabolites (B, <0.70; A, <0.20 µg kg⁻¹) were detected in small mammals from field plots in central Alberta at 9 days after treated with hexazinone (as Pronone 10G) at 4 kg a.i. ha⁻¹ (Penner 1990). The concentrations declined with time and were below the detection levels (<0.05 µg kg⁻¹ metabolites A and B) at the end

1st growing season (360 days after treatment) following herbicide treatment.

Few studies have focused on the effects of hexazinone on the soil microorganisms. In general, Wainwright (1978) found herbicides are not toxic to the majority of soil organisms. Hexazinone has been found to have no effect on nitrification or on numbers of fungi and bacteria in soil at typical application rates (Rhodes *et al.* 1980). Kelly and Smith (1980) found that some, but not all of the 10 ectomycorrhizae tested were inhibited by hexazinone at concentrations as low as 1 µg/ml of agar. Hexazinone at concentrations of up to 10 µg g⁻¹ did not effect the *in vitro* growth of ectomycorrhizal fungi (Chakravarty and Sidhu 1987). They reported reduction in mycorrhizal infections in the greenhouse at 1 to 4 kg a.i. ha⁻¹ rates (Chakravarty and Sidhu 1987a) and under field conditions at 4 kg a.i. ha⁻¹ (Sidhu and Chakravarty 1990). In contrast, Andriese and Vitousek (1988) found increased nitrate concentrations in soils treated with hexazinone within hours of application. They attributed this to lysing of the microbial cells resulting in the release of nitrate.

Pehl (1984) studied the effects of non-herbicide methods of site preparation on various soil properties and soil and foliar nutrient. Changes in Ca and N concentrations in soil and N in foliage were still significant in the fifth growing season after treatments. In addition, herbicide treatments have been shown to alter the morphology of leaves and reduce the leaf biomass production by 23 to 40 % (Dunsford 1979). This could indirectly alter nutrient dynamics by reducing nutrient input to the soil via litterfall. Carter *et al.* (1984) found in loblolly 4-year-old pine (*Pinus taeda* L.) stands that competing vegetation reduced available K, Ca, Mg, and Mn in the soil, however, removal of the competing vegetation did not affect the foliar nutrient concentrations in the pine.

We carried out a large multidisciplinary study, from 1985 to 1991, in a boreal mixedwood cutover dominated by aspen regrowth and marsh reed grass. The overall purpose of this study was to assess the environmental impact of different vegetation management practices, in particular the application of hexazinone by PRONONE 10G on the forest ecosystem (Sidhu and Feng 1990). The granular formulation of hexazinone was selected for the present study to minimize the off-target deposition of the herbicide.

Four objectives of the study are reported here:

- 1) Determine the response of woody species (stem densities) to hexazinone and mechanical treatments;
- 2) Determine the changes in the composition and structure of target

- and non-target vegetation to hexazinone and mechanical treatments;
- 3) Monitor the environmental distribution, movement and persistence of hexazinone and its metabolites in soil, water and vegetation, and
 - 4) Determine the effects of hexazinone on the nutrient dynamics of foliage and soil.

Materials and Methods

Study site and Vegetation.

The study area was located on a clear-cut within the mixedwood section of boreal region (Rowe 1972) on the Alberta Plateau (Bostack 1970) about 21 km south of Grande Prairie, Alberta, Canada (Lat 54° 55' N, Long. 118° 48' W). The area was logged in 1983. Prior to logging, the site supported an aspen dominated (80%) forest with white spruce and lodgepole pine (20%). The aspen was 50 to 65-yr-old and 19 to 25 m high with a 71 to 100% crown closure. Before harvest, the vegetation belonged to the aspen facies of the white spruce (*Picea glauca* (Moench) Voss), bush cranberry (*Viburnum edule* (Michx.) Raf.), sarsaparilla (*Aralia nudicaulis* L.) ecosystem described by Coms and Annas (1986). After logging, aspen suckers (1 to 2 m tall) dominated and formed a continuous canopy. Suckers were shorter and their canopy more open in seasonally wet areas. Small number of green alder (*Alnus crispa* [Ait] Pursh), Saskatoon berry, and willow were intermixed with trembling aspen in the shrub layer. Low woody shrubs included blueberry (*Vaccinium myrtilloides* Michx.), dwarf bilberry (*V. caespitosum* Michx.), meadowsweet, snowberry (*Symphoricarpos albus* [L.] Blake), and wildrose (*Rosa acicularia* Lindl.). Herbaceous vegetation was dominated by showy and Lindley's asters (*Aster conspicuus* Lindl. and *A. ciliolatus* Lindl.), bunchberry, fireweed (*Epilobium angustifolium*), meadowsweet, sarsaparilla, and wild strawberry (*Fragaria virginiana* Duchesne). Marsh reedgrass was the dominant species among grasses.

Soils.

Twardy and Dowgray¹ categorized the majority of the soils of the study site as gleyed solonchic grey luvisols developed on clay to heavy clay textured lacustro-till deposits. The mean depth and texture of horizons from a typical profile were: LFH, 0-6 cm; Ah, loam, 6-12 cm; Ae, silty clay loam, 12-22 cm; AB, clay, 22-28 cm; Bnt, heavy clay, 66-76 cm; C, heavy clay, 76 cm.

Climate.

The climate of the area is dry subhumid with moderately warm summers and long cold winters. July is the warmest and January the coldest month with mean temperatures of 16 and -18°C, respectively. The frost free period averages

less than 116 days/year. The average annual precipitation for the area is 453 mm with 232 mm occurring during the growing season (May to August).

There was no precipitation for seven days after the application of the herbicide on August 26, 1986 and only 7.8 mm cumulative rainfall 11 days after the herbicide application, (Grande Prairie weather station, Environment Canada 1986). Total rainfall during the 30 days following application amounted to 77.5 mm, significantly greater than 26 mm required for 99% release of hexazinone from the granules (Feng *et al.* 1989).

Experimental design.

Six chemical, mechanical and their combination methods for site preparation were tested. Chemical treatment included hexazinone applied at 0, 2(LH) and 4(HH) kg a.i. ha⁻¹ as a 10% granular formulation. The mechanical methods were disk trenching (DT) and double row disking (DD). The combination methods were DT+LH and DT+HH. Three replicates of each treatment were established as complete blocks (Fig. 1). Each treatment plot was 80 m wide by 180 m long separated by 5 m-wide buffer strips from the other plots. Vegetation sampling was restricted to the 30 m by 150 m central portion of each treatment plot. Three over-lapping swaths of the granular formulation were applied aerially by a Isolair Series 2600-45 applicator attached to a Bell-206 helicopter under no wind conditions on 26 August 1986 (Sidhu and Feng 1990). The mechanical treatments (DT, DD) were applied in May 1987. The DT-treatment involved Donaren 180-D disk-trencher (AB skogsbrusksmaskiner) mounted to John Deere-740 skidder. The two toothed disks resulted in approximately 30 cm deep trenches, berms created on edges of trenches by excavated and overhauled material and undisturbed areas between trenches. Double-disking involved tandem discs pulled by D8 Caterpillar tractor. It resulted in cutting and mixing of soil to a depth of 20 cm and DD-treated area appeared as a farmers field with little vegetation cover.

Vegetation sampling and data analysis.

In each treatment plot, thirty 5m × 5m permanent subplots were established in three rows of 10 plots for density counts of woody species over 50 cm high by height classes; A = 50 to 150 cm, B = 150 to 500 cm, and C = >500 cm. Each 5m × 5m was divided into 4 quadrants to facilitate stem counts (Fig. 1). All plots in all treatments were sampled for stem density in 1986, 1987, 1988 and 1989 (only one replicate of mechanical treatments). Only the control and herbicide treatment plots were sampled in 1991. The sampling intensity in 1989 and 1991 was

¹Twardy, A.G. and Dowgray, A.I.T. 1985. Soil survey of two clearcut areas detailed analysis of blocks within the test area. Report prepared for Canada-Alberta Forest Resources Development Project. Pedology consultants, Edmonton, Alberta.

50% and 25% of that in 1986 to 1988. Stem density data for 1986 to 1988 from all treatments were tested for departure from normality and homogeneity of variances. No data sets were found to be normally distributed and variances were not homogenous. As a result, stem density data were analyzed for variances among treatments by Friedman's non-parametric test for a randomized complete design ($p=0.05$) and Tukey's procedure for ranked data in a randomized block analysis of mean separation at $p=0.05$ (Zar 1980). Percent change in density from 1986 (pretreatment year) to another year (Y) was calculated as $[(Y - 1986)/1986] \times 100$.

In each quadrant of each 5 m \times 5 m woody density subplot, a 1 m \times 1 m permanent plot was set up for sampling cover of all vegetation strata and presence by species of forbs and low woody species, graminoids, and mosses and bryophytes. As a result, a total of 120 quadrats were sampled in each treatment plot during mid July to mid August of 1986, 1987, and 1988. The sampling intensities in 1989 and 1991 were 16.6% and 25% of that in 1986 to 1988. The cover was estimated by cover class as: 0 = absent, 0.5 = present with < 1.0% cover, and 5, 15, 25, 35, 45, 55 ... 95 representing mid point of cover classes of 1-10, 11-20, 21-30, 40-45, 50-60 ... 91-100% cover. Frequency for each cover class of all species separately and together by strata were calculated. Changes in cover class frequencies for leading species and of different vegetation strata for different years within treatments and different treatments within a year were tested for significance ($P = 0.05$) using χ^2 -test for contingency tables (Zar 1984). Cover classes with less than 1.0 frequency were combined with adjoining classes until no class was less than 1.0 frequency and no more than 20% of the expected class frequencies were less than 5.0 as suggested in Cochran (1954) and Zar (1984). For all leading species which occurred in >20% of quadrats within one or more treatments in one or more years, percent frequency and 95% binomial confidence limits for their frequency were set according to Burstein (1971). Quadrat- and treatment plot-based species richness was determined.

Fate of hexazinone.

The methods used for the environmental fate of hexazinone on Pronone 10G (off site drift, run off in permanent streams, movement in soil, and residues in soil and vegetation) are

described in various publications (Feng and Sidhu 1989; Feng, Feng and Sidhu 1989; Feng *et al.* 1989; Sidhu and Feng 1990; Feng, *et al.* 1992; Sidhu and Feng 1990 and 1993). The hexazinone residues were determined by methods following Feng (1992).

Nutrient dynamics methods

Vegetation.

The environmental impact of vegetation management on nutrient dynamics in vegetation included seasonal, year to year, and hexazinone related changes in the macronutrients in the foliage of a number of boreal species from hexazinone treated and control plots. The sampling methods have been described by Sidhu and Feng (1990). Foliage samples were oven-dried at 60°C for 24 hr and ground to pass through 20 mesh screen. Total elemental analysis (Ca, Mg, Na, K, P, and S) was done by ICP-AES following wet digestion in a microwave oven (Kalra *et al.* 1989). Total N was determined, by Kjeltac Auto 1030 Analyzer following a wet digestion (Kalra and Maynard 1991). Only general conclusions are presented in this paper. Details on nutrient dynamics are available in Sidhu (1993)².

Soils and Litter.

Samples were collected from the 0, 2, and 4 kg a.i. ha⁻¹ treatments of block II only (Fig. 1). In each treatment, adjacent to the vegetation sample plots, fifteen 3 m \times 3 m soil subplots were set up. Two soil pits were dug within each sub-plot. Four horizons; a LFH (surface organic horizon), Ah or Ahe, Ae, and Bnt(gj) were sampled for analysis. In some pits the Ah (Ahe) horizon was not present. Samples were collected prior to the herbicide application, July 28-30, 1986 and for two years following the herbicide application, August 17-18, 1987 and August 30-31, 1988. The resampling in 1987 was delayed until after significant amounts of litter had fallen as a result of the herbicide application.

²Sidhu, S.S. 1993. Foliar nutrient dynamics in boreal mixedwood species 3 years following hexazinone application (inpreparation).

Table 1. Average^a densities of live woody stem (numbers of ha) over 50 cm in height, % change from pretreatment lands, and % aspen component in control, hexazinone^b and mechanically^c treated plots.

Year ^d	Item	Average number of stems ha ⁻¹ in treatment plots						
		Control	LH	LH + DT	HH	HH + DT	DD	
Pretreatment								
1986	Stem density							
	Average (± S)	53 266 X ^e (3 892)	59 969 Y (16 195)	61 739 Y (3 940)	63 617 Y (11 999)	45 783 X (2 547)	62 573 Y (26 171)	
	% Aspen (± S)	84 (3.5)	85 (10.1)	82 (3.2)	81 (20.1)	85 (6.4)	78 (32)	
	Sum stem length ^f (cm x 10 ³)							
	all spp	4 793	5 372	5 601	5 789	3 941	5 916	
	aspen	4 026	4 566	4 593	4 689	3 349	4 613	
	Median % cover - class	15	15	15	15	15	15	
Post treatment								
1987	Stem density							
	Average (± S)	61 027 X (10 410)	65 577 X (22 890)	43 987 Y (10 813)	61 928 X (11 566)	34 830 Y (2 127)	97 Z (124)	
	% Aspen (± S)	77 (5.3)	80 (11.5)	75 (5.5)	77 (22.7)	81 (12)	82 (80)	
	% change from 1986 ^e	+ 16	+ 9	- 28	- 2	- 23	- 99	
	Sum stem length (cm x 10 ³)							
	all spp	6 729	8 888	4 154	7 321	2 703	26	
	Aspen	5 181	6 470	3 116	64 049	2 298	20	
	% change from 1986	+ 40	+ 65	- 26	+ 26	- 31	- 97	
	Median % cover class	25	15	15	5	5	< 0.1	
	1988	Stem Density						
		Average (± S)	73 690 X (8 512)	63 208 Y (27 565)	33 977 Z (10 525)	45 848 Z (9 674)	17 945 W (4 297)	1 836 V (697)
		% Aspen (± S)	62 (10.0)	77 (14.7)	82 (5.8)	77 (30.0)	88 (22)	81 (3.5)
		% change from 1986	+ 38	+ 7	- 45	- 28	- 61	- 97
Sum stem length (cm x 10 ³)								
all spp		8 367	6 918	3 786	5 165	1 682	141	
Aspen		6 121	6 053	3 277	4 476		141	
% change from 1986		+ 65	+ 29	- 32	- 11	- 57	- 98	
Median % cover class		25	25	15	5	5	< 0.1	
1989		Stem Density						
		Average (± S)	77 227 X (10 750)	65 635 Y (37 918)	67 333 ^b	40 293 Z (13 679)	27 381 ^b	7 931 V (3 993)
		% Aspen (± S)	64 (9.5)	69 (20.3)	52	72 (27.8)	56	73 (36)
		% change from 1986	+ 44.9	+9.4	+9.0	-36.6	- 40.1	- 88
	Total stem length (cm x 10 ³)							
	all	8 138	7 469	4 706	4 733	2 719	716	
	aspen	6 726	6 512	2 904	4 035	1 799	422	
	% change from 1986	+ 69	+ 39	- 16	- 18	- 30	- 88	
	Median % cover class	35	45	25	15	15	<1	

Table 1. Continued

Year ^d	Item	Average number of stems ha ⁻¹ in treatment plots					
		Control	LH	LH + DT	HH	HH + DT	DD
1991	Stem Density						
	Average (\pm S)	68 640 X (8 855)	52 529Y (29 328)	N.S. ⁱ	42 366Z (15 995)	N.S.	N.S.
	% Aspen (\pm S)	44 (15.5)	49 (18.9)		50 (14.6)		
	% change from 1986	+ 28.8	-11.7		-33.4		
	Sum stem length (cm \times 10 ³)						
	all spp	6 912	6 147	N.S.	4 430	N.S.	N.S.
	aspen	6 281	5 331		3 537		
	% change from 1986	+4.4	+14.4		-23.4		
	Median % cover class	35	45	N.S.	15	N.S.	N.S.

^a Average of three replicates of a treatment, each replicate of a treatment value average of thirty 5 m x 5 m sample plots.

^b Hexazinone applied as granular PRONONE 10G applied on 26 August 1986; LH = 2 kg a.i. ha⁻¹, HH = 4 kg a.i. ha⁻¹.

^c Mechanical treatments; DT = Disk trenching, DD = Double Rome Disk. Mechanical treatment super imposed in herbicide treated plots in May 1987.

^d 1986 sampling is a pre-treatment sample, 1987 to 1991 are post-treatment samples.

^e Mean stem density values followed by the same letter were not significantly different ($P=0.05$) among treatments in the same year. Friedman's non-parametric ANOVA and Tukey's procedure for ranked data was used for mean separation (ZAR 1984).

^f Sum stem length = sum of average number of stems of each species/ha multiplied by its representative height over all woody species in a plot.

^g % change = $(Y-1986 + 1986) \times 100$, where Y = post-treatment year.

^h Only one replicate block sampled, treatments not included in statistical analysis.

ⁱ N.S. = Not sampled

The soils and litter samples were handled in the same manner at all sampling dates. The soils were kept cool after sampling and transported back to the laboratory and frozen (-20°C) until analyses were done. The LFH material was thawed, homogenized in a Waring blender, and subsamples weighed out moist for NO₃⁻-N and NH₄⁺-N. Subsamples were air-dried for cation exchange capacity (CEC) and extractable cations (Ca, Mg, K, Na) and total N analysis. The air-dried samples were crushed to 2 mm size and mixed prior to weighing for CEC and exchangeable cations. For total N analysis, air-dried subsamples were further ground in a Wiley mill to pass through a 20 mesh sieve.

Ammonium (NH₄⁺) and nitrate (NO₃⁻) were determined in a 2 M KCl extract (approximately 20:1 solution to soil ratio, oven-dried weight (odw) basis by a Technicon Auto Analyzer II system (AA II). Ammonium was determined by the indophenol blue colorimetric technique (Technicon 1973) and nitrate was determined colorimetrically using the copperized cadmium (Cd) reduction method (Technicon 1971). The Cd reduction technique includes nitrite (NO₂⁻) plus NO₃⁻.

Extractable cations and S were determined by extraction with unbuffered 1.0 M NH₄Cl on a mechanical vacuum extractor using methods described by Kalra & Maynard (1991). Total N concentrations in the LFH horizons were determined using the same method as for vegetation (Kalra and Maynard 1991).

The soil elemental concentrations (except nitrate) were compared using one-way Anova comparing treatments within a year (SAS Institute Inc. 1989). Nitrate concentrations among treatments within a year were compared using a Kruskal-Wallis nonparametric test with a Tukey's mean separation procedure (Zar 1984), due to the departure of data from normality and unequal variances.

Results and Discussion

Vegetation changes

Woody stem density.

Analysis of pre-treatment stem density indicated large variations among sample subplots (5 m x 5 m) within a treatment plot and among treatment plots within a treatment and between treatments. Within treatment plots coefficient of variation ranged from 28-78% indicating a very low density to very high density of aspen in subplots within treatments. The aerial application of PRONONE 10G did not result in uniform deposition rates at the sub-plot level. Variability among replicates of the same treatment and among treatments were as great. For example, in 3 treatment plots designated for double disking, the

treatment years are summarized in Table 1 and changes in all woody and aspen stems are presented in Table 1 and Fig. 2.

In the control plots, woody stem density increased yearly from 1986 to 1989 with a 16% decline from 1989 to 1991 (Table 1). The lower density could have been partly confounded in the smaller size of sample size, 50% of 1986 in 1989 and 25% in 1991. Aspen component as % of the total stems declined continuously from 1986 to 1991 even though the density of all woody stems increased (Table 1, Fig. 2). The increase in total woody stem density was due to regeneration of non-aspen species, such as Saskatoon berry, wildrose (*Rosa acicularis* L.) and low-bush cranberry (*Viburnum edule* (Michx.) Raf.). The changes in total stem heights per hectare were similar to the changes in stem densities from 1986-base in 1987 to 1991 (Table 1). However, changes based on total stem heights were of greater magnitude than those based on stem densities and may be more meaningful in terms of total demand on nutrients and moisture by competing species in the control and treated sites. Besides the change in stem numbers and total stem heights, there was a progressive increase in % foliage cover of woody species; 10% increase over 1986 in 1987 and 1988 and 20% in 1989 and 1991, presented as change in median % - cover class (Table 1).

The application of hexazinone alone and in combinations with disc-trenching and double-discing alone resulted in a varied degree of control of woody stems. At low herbicide rates there was a net increase in the total number of woody stems despite a net decrease of 20% in aspen stems by the end of the 1989 growing season (Table 1 and Fig. 2). Low herbicide in combination with disc-trenching resulted in a control of over 45% of woody stems during the first two years. However, they recovered to near pre-treatment levels by the third year after treatment (Table 1). The LH+DT treatment resulted in a net decrease of 30% of aspen stems from the 1986 levels. The lack of net change in density of woody stems by 1989 was due to an increase in stems of non-aspen woody species such as wild rose, Saskatoon berry and low-bush cranberry. The increase in these stems continued in the low herbicide treatment for 4 years after treatment. Their competitive influence on crop seedlings may be lower because of their low average height. In 1991, average heights of wildrose, Saskatoon berry, and cranberry were 64, 82 and 55 cm in the controls and 61, 68, and 52 cm in the 4 kg a.i. h⁻¹ treatments. These species are important as browse for wildlife. The shift in species may affect

the quality and quantity of browse available to wildlife in the short-term. High herbicide (HH) alone and HH + DT resulted in a 36% and 40% decrease of woody stems compared to 45% increase in controls. There was a 50% and 60% control of aspen stems by 1989 respectively (Table 1 and Fig. 2). Non-aspen woody stems increased in 1991. Double-discing (DD) virtually eliminated the woody species for the first 2 post-treatment years followed by a 12% recovery in the third year (Table 1 and Fig. 2).

The 1986 stem density data (both for all species and for aspen) were very similar among treatment plots. Herbicide application in the late summer 1986 had little immediate impact on live stem density. The decrease in 1987 density reflects the effect of disk-trenching and to a lesser extent the herbicide effects. Nonparametric analyses identified the presence of two distinct density groups: one consisting of untreated and herbicide-treated plots, and the other of plots that were mechanically disc-trenched. Analysis of both the total number of live stems and the number of live aspen stems showed similar results. The reduction in stem density in the combined herbicide and mechanical treatments was primarily due to mechanical treatments during 1987 (Table 1 and Fig. 2). The effects of all treatments except HH had peaked by the end of 1988. On HH-plots, total stems were lowest in 1989 and aspen stems continued to decrease through 1991 (Table 1). Recovery in stem density in all treatments except HH was evident by 1989. Most of the increase in total number of stems in the controls was due to an increase in non-arborescent species such as *Amelanchier*, *Rosa* and *Viburnum*. The number of aspen stems over 50 cm decreased in controls from 1986 to 1991. There was some (1.5% of 1986 number) increase in stem density in DD-plots from 1987 to 1989 (Table 1 and Fig. 2). The high herbicide rate and other intensive mechanical treatments had a significant effect on nontarget species for at least two years followed by recovery of woody stems in the third and subsequent years. The dynamics of the non-aspen species needs further examination for their non-fibre use and their functional role in the forest ecosystem.

In the 3-year-old mixedwood cutover dominated by aspen, density of all woody species including aspen was extremely variable in sample sub-plots within treatment plots, among replicates of treatments, and treatment plots within blocks. In addition, the deposition pattern of the aerially applied Pronone 10G was not uniform at the

Table 2. Average height and volume expressed as ratio of treatment: Control in lodgepole pine and white spruce 3 years after planting in control and site prepared plots

Treatment ¹	Lodgepole pine		White spruce	
	Height (cm)	Volume (cm ³)	Height (cm)	Volume (cm ³)
Control	1 (30.7) ²	1 (2.8)	1 (32.3)	1 (10.4)
LH	1.1	2.6	1.0	1.2
LH + DT	1.2	3.0	1.1	1.3
HH	1.3	4.0	1.1	1.7
HH + DT	1.4	6.9	1.2	2.1
DD	1.5	5.1	0.9	1.1

¹Control = no treatment, LH = 2 kg hexazinone ha⁻¹, DT = Disk-trenching, HH = 4 kg hexazinone ha⁻¹, and DD = Double disc-disking.

²Values in parentheses are average height and volume of pine and spruce 3 years after site preparation and planting. Average heights of pine and spruce seedlings were 13.1 cm and 18.9 cm.

subplot levels producing patchy control of vegetation ranging from 0% to 100% control. The average values for three blocks (Table 1) reflect the changes that would occur on an operational scale in hexazinone alone or in combination with mechanical treatment plots. In contrast, the double-disked treatment resulted in a complete destruction of vegetation and soil integrity. Significant early gains in height and volume growth in the planted conifers, lodgepole pine and white spruce are reported by Todd and Brace (1990) as a result of some site preparation treatments. A summary of results from Todd and Brace (1990)³ is presented in Table 2. The DD, HH alone or in combination with DT were the most effective treatments for pine whereas spruce growth was best in HH and HH+DT treatments where partial vegetation cover was maintained.

Changes in species richness and frequency.

There were 110 plant species recorded from the study area (Sidhu and Feng 1990). Changes in species richness, their frequency of occurrence, and cover were studied only in the herbicide treated and control plots. Prior to the treatments, species richness varied within plots and among plots with CV's of 13-22% (Table 4). Considerable post treatment variation occurred between treatments within each block and among replicate blocks

within each treatment (Table 4). During the first post treatment growing season quadrat-based (1m x 1m) species richness decreased as a result of the herbicide treatment. After the second growing season, the species richness recovered to the pretreatment levels in the 2 kg a.i. ha⁻¹ herbicide rate but it continued to be low in the 4 kg rate until 1989. In all treatments the species richness appeared to recover to the pretreatment levels in 1991, (5th year following the treatment). Similar trends were observed in species richness on a treatment plot basis (Table 3).

Changes in frequency of occurrence of leading species (species that occurred in >20% of quadrats in one or more treatments in one or more years) in the herbicide and control treatments were analyzed using the pooled data from the three blocks (replicates). The results of selected leading species for years 1986 to 1989 are presented in Table 4. In control plots, frequency of 65% of the species increased from 1986 to 1989, 25% of the species showed no change, and only 10% were less frequent in 1989 than in 1986. About 70% of the 57 leading species suffered a significant ($P = 0.05$) decrease in their frequency as a result of hexazinone application at both 2 and 4 kg a.i. ha⁻¹ rates. In the second year after treatments there was some recovery but 50% of species in LH and 70% in HH treatments showed a net decrease in their frequency. The recovery continued in 1989 (Sidhu and Feng 1990) and a preliminary analysis of 1991

³Todd, P. and Brace, L. 1990. A summary of third year results from the FRDA forest vegetation management project. Canada - Alberta Agreement. Progress Report, Northern Forestry Centre, Edmonton, Alberta. pp. 40.

Table 3. Species richness and number of species in control and herbicide-treated plots in 1986 to 1991

Treatment		Species Richness ^a					Total number of species in treatment plots				
		Pre-treatment		Post-treatment			Pre-treatment		Post-treatment		
		1986	1987	1988	1989	1991	1986	1987	1988	1989 ^b	1991
Control	B1	20.6 ± 3.1	22.0 ± 3.3	24.1 ± 3.3	22.0 ± 2.8	23.1 ± 3.8	69	71	79	57	58
	B2	20.7 ± 2.8	22.0 ± 3.6	23.6 ± 3.5	22.9 ± 2.8	21.4 ± 2.4	68	78	80	60	52
	B3	18.8 ± 2.5	19.2 ± 2.4	20.0 ± 3.1	N.S. ^c	18.5 ± 3.3	65	71	74	N.S.	47
LH	B1	17.4 ± 3.8	10.8 ± 3.3	11.4 ± 5.2	N.S.	15.5 ± 4.0	63	59	61	N.S.	57
	B2	22.2 ± 3.6	18.5 ± 4.0	21.2 ± 4.0	19.1 ± 3.7	21.2 ± 3.4	74	77	84	51	55
	B3	17.8 ± 3.1	13.7 ± 5.1	17.2 ± 3.4	N.S.	18.5 ± 3.6	78	68	93	N.S.	63
HH	B1	18.2 ± 3.5	10.4 ± 2.6	13.7 ± 4.5	13.9 ± 4.1	16.4 ± 3.5	58	53	71	55	57
	B2	21.6 ± 3.4	13.2 ± 3.2	16.3 ± 4.0	15.3 ± 3.4	18.5 ± 3.4	75	69	87	64	65
	B3	18.9 ± 3.4	14.1 ± 3.6	12.1 ± 5.5	18.5 ± 3.1	20.1 ± 3.0	71	59	72	51	58

^aSpecies richness = average number of species (±S) per 1 m × 1 m quadrat based on 120 quadrats.

^bNo. of species in 1989 and 1991 based on 25% sample size of that in 1986 to 88.

^cN.S. = not sampled

Table 4. Frequency^a of occurrence of some leading species^b by year and treatment, with 95% binomial confidence limits.

Species	Year	Herbicide Treatment (kg hexazinone ha ⁻¹)								
		0 (Control)			2 (LH)			4 (HH)		
		L ^d	O	U	L	O	U	L	O	U
<i>Rosa acicularis</i> (< 50 cm)	1986	95	97	98	91	94	96	91	94	96
	1987	94	96	98	91	94	96	83	86	90
	1988	97	99	100	86	89	93	79	83	87
	1989	94	100	100	88	100	100	57	68	77
<i>Cornus canadensis</i>	1986	95	97	98	75	80	84	72	77	81
	1987	78	83	86	80	84	88	78	82	86
	1988	80	84	88	79	83	87	79	84	87
	1989	91	98	100	83	97	100	67	77	85
<i>Lathyrus ochroleucus</i>	1986	94	96	98	92	95	97	90	93	96
	1987	87	90	93	68	73	77	44	49	54
	1988	74	78	83	51	56	62	17	21	25
	1989	38	52	65	47	67	83	15	23	33
<i>Epilobium angustifolium</i>	1986	88	91	94	82	86	89	83	86	90
	1987	90	93	95	90	93	95	66	71	75
	1988	82	86	89	81	85	89	73	78	82
	1989	84	93	98	73	90	98	78	87	93
<i>Aster conspicuus</i>	1986	88	91	94	70	75	79	73	77	81
	1987	91	94	96	58	63	68	50	55	60
	1988	91	94	96	63	68	73	64	69	73
	1989	86	95	99	44	63	80	65	76	84
<i>Calamagrostis canadensis</i>	1986	82	86	89	77	81	85	68	73	77
	1987	90	93	95	35	40	46	5	7	10
	1988	90	93	95	34	39	44	13	17	21
	1989	84	93	98	25	43	62	9	16	25
<i>Vicia americana</i>	1986	78	82	86	71	76	81	74	78	82
	1987	68	73	78	49	54	60	55	69	65
	1988	49	54	59	37	42	48	23	27	32
	1989	45	58	71	15	30	49	25	34	46
<i>Galium boreale</i>	1986	79	83	87	68	73	77	81	85	88
	1987	86	90	93	74	78	82	67	72	76
	1988	86	89	93	69	74	78	76	80	84
	1989	73	85	93	73	90	98	75	84	91
<i>Fragaria virginiana</i>	1986	71	76	80	49	55	60	49	54	59
	1987	57	62	67	28	33	38	0	0	2
	1988	59	64	69	7	10	14	2	4	6
	1989	75	87	94	10	23	42	1	3	9

Table 4. (Continued)

Species	Year	Herbicide Treatment (kg hexazinone ha ⁻¹)								
		0 (Control)			2 (LH)			4 (HH)		
		L ^d	O	U	L	O	U	L	O	U
<i>Maianthemum Canadense</i>	1986	69	74	79	69	74	78	49	54	59
	1987	53	58	63	66	71	76	39	45	50
	1988	59	64	69	65	70	75	61	66	71
	1989	59	72	83	54	73	88	47	58	68
<i>Aralia nudicaulis</i>	1986	62	67	72	53	58	63	50	56	61
	1987	66	67	72	56	61	66	54	60	65
	1988	61	64	73	56	61	66	39	44	49
	1989	66	78	88	83	97	100	51	62	83
<i>Oryzopsis asperifolia</i>	1986	53	58	63	24	28	33	24	29	34
	1987	32	37	43	34	39	44	1	2	4
	1988	38	43	48	16	20	25	10	13	17
	1989	31	43	57	17	33	53	0	0	4
<i>Populus tremuloides</i> (>50 cm)	1986	37	42	47	29	33	38	29	34	39
	1987	63	68	73	60	65	70	48	53	58
	1988	83	87	91	61	66	71	39	44	50
	1989	82	92	97	88	100	100	56	67	76
<i>Agrostis scabra</i>	1986	11	15	19	13	17	21	13	16	20
	1987	11	15	19	1	3	5	1	1	3
	1988	18	14	18	10	14	18	20	24	29
	1989	13	23	36	4	13	31	21	30	41
<i>Agropyron trachycaulum</i>	1986	8	11	15	7	10	14	18	22	27
	1987	8	11	14	1	2	4	1	2	4
	1988	10	14	18	9	12	16	16	19	24
	1989	4	10	21	1	7	22	13	21	31
<i>Castilleja miniata</i>	1986	7	10	14	1	3	5	1	2	4
	1987	21	26	31	2	3	6	1	1	3
	1988	25	30	35	3	5	8	2	3	5
<i>Crepis tectorum</i>	1986	1	2	4	5	8	11	10	13	17
	1987	4	6	9	1	3	5	3	5	8
	1988	1	3	5	11	14	18	27	32	37
<i>Arabis holboellii</i>	1986	0	0	1	0	0	0	0	0	1
	1987	0	0	1	0	0	0	0	0	1
	1988	0	0	1	0	0	0	11	15	19

^aFrequency is percentage of quadrats in which species occurs: 1986-88 n = 360; 1989: 4 kg ha⁻¹ n = 90; 2 kg ha⁻¹ n = 30; 0 kg/ha n = 60.

^bLeading species are those occurred in >20% of the quadrats within one or more treatments in one or more years.

^c95% binomial confidence limits calculated according to Burstein (1971).

^dL = lower confidence limit, U = upper confidence limit, O = observed value.

data showed further recovery to the pre-treatment levels in most species. Recovery in species frequencies are consistent with the trends in recovery in woody stem density and cover of various vegetation strata.

Agropyron trachycaulum, *Agrostis scabra*, *Arabis holboellii*, *Crepis tectorum* increased significantly as a result of hexazinone application. Species like *Epilobium angustifolium* and *Galium boreale* decreased insignificantly as a result of hexazinone treatment at 4 kg ai ha⁻¹ and increased slightly at 2 kg ai ha⁻¹ treatment. Other species were highly to moderately sensitive and decreased in frequencies. Sensitive species included *Calamagrostis canadensis*, *Castilleja miniata*, *Fragaria virginiana*, *Oryzopsis asperifolia* and moderately sensitive species were *Aralia nudicaulis*, *Cornus canadensis*, *Lathyrus ochroleucus* and *Vicia americana*.

Changes in vegetation cover.

Changes in cover of individual species and species complex were considered in various strata; tall shrubs (over 150 cm), medium shrubs (50-150 cm), forbs, graminoids, and mosses and bryophytes. Each quadrat was classified into a cover class depending on the estimated cover by strata and species. The process was repeated for all leading species and all vegetation strata for control and herbicide treatments. From the frequency distribution of cover classes, median class cover was determined for each stratum and leading species for 1986 to 1991. The results for different vegetation strata are presented in Figures 3 to 5. Average % cover by strata calculated from cover-class frequencies is presented in Table 5.

In control plots, vegetation cover in the tall shrub stratum increased by two median cover classes with an average cover of 1.4% in 1986 to 18.7% in 1991 (Fig. 3 and Table 5). The tall shrub cover doubled every year from 1986 to 1991. During the period there was optimization of cover in the medium shrub stratum. Most quadrats belonged to the 15% median cover class. There was no overall change in the cover of the medium shrubs, however, there was a shift towards classes with medians of 15, 25, and 45%. Median class cover in the forb layer was 55% in 1986 and 1987 and decreased to a class lower (45%) in 1989 and 1991 with an overall decrease in % cover (Table 5). The grass cover remained unchanged from 1986 to 1989 as determined by median class cover but average cover increased significantly to over 15% in 1991 (Fig. 3 and Table 5).

The application of hexazinone at the 2 kg ha⁻¹ rate had no significant effect on the cover of medium shrubs, forbs, and mosses and bryophyte strata. Their medians were the same as in controls except medium and tall shrubs strata increased by 10% in 1989 and

1991. The graminoid cover decreased by one median cover class (10%) from 1987 to 1989 and then recovered to the pretreatment level by the fifth year (1991) following herbicide application. Changes in stem density and cover both show that hexazinone at the 2 kg rate did not control the vegetation to levels that improved the growth of white spruce and lodgepole pine significantly (Table 2). This was confirmed by seedling growth assessments by Todd and Brace (1990)³.

Hexazinone at the 4 kg rate resulted in a significant decrease in cover of all strata except for tall shrubs and mosses and bryophytes. The maximum decrease was from 1986 to 1987. Though the recovery in vegetation cover occurred from 1988 to 1991, the cover remained lower by 10 to 20% in medium shrub, forb and graminoids strata (Table 5, Fig. 5). The tall and medium shrub strata were dominated by trembling aspen. The decrease in % cover resulted predominantly from a decrease in number and the total height of stems of trembling aspen and other woody species. This resulted in increased light reaching the ground level and less demand on the moisture and nutrients in the treated plots. The decrease in percent-cover of the forb and the graminoid strata was much greater than in the upper woody shrub strata. As a result of increased light reaching the ground, the bare-ground patches were gradually invaded by mosses and bryophytes. The total decrease in stems, and foliage cover resulted in lesser competition and improved growth of lodgepole pine and white spruce seedlings (Table 2).

The frequency distributions of cover classes for all strata and leading species for the years 1986 to 1989 were significant (χ^2 , $P=0.05$). The results indicated strong vegetation changes at the species and stratal cover level in individual quadrats due to both natural changes and hexazinone. There was no loss of any species present in the pretreatment surveys. Detailed frequency distribution tables and figures for species and strata are available in Sidhu and Feng (1990).

The greatest changes in vegetation cover occurred in mechanically treated plots where surface organic horizons of soil and associated vegetation were partially or completely removed. Before site preparation and crop release treatments, the terrain was disturbed by slash and slash piles, skid roads and scrape-offs. The disk-trenching resulted in trenches of varied depths and widths and berms on the edges of trenches of excavated and overturned material. Approximately 20 to 40% of the surface was disturbed. The double-disking resulted in complete terrain disturbance resembling newly broken fields with a complete removal of

Table 5. Pre- (1986) and post treatment (1987 to 1991) average (median class) % cover based on cover class frequency of vegetation in plots treated with 0, 2 and 4 kg hexazinone ha⁻¹ as Pronone 10G^{a, b}.

Spectrum	Year	Hexazinone rate (kg ha ⁻¹)		
		0 (Control)	2 (LH)	4 (HH)
Tall shrubs (>150 cm high)	1986	1.4(0.0)	1.0(0.0)	1.0(0.0)
	1987	2.5(0.5)	2.6(0.5)	1.5(0.5)
	1988	5.2(5.0)	6.2(5.0)	2.7(0.5)
	1989	9.4(5.0)	24.7(25.0)	4.8(0.5)
	1991	18.7(15.0)	16.9(15.0)	9.5(5.0)
Medium shrubs (50-150 cm high)	1986	18.0(15.0)	18.2(15.0)	16.7(15.0)
	1987	18.7(15.0)	16.3(15.0)	7.4(5.0)
	1988	20.3(15.0)	16.2(15.0)	11.0(5.0)
	1989	21.3(15.0)	18.3(15.0)	11.5(5.0)
	1991	20.6(15.0)	28.2(25.0)	9.8(5.0)
Forbs and low shrubs (<50 cm high)	1986	53.2(55.0)	50.7(55.0)	51.7(55.0)
	1987	58.2(55.0)	46.5(45.0)	21.6(25.0)
	1988	45.0(45.0)	59.0(55.0)	39.6(35.0)
	1989	50.0(45.0)	47.0(45.0)	40.9(35.0)
	1991	42.7(45.0)	44.0(45.0)	35.8(35.0)
Graminoids (grasses and sedges)	1986	8.2(5.0)	7.4(5.0)	5.0(5.0)
	1987	7.2(5.0)	2.0(0.5)	0.1(0.0)
	1988	5.3(5.0)	0.5(0.5)	1.0(0.5)
	1989	9.8(5.0)	1.7(0.5)	2.0(0.5)
	1991	16.2(15.0)	4.9(5.0)	2.7(5.0)
Mosses and bryophytes	1986	6.6(5.0)	7.8(5.0)	5.5(5.0)
	1987	8.1(5.0)	7.1(5.0)	5.6(5.0)
	1988	6.2(5.0)	9.6(5.0)	6.3(5.0)
	1989	2.7(0.5)	4.0(5.0)	8.9(5.0)
	1991	5.0(5.0)	7.4(5.0)	13.0(15.0)

^aBased on 360 quadrats treatment in 1986 to 1988, 60 quadrats in 1989, and 90 quadrats in 1991.

^bNote: 1986 is the pretreatment year and all other years are post-treatment years.

Table 6. Hexazinone concentrations in surface water and bottom sediments from seven sampling sites between treatment plots and Campbell River for one year after pronone 10G application on 26 August, 1986.

Days postspray	Date sampling	Water ($\mu\text{g L}^{-1}$)		Sediments ($\mu\text{g g}^{-1}$ dry wt.)	
		Site No. 1 ^a	Site No. 2-7 ^b	Site No. 1	Site No. 2-7
12	09-09-86	-	< 1	< 0.03	< 0.03
47	14-10-86	< 1	< 1	< 0.03	< 0.03
236	21-04-87	4.2	< 1	< 0.03	< 0.03
264	19-05-87	4.2	< 1	0.24	< 0.03
271	26-05-87	1.1	< 1	0.03	< 0.03
277	01-06-87	1.0	< 1	Trace	< 0.03
340	03-08-87	-	-	Trace	< 0.03
343	06-08-87	1.5	< 1	Trace	< 0.03
344	07-08-87	5.0	< 1	-	-

^asite #1 was a drainage ditch 40 m from the edge of treated plot.

^bSites 2 to 7 were from <1 km to 3.5 km from the edge of the treated plot down stream.

vegetation cover and exposure of a variety of surface and deep soil horizons. Double-disking resulted in 80-100% surface disturbance and areas resembled newly broken fields. In disk-trenched and double-disked areas without any vegetation cover, strong off-site movement of soil was observed during heavy rainfall in July 1987. Sidhu and Feng (1990) reported that control areas and those treated with herbicide exhibited <20% surface disturbance in over 80% of the plots, and the disturbance was mainly due to harvest-related activities.

Fate of hexazinone.

Hexazinone release rate from granules depended on the cumulative precipitation and length of exposure period to ambient environment. Fifty mm of rain for 4 hours and 10 mm of cumulative rain in 7 days released 90% of the hexazinone under laboratory and field conditions respectively (Feng *et al.* 1988; 1989).

Hexazinone concentrations were monitored in stream and surface water and sediments for two years after application (Sidhu and Feng 1990). Results summarized in Table 6 indicate that no hexazinone residues were carried by the surface runoff to enter the Campbell River about 1 km west of the treatment area. Small amounts of hexazinone residues (up to 5 $\mu\text{g L}^{-1}$) were found in the surface water and up to 0.24 $\mu\text{g g}^{-1}$ dry weight in sediments in the shallow pool, about 40 m from the corner of a treatment plot. Hexazinone residue levels dissipated to the nondetectable level by the second year after hexazinone application. Amounts of hexazinone residues found in surface water pool near the treatment plot were small and were 50 000 to 1 000 000 times lower than the reported LC_{50} for fish and wildlife (WSSA 1989) and are unlikely to pose any detrimental long-term effect to the environment.

Movement and persistence of hexazinone and its metabolites were studied in soil leachates and soils up to depths of 80 and 210 cm. In our study, the rate of hexazinone movement in soil leachate increased with the rate of soil water percolation but, in general declined over time. The cumulative rainfall in the first 112 days after application was 110 cm, followed by 95 cm snowfall and 300 cm rainfall in the second year. There was no collectable amounts of soil leachate in the first 112 days after application and before ground freeze. Leaching of hexazinone was triggered during the snow melt during the first spring following application. Total amounts of residues were the highest in the first postwinter collection (227 days after treatment); 205 and 61 μg at 30 cm depth in the 4 and 2 kg a.i. ha^{-1} treatment plots, respectively. Corresponding amounts were 89 and 39 μg at 80 cm depth. At 55 cm depth the peak concentrations were 178 μg after 264 days in the 4 kg a.i. ha^{-1} and 28 μg after 351 days in the 2 kg a.i. ha^{-1} treatment. Hexazinone residues declined to less than 17 μg after 448 days at all depths for both application rates. The concentration of hexazinone in soil leachates was inversely related to the volume of leachate (Feng, Sidhu, Feng, and Servant 1989).

Persistence and mobility of hexazinone and its metabolites were studied using granules fortified with known quantities of hexazinone placed on the soil surface at rates equivalent to 2 and 4 kg a.i. ha^{-1} . Residues of hexazinone and its two major metabolites A and B in soils were analyzed up to 767 days after treatment. Residues leached to soil depths of 10-20, 20-30, 30-35, and 35-40 cm within 8, 37, 37, and 365 days, respectively, in both 2 and 4 kg a.i. ha^{-1} hexazinone treatment. Large variations of hexazinone residues (7 and 70% CV) were observed among nine replicated samples during the first two months of sampling in both 2 and 4 kg a.i. ha^{-1} treatments.

Mean hexazinone residues remaining in the 0-40 cm soils were about 82, 58, 50, 40, 23, 17, 15, 9, 8, and 4%, respectively, after 4, 8, 37, 61, 286, 321, 399, 627, 680, and 767 days. Dissipation time to 50% of the applied amounts of hexazinone in soil were 12 and 27 days, respectively, based on its total residues remaining in 0-10 cm and 0-40 cm layers in 2 kg a.i. ha⁻¹ treatment. These periods were 13 and 29 days, respectively, for the 4 kg treatment. The metabolites were present at proportionately lower levels indicating continuous breakdown of hexazinone over time from the surface layer down to 40 cm soil depth. These trends were confirmed by results from the large experimental area aerially treated with Pronone 10G (Feng *et al.*, 1992). One year after application, residues of hexazinone in the 0-10 cm surface soil averaged 0.25 ± 0.09 and 0.40 ± 0.02 kg a.i. ha⁻¹ in 2 and 4 kg a.i. ha⁻¹ treatment, respectively. Relative vertical distribution of hexazinone in soil at 0-10, 10-20, and 20-30 cm was in the ratio 10:11:2 and 10:5:2, respectively, in 2 and 4 kg a.i. ha⁻¹ treatments. Metabolites A and B amounted to 15 and 30% of hexazinone, respectively. Two years after application, the vertical movement of hexazinone in soil was quantifiable up to the 40-cm depth in both 2 and 4 kg a.i. ha⁻¹ treatment plots. Trace amounts of hexazinone were detected at 130 cm only in the 2 kg a.i. ha⁻¹ plot. It was probably due to the free downward movement of hexazinone to deeper horizons via root channels (Feng *et al.* 1992).

Uptake and dissipation of hexazinone were investigated in a number of plant species by Sidhu and Feng (1990) and in small mammals by Penner (1990). Concentrations of hexazinone and two metabolites in vegetation were determined for two years after aerial broadcast application of a 10% granular formulation of hexazinone at 2 and 4 kg a.i. ha⁻¹ in the end of August (in our study) in a boreal forest. Average concentration of hexazinone in overwintering stems of three woody species (trembling aspen, Saskatoon berry, willow) ranged from 0.02 to 0.05 $\mu\text{g g}^{-1}$ dry wt. Absorption of hexazinone accelerated after snow melt in the spring after application in August 1986 and residues in foliage of several woody, forb, and grass species peaked between May and July. Patterns of accumulation of hexazinone and its metabolites varied with the species. The foliar concentrations diminished significantly by the end of the first growing season (1987) and were non-detectable or extremely low at the end of the second growing season (1988) following application. Based on the highest residue concentrations detected at anytime among several plant species, wildlife is expected to consume a maximum of 16, 28, and 24 mg of hexazinone, metabolite A and metabolite B respectively for every kg of dry matter consumed. Reported LD₅₀ and no observable effect level (NOEL)

(Chakravarty and Sidhu 1987 and 1990, USDA 1984, WSSA 1989) values suggest that application of hexazinone at 4 kg a.i. ha⁻¹ or lower rates would not pose any known toxicological threat to wildlife. Penner (1990) reported in a small mammal study that very small amounts of residues of hexazinone and metabolite B were detected in composite samples of liver and kidney of a number of rodents. The highest concentrations, reported were 0.21 and 0.24 $\mu\text{g g}^{-1}$ of hexazinone and metabolite-B, respectively. According to Rhodes and Jewell (1980), most hexazinone compound consumed by rodents are excreted within 72 hours.

Nutrient Dynamics

Vegetation.

In the untreated plots the nutrient dynamic pattern in a number of boreal species followed those for aspen and other species reported in the literature (Alban 1982 and 1985; Alban *et al.* 1978; McColl 1980; Verry and Timmons 1976; Tappeiner and Alm 1975; Van Den Driessche 1974; Tilton 1977; Shaver and Chapin III 1980; Grigal, *et al.* 1976; Woodwell 1974; Woodwell *et al.* 1975; Chapin III *et al.* 1980; Chapin III and Kedrowski 1983; Kubota *et al.* 1974 Pastor and Bockheim 1984). Seasonal and year to year variation in elemental concentrations were large between species. In general for all species, Ca increased from spring to fall. Potassium, P, N, and S peaked in the early summer and decreased towards fall. Magnesium did not show any definite trends. Some species showed specific affinities to certain elements. For example, herbaceous species such as northern bedstraw (*Galium boreale* L.) and red paintbrush (*Castilleja miniata* Dougl.) were identified as high K-accumulators, bunchberry as high Ca-accumulator, and species like marshreed grass, Saskatoon berry, and fire weed (*Epilobium angustifolium* L.) as high P-accumulators.

The application of hexazinone as Pronone 10G had a consistent affect on foliar nutrient status of a number of species. The trends were similar at both rates of application, however, effects were mostly significant ($P=0.05$) at the 4 kg a.i. ha⁻¹. In general, hexazinone at both 2 and 4 kg a.i. ha⁻¹ rates resulted in elevated concentrations of Ca, Mg, K, P, S and N (Table 7). In most cases significant effects lasted until July of the first growing season following herbicide application and the second growing season (1988) in some species and elements. For all elements (except N) the differences among sample from treated and untreated plots were non-significant in July 1989, the third growing season after application. The return of nutrient concentration to control levels in the foliage coincided with the recovery of vegetation without visual herbicide damage symptoms in 1989 (Sidhu

1993)². In summary, we found that nutrient levels and their seasonal and annual patterns are impacted significantly at least for two years, following hexazinone application. Species are impacted differently and as a result, their change in relative dominance with treatment along with their affinity to specific elements and nutrient demand would determine change in the nutrient distribution in hexazinone impacted sites.

Soil and Litter.

Ammonium-($\text{NH}_4^+\text{-N}$), nitrate ($\text{NO}_3^-\text{-N}$), and total-N concentrations in the surface organic horizon (LFH) are given in Table 8. Total N and $\text{NO}_3^-\text{-N}$ concentrations were higher in the LFH of the control in the pre-treatment year (1986) but ammonium concentrations did not differ. In the year following the herbicide application, $\text{NO}_3^-\text{-N}$, $\text{NH}_4^+\text{-N}$ and total N were all lower in the control compared to the 2 and 4 kg a.i. ha^{-1} treatments. Higher total N and $\text{NO}_3^-\text{-N}$ concentrations in the 4 kg a.i. ha^{-1} treatment were still observed in the second year following the herbicide application. The total N and $\text{NO}_3^-\text{-N}$ concentrations in the LFH of the control and low herbicide treatment (2 kg a.i. ha^{-1}) were similar. Ammonium concentrations in the LFH were not different ($p=0.1$) among treatments in 1988; however, the highest $\text{NH}_4^+\text{-N}$ concentration in the LFH was still observed in the HH treatment (4 kg a.i. ha^{-1}).

Elevated $\text{NO}_3^-\text{-N}$ concentrations have been observed in forest soils following disturbances such as harvesting and site preparation including herbicide applications (Vitousek and Matson 1985). This increase has usually been attributed to a reduction in the vegetation cover resulting in reduced demand for N. Other possible causes include: an increase in $\text{NO}_3^-\text{-N}$ released from litterfall prematurely dropped as a result of the herbicide application and an increase in nitrate release from soil microorganisms lysed by the herbicide (Andriese and Vitousek 1988). The reasons for the increased $\text{NO}_3^-\text{-N}$ levels in the 2 years following the herbicide application are not known. Results from a small scale field study set up adjacent to the operational plots indicate increased N inputs in the litterfall in the year of the herbicide application. This could be contributing to higher N levels but are not likely the only reason (unpublished information, D.G. Maynard). In a growth chamber study (Maynard 1993), Hexazinone had no effect on the rate of N mineralization. Therefore, increased N levels in the LFH horizon of the herbicide treated plots were probably the result of lower N demand with reduced vegetative cover, and increased N inputs from premature litterfall as a result of the herbicide application.

Extractable cations and sulfur in the LFH are given in Table 9. Total analyses were also done but are not

Table 7. Average (one standard deviation) foliar concentration ($\mu\text{g g}^{-1}$ except % N) of macronutrients in hexazinone

Stratum (No. of species)	Treatment (Kg hexazinone ha^{-1})	Ca		Mg		K		P		S		N	
		1987	1988	1987	1988	1987	1988	1987	1988	1987	1988	1987	1988
Average of 16 species in all strata	0	11 001 (4070)	12 852 (5868)	3 214 (1461)	2 981 (1461)	14 997 (5813)	15 694 (6015)	2 677 (520)	2 681 (602)	1 564 (411)	1 617 (290)	2.54 (0.62)	1.63 (0.33)
	2	9 555 (4449)	12 800 (5707)	3 058 (1395)	3 023 (898)	15 390 (7757)	15981 (5845)	2 747 (810)	2 685 (488)	1 830 (506)	1 649 (222)	2.75 (0.91)	1.82 (0.24)
	4	9 652 (4525)	12 016 (4973)	3 434 (1654)	3 408 (1116)	18 058 (12487)	16 900 (7263)	3 398 (1694)	2 893 (432)	2 131 (776)	1 861 (570)	4.16 (1.80)	1.94 (0.25)

¹Plots were treated with hexazinone on 26 August 1986.

²1987 values are samples collected 15 July 1987 and 1988 values for samples collected 2 August 1988.

Table 8. Total N (g kg^{-1}), NO_3^- -N and NH_4^+ -N (mg kg^{-1}) concentrations in the surface horizon (LFH) of control and hexazinone plots

	Year	Hexazinone rate (kg a.i. ha^{-1})		
		0	2	4
Total N	1986	$18.6 \pm 1.0 \text{ a}^*$	$16.9 \pm 1.2 \text{ b}$	$15.4 \pm 1.4 \text{ b}$
	1987	$12.3 \pm 1.0 \text{ b}$	$14.0 \pm 0.9 \text{ a}$	$14.5 \pm 1.4 \text{ a}$
	1988	$13.8 \pm 1.2 \text{ a}$	$14.8 \pm 1.0 \text{ a}$	$15.8 \pm 0.9 \text{ a}$
NH_4^+ -N	1986	$196 \pm 22 \text{ a}$	$229 \pm 26 \text{ a}$	$186 \pm 28 \text{ a}$
	1987	$59 \pm 8 \text{ b}$	$102 \pm 15 \text{ a}$	$139 \pm 21 \text{ a}$
	1988	$138 \pm 47 \text{ a}$	$98 \pm 26 \text{ a}$	$161 \pm 40 \text{ a}$
NO_3^- -N	1986	$3.6 \pm 2.0 \text{ a}$	$0.2 \pm 0.2 \text{ b}$	$0.1 \pm 0.2 \text{ b}$
	1987	$1.1 \pm 0.6 \text{ b}$	$7.2 \pm 1.4 \text{ a}$	$6.3 \pm 1.8 \text{ a}$
	1988	$0.8 \pm 0.8 \text{ b}$	$0.8 \pm 0.5 \text{ b}$	$6.3 \pm 3.3 \text{ a}$

* Concentrations within a year followed by the same letter are not significantly different ($P \leq 0.05$).

Table 9. Extractable cations and sulfur (1.0 M unbuffered NH_4Cl) in the surface organic horizons (Mean \pm 95% C.L.)

	Year	Hexazinone rate (kg a.i. ha^{-1})		
		0	2	4
Ca	1986	14080 \pm 914 a*	12240 \pm 1053 b	11000 \pm 1076 b
	1987	11630 \pm a	12150 \pm 906 a	12500 \pm 1067 a
	1988	13240 \pm a	13820 \pm 998 a	14510 \pm 1063 a
Mg	1986	1895 \pm 132 a	1895 \pm 143 a	1871 \pm 174 a
	1987	1200 \pm 83 b	1249 \pm 94 b	1565 \pm 126 a
	1988	1620 \pm 142 b	1925 \pm 117 a	2092 \pm 137 a
K	1986	1077 \pm 88 a	966 \pm 105 a	966 \pm 60 a
	1987	925 \pm 137 s	752 \pm 56 a	868 \pm 51 a
	1988	976 \pm 114 a	892 \pm 121 a	852 \pm 101 a
Na	1986	61 \pm 14 b	84 \pm 18 a	56 \pm 9 b
	1987	62 \pm 14 ab	54 \pm 15 b	79 \pm 13 a
	1988	47 \pm 12 ab	42 \pm 11 b	60 \pm 13 a
S	1986	91 \pm 5 a	85 \pm 6 a	82 \pm 7 a
	1987	70 \pm 6 a	80 \pm 6 a	80 \pm 6 a
	1988	118 \pm 13 a	123 \pm 10 a	125 \pm 14 a

* Concentrations within a year followed by the same letter are not significantly different ($P \leq 0.05$).

shown because the total concentrations followed the same pattern as the extractable concentrations. Magnesium in the LFH was the only cation that showed a response to the herbicide. In the year following application of Pronone, Mg in the LFH was higher in the 4 kg a.i. ha^{-1} treatment than either the 0 or 2 kg a.i. ha^{-1} . In the second year after treatment the LFH from herbicide plots had higher Mg concentrations than the control. Decreased demand for Mg in the herbicide treated plots (lower vegetation cover) most likely resulted in the increased Mg concentrations.

Calcium concentrations remained constant in the 2 and 4 kg a.i. ha^{-1} treatments; however, Ca concentrations decreased from 1986 to 1988 in the control LFH. Aspen absorbs large amounts of Ca and the aspen biomass of the control increased from 1986 to 1988. Thus, the decreasing Ca concentration in the LFH of the control could be the result of increased Ca demand by the aspen. Aspen biomass of the herbicide treated plots was reduced as a result of lower stem density and foliage cover and probably reduced the demand for Ca.

Increased concentrations of total N, NO_3^- -N and extractable Mg in the LFH of soils treated with 4 kg a.i. ha^{-1} Pronone were observed for at least 2 years following the application. Increases in NH_4^+ -N were found only in the first year following the herbicide application. The variability associated with an

operational application combined with the inherent soil variability in large plots has resulted in relatively high variances. This limits our ability to interpret the changes observed in the LFH nutrient status. The results from the operational plots do suggest that the herbicide has altered the short term nutrient dynamics of this site. The biological importance and long-term affects of these changes are unknown. A small scale, controlled application study was set up to address the problems of high variability and to examine the processes involved in the changes observed in the operational study. These results are currently being analyzed.

Summary

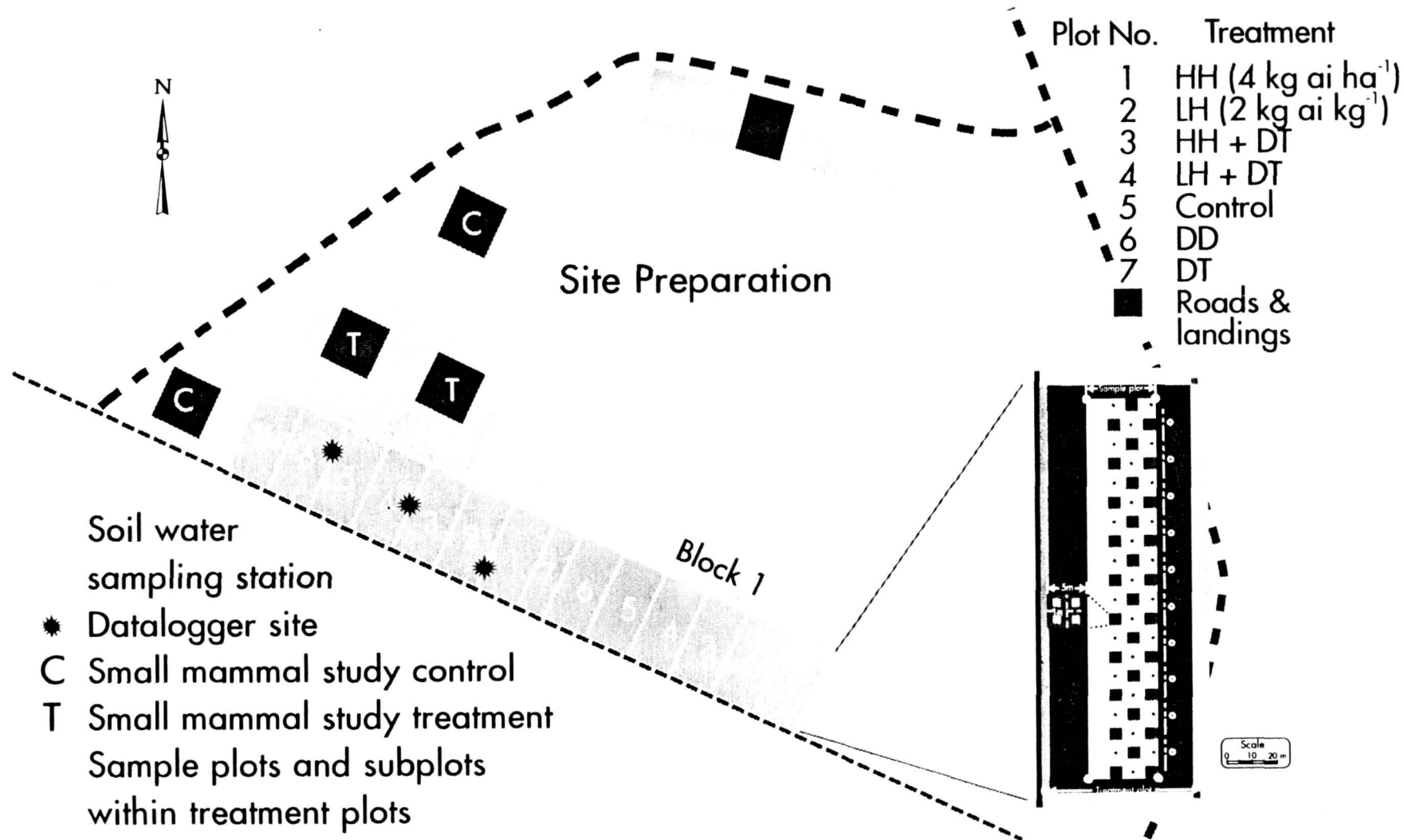
The environmental impact of mechanical site preparation and hexazinone on vegetation management was studied for 5 years following site-preparation treatments. The efficacy of treatment in controlling competing vegetation was in the order: DD > DR > HH > DT + LH > LH control. Measurable changes in vegetation cover, plant and soil nutrient concentrations and detectable amounts of hexazinone residues in soils, leachates, surface water and sediments were observed in the first two years following the application of hexazinone. Detected hexazinone and metabolites A and B were well below the acute and chronic toxicity levels for various

organisms. There was no loss of plant species; however, species abundance and cover were reduced. Nutrient concentrations of several elements in the soils and foliage were altered but were still within ranges often seen in undisturbed systems. Despite these observations, there is still concern over the potential long-term effects. There are indications that successional trends in the herbicide treated areas are following different pathways than in the control areas. The impact of changes in foliar and soil nutrient levels on the long-term site productivity could not be addressed in only two years. Continued monitoring of the soils and vegetation over the next five to eight years will be needed to answer some of these concerns.

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Schematic Layout of Blocks and Treatment Plots

Figure 1.

Schematic layout of blocks, treatment plots (80m x 120m), sample plots (30m x 100m), subplots (5m x 5m) for sampling woody stem density and quadrats (1m x 1m) for vegetation cover estimates by vegetation strata and species, and presence frequency of all plants species. C = no treatment, LH = 2 kg hexazinone (as Pronone 10G) ha⁻¹, HH = 4 kg hexazinone ha⁻¹, DT = disk-trenching, DD = Double romo disk. NS = not sample in 1989 and 1991.

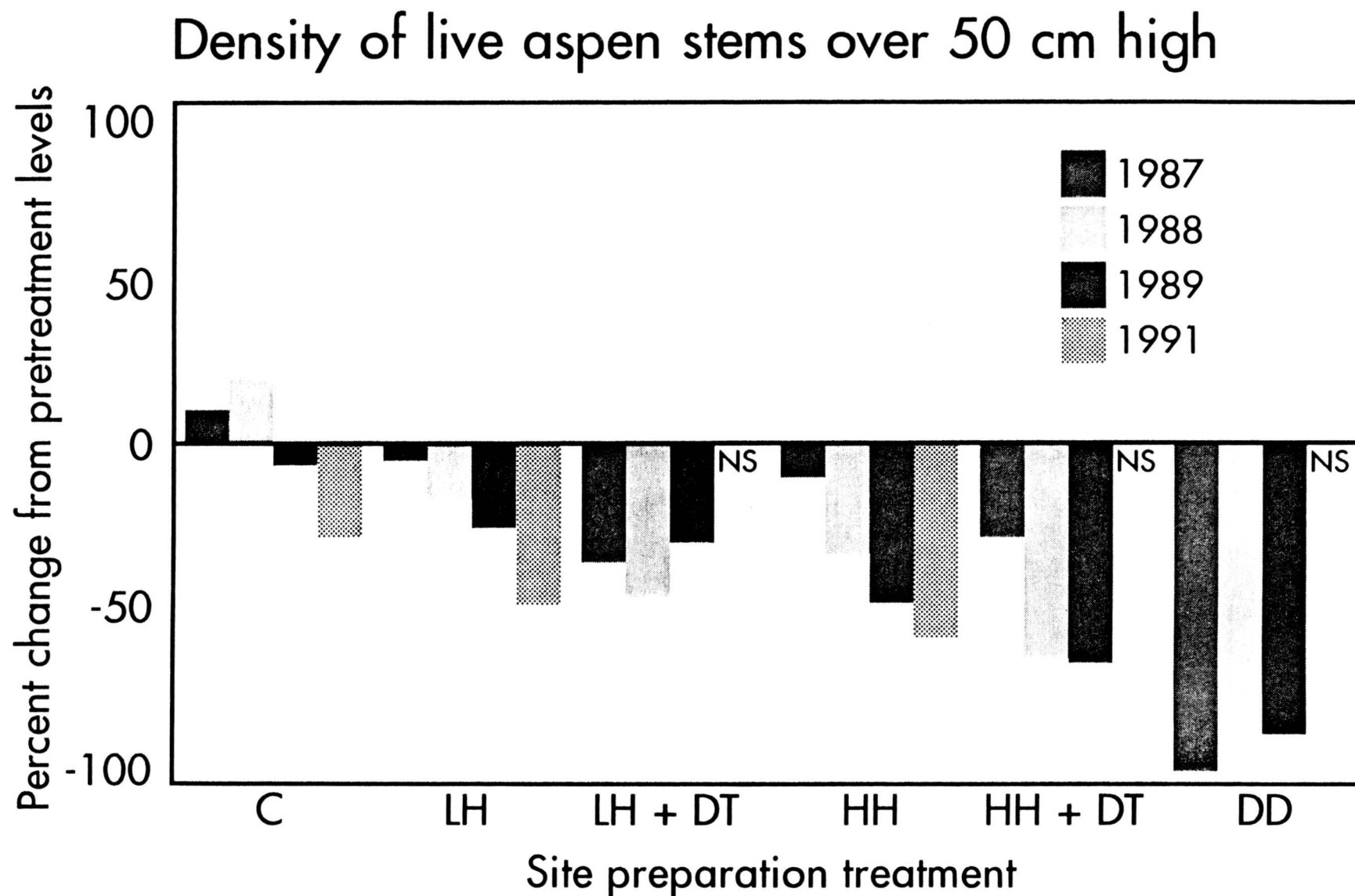


Figure 2. Percent change from pretreatment (1986) levels in density of live aspen stems 50cm or greater in height as a result of various site preparation treatments on 3-year old aspen (*Populus tremuloides*) cutover; C = no treatment, LH = 2 kg hexazinone (as Pronone 10G) ha⁻¹, HH = 4 kg hexazinone ha⁻¹, DT = disk-trenching, DD = Double round disk. NS = not sample in 1989 and 1991.

Vegetation cover by stratum – Control treatment

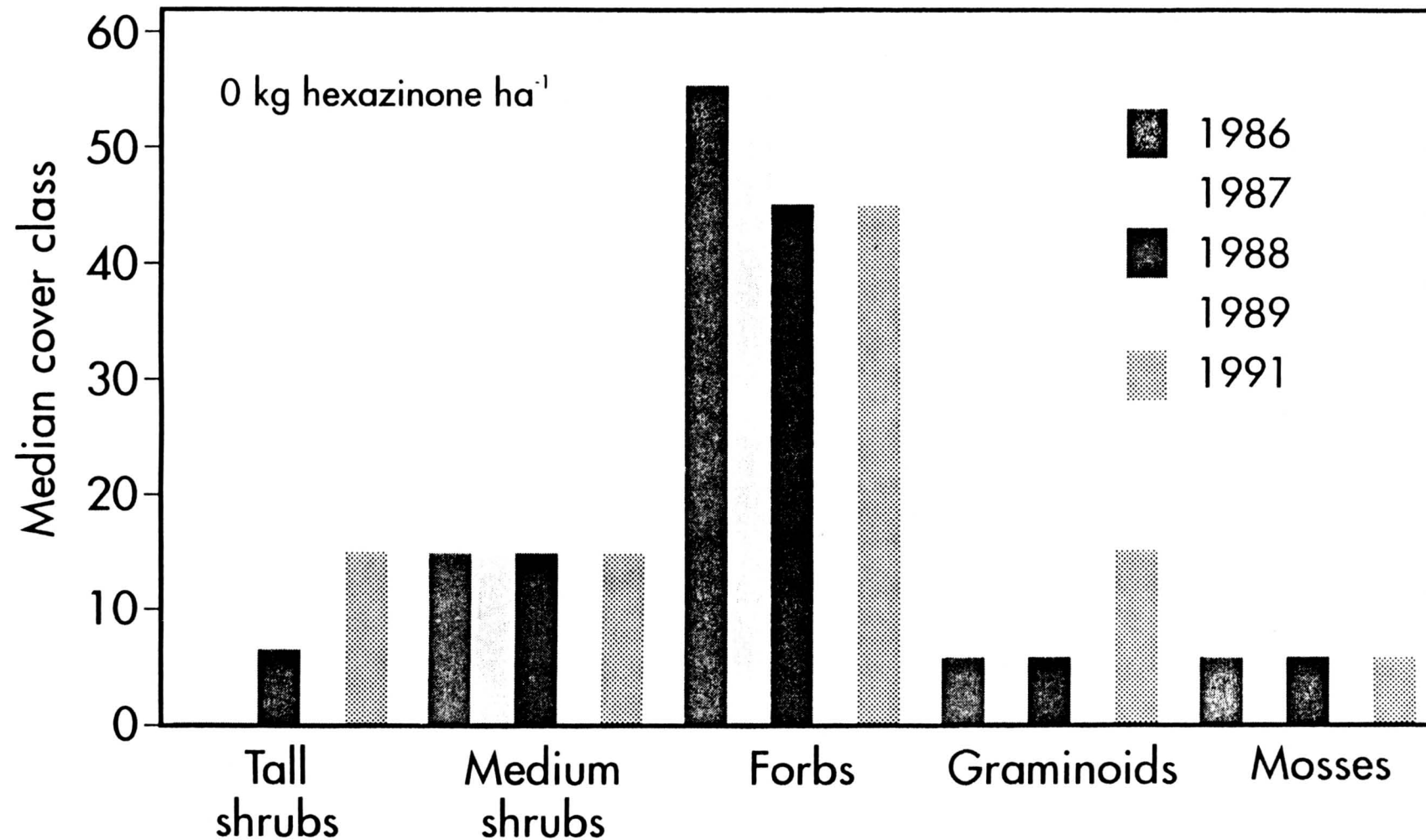


Figure 3.

Changes in the median cover class of various vegetation strata for one pretreatment (1986) and 4 post-treatment years (1987-1991) in control plots on a 3-year old aspen cutover in the mixedwood forest region of Alberta. Median class is based on a sample of 360 quadrats in 1986 to 1988, 60 samples in 1989 and 90 in 1991. Cover classes were: 0 = absent, 0.5 = present with <1% cover, and 5, 15, 25 ... 95 representing mid points of 1 - 10, 11 - 20, 21 - 30 ... 91 - 100% cover classes. Tall shrubs = all woody species > 150cm in height, Forbs = all woody species < 50 cm in height and all herbaceous species other than grasses, graminoids = all grasses and sedges and Mosses = all mosses and dryophytes.

Vegetation cover by stratum – Low herbicide treatment

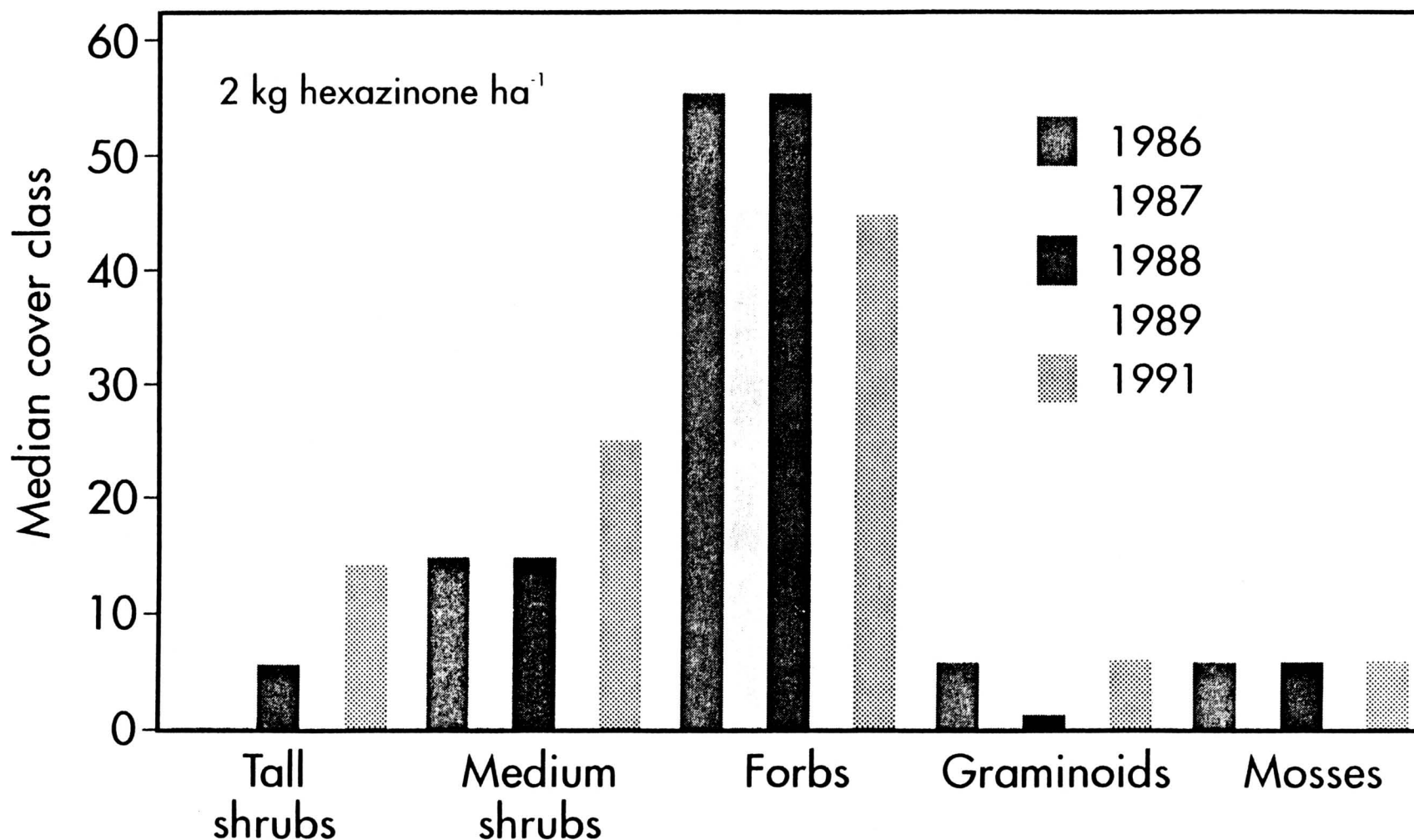


Figure 4. Changes in the median cover class of various vegetation strata for one pretreatment (1986) and 4 post-treatment years (1987-1991) in 3-year old aspen cutover treated with 2 kg hexazinone (Pronone 10G) ha⁻¹ in the mixedwood forest region of Alberta. Median is based on a sample of 360 quadrats in 1986 to 1988, 60 samples in 1989 and 90 in 1991. Cover classes were: 0 = absent, 0.5 = present with <1% cover, and 5, 15, 25 ... 95 representing mid points of 1 - 10, 11 - 20, 21 - 30 ... 91 - 100% cover classes. Tall shrubs = all woody species > 150cm in height, medium shrubs = all woody species 50 to 150 cm in height, Forbs = all woody species < 50 cm in height and all herbaceous species other than grasses.

Vegetation cover by stratum – High herbicide treatment

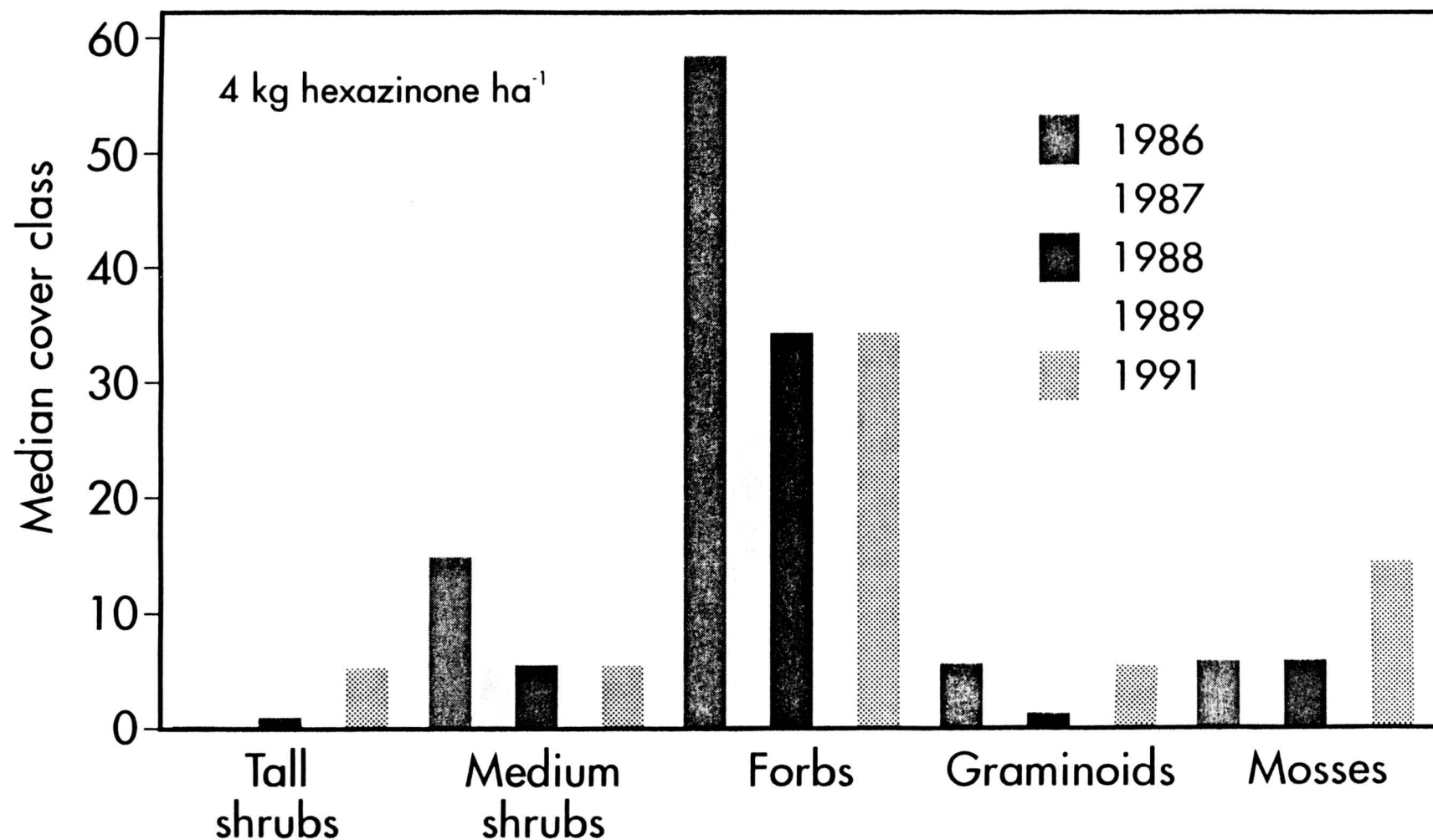


Figure 5. Changes in the median cover class of various vegetation strata for one pretreatment (1986) and 4 post-treatment years (1987-1991) in 3-year old aspen cutover treated with 4 kg hexazinone (Pronone 10G) ha⁻¹ in the mixedwood forest region of Alberta. Median is based on a sample of 360 quadrats in 1986 to 1988, 60 samples in 1989 and 90 in 1991. Cover classes were: 0 = absent, 0.5 = present with < 1% cover, and 5, 15, 25 ... 95 representing mid points of 1 - 10, 11 - 20, 21 - 30 ... 91 - 100% cover classes. Tall shrubs = all woody species > 150 cm in height, medium shrubs = all woody species 50 to 150 cm in height, Forbs = all woody species < 50 cm in height and all herbaceous species other than grasses, graminoids = all grasses and sedges and Mosses = all mosses and bryophytes.

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