Effects of herbicide treatments on biotic components in regenerating northern forests

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We reviewed literature, primarily since 1990, that documents effects of herbicide treatments on major biotic components in northern forested ecosystems. Vegetation changes are responsible for changes in all other biotic components. Non-conifer vegetation is commonly reduced for two to five years following broadcast herbicide treatments. Fungal components, however, seem relatively unaffected. Short-term vegetation reductions in cover, density, and related biomass, if they occur, are species and/or vegetation group specific; longer-term changes are linked to conifer stocking, site quality, and the ability of conifers to dominate treated sites. Herbicide treatments do not reduce, and may increase, stand- and landscape-level plant species richness. Those treatments seldom produce monocultures when used by foresters for boreal or boreal mixedwood management. The active ingredients in the herbicide products used in forestry in northern ecosystems have no direct effect on the general health (survival, growth, reproduction) of animals in treated areas. Specific, stand-level forest management practices, particularly effects of site preparation and conifer release, must be examined in relation to the landscape mosaic and the desired future forest conditions. At broad scales, across boreal and boreal mixedwood ecosystems, conifers have been consistently replaced by hardwoods since Europeans began harvesting timber from those ecosystems. Herbicides provide a safe, effective tool for restoring conifers in previously conifer-dominated ecosystems. Forest scientists presently have a reasonable understanding of effects of a variety of herbicide treatments on conifer growth and a variety of environmental components. However, they need to continually update that understanding relative to treatments (replicates, chemicals, combinations, or timing) that may be used in the future.

Key words: amphibians, conifer release, deer, disturbance, environment, glyphosate, herbicides, invertebrates, landscape, moose, reptiles, site preparation, small mammals, songbirds, snowshoe hare, triclopyr, vegetation

Nous avons révisé la littérature, principalement depuis 1990, qui documente les effets des traitements phytocides sur les principaux éléments biotiques dans les écosystèmes forestiers nordiques. Les modifications apportées à la végétation sont responsables des changements survenus chez tous les autres éléments biotiques. La végétation non-résineuse est habituellement réduite de deux à cinq ans suivant les traitements d'épandage généralisé de phytocides. Les composantes fongiques, cependant, ne semblent relativement pas affectées. Les réductions à court terme de la végétation au niveau du couvert, de la densité et de la biomasse impliquée, si tel est le cas, touchent spécifiquement certaines espèces ou groupe de plantes; les changements à long terme sont reliés au nombre de semis de résineux, la qualité de la station et la capacité des résineux à dominer dans les sites traités. Les traitements phytocides ne réduisent pas, et pourraient accroître la variété d'espèces de plantes au niveau du peuplement et du paysage. Ces traitements produisent rarement des monocultures lorsque utilisés par des forestiers qui aménagent les forêts boréales ou mélangées nordiques. Les ingrédients actifs dans les produits phytocides utilisés en foresterie dans les écosystèmes nordiques n'ont pas d'effet direct sur la santé globale (survie, croissance, reproduction) des animaux dans les zones traitées. Les pratiques d'aménagement forestier spécifiques au niveau du peuplement, notamment les effets de la préparation du site et le dégagement des résineux, doivent être examinées en fonction de la mosaïque du paysage et des conditions forestières futures souhaitées. De façon générale, dans les écosystèmes boréaux et les forêts mélangées nordiques, les résineux ont été systématiquement remplacés par les feuillus depuis que les Européens ont commencé la récolte du bois dans ces écosystèmes. Les phytocides s'avère un outil sécuritaire et efficace pour réintroduire les résineux dans des écosystèmes qui étaient dominés antérieurement par les résineux. Les chercheurs forestiers ont actuellement une compréhension raisonnable des effets de plusieurs traitements phytocides sur la croissance des résineux et la variété des composantes environnementales. Cependant, ils doivent continuellement mettre à jour leur compréhension relative aux traitements (répétitions, éléments chimiques, combinaisons ou moment d'application) qui pourraient être utilisés dans l'avenir.

Mots- clés : amphibiens, dégagement des résineux, chevreuil, perturbation, environnement, glyphosate, phytocides, invertébrés, paysage, orignal, reptiles, préparation du site, petits mammifères, oiseaux chanteurs, lièvre d'Amérique, triclopyr, végétation

Introduction

During the last five decades, silvicultural intensity has increased gradually in northern forested ecosystems. Although Clawson (1975) provided the framework nearly three decades ago, identifying specific use zones within broad management areas has re-emerged as a forest management recommendation

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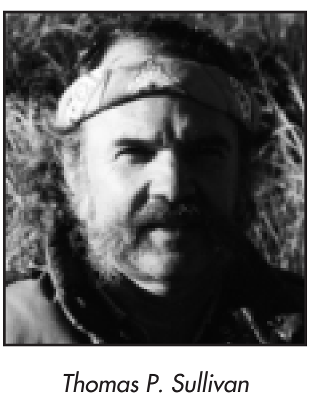

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associated with intensive silviculture (Seymour and McCormack 1989; Seymour and Hunter 1992; Binkley 1997; Taylor 1999; Lautenschlager 1999a, 2000). Intensive silviculture can focus on a variety of species or species groups (conifers, hardwoods, mixedwoods) any time during the rotation. However, fibre production benefits, especially for conifers, have consistently come from treatments that occur during the establishment phase after harvesting or natural disturbances (Lautenschlager 2000). Depending on the site, treatments during that phase are used to reduce the abundance of non-conifer competition from pioneer species. The severity of competition experienced by conifers varies with competing species and increases with increasing abundance of competitors (Walstad and Kuch 1987; Lautenschlager 1995, 1999b; Wagner *et al.* 1999).

Individually and collectively, early seral plant species compete with conifer seedlings for resources (Radosevich and Osteryoung 1987, Lautenschlager 1999b). Volume growth of conifer seedlings consistently increases after competition is controlled (Walstad and Kuch 1987, Newton *et al.* 1992, Freedman *et al.* 1993, Lautenschlager 1995, Wagner *et al.* 1999). This and other management realities have led to the suggestion that repeated herbicide treatments, or other silvicultural practices (e.g., genetic improvement, fertilization), could produce an eight-fold increase in conifer production on selected sites in Canadian forests (Taylor 1999, Lautenschlager 2000). Conifer growth responses, however, are not examined in detail in this paper. Interested readers should see Walstad and Kuch (1987) for an overview of those responses in North American forests.

Not surprisingly, intensive silvicultural techniques with proven operational benefits—site preparation and conifer release—are now commonly used in many managed northern conifer and mixedwood ecosystems (Lautenschlager 2000). Where conifers have been planted, and competition has been controlled, primarily via spray solutions containing herbicide products, conifer growth has increased in direct proportion to the degree and duration of the control received (Walstad and Kuch 1987, Wagner *et al.* 1999). However, conifer growth benefits associated with early and repeated release have both financial and social consequences. Early release is considered cost and biologically effective, but most people (publics) in North America are opposed to herbicide use, especially aerial use (Lautenschlager 1986, Smith 1986, Freedman 1991, Lautenschlager *et al.* 1998, Wagner *et al.* 1998), at any time. Herbicide applications have led to conflicts with concerned publics and repeated applications could increase the probability of conflicts (Lautenschlager 2000).

Public concerns about herbicide use in forestry seem based on a combination of philosophy, caution, and lack of scientific information and/or understanding. Although the views of publics and stakeholder groups must be considered when making responsible forest management decisions (CCFM 1995a, Lautenschlager 1999c, Messier and Kneeshaw 1999, Lautenschlager *et al.* 2000), natural resource management decision makers generally believe that science should provide the foundation for those decisions (CCFM 1995a, Lautenschlager *et al.* 2000, Lautenschlager 2001, Willick 2001).

Historically, research examining environmental consequences of herbicide use has been relatively inconsistent in terms of the chemicals and post-treatment periods studied (Lautenschlager 1993a). For instance, some tests have been conducted using the active ingredients found in herbicide products, while others have been conducted using the formulated products themselves (Roshon *et al.* 1999). The surfactants (which may have properties similar to soap) in some products, as well as some active ingredients, can cause products to be slightly to moderately toxic to zooplankton, invertebrates, fish, and amphibians (Hildebrand *et al.* 1980, Sullivan *et al.* 1981, Mitchell *et al.* 1987, Scrivener and Carruthers 1989, Roshon *et al.* 1999). However, most scientists who have studied the toxicity of the herbicide active ingredients and/or the formulated products have concluded that when used at recommended rates, under normal-use scenarios, herbicide spray solutions used in forestry for site preparation or conifer release pose minimal toxicological hazard for terrestrial vertebrates or risk of bioaccumulation in the environment (Morrison and Meslow 1983; Newton *et al.* 1984; Atkinson 1985; Sullivan 1985, 1990a,b; Newton *et al.* 1989; Giesy *et al.* 2000; Williams *et al.* 2000).

It has been nearly a decade since the last review of effects of forest herbicides on major environmental components (Lautenschlager 1993a,b). That combined with an increased interest in intensive silviculture and the publication of additional studies, suggest that a review at this time would be valuable. The objective of this review is to provide a synthesis of recent literature so that operational foresters, managers, and policy makers can make informed decisions and better address the concerns of the variety of interested publics. This review updates Lautenschlager's (1993a) earlier work that synthesized the previously available literature examining effects of herbicide treatments, primarily for conifer release, on the major wildlife groups found in northern forested ecosystems. To avoid duplication, the current review concentrates on literature that was not examined or not stressed in the earlier review or has become available since then. In addition, the current review examines effects on vegetation and attempts to draw conclusions at stand and landscape levels. Categorized abstracts of much of the reviewed literature are found in Sullivan and Sullivan (2000) and Mihajlovich (2001).

Review

Vegetation (Table 1)

Abundance and Diversity

Spray solutions containing herbicides used for site preparation and/or conifer release reduce competitive biomass and release young conifers from non-conifer competition. Depending on geographic location, that competition often is from alder (*Alnus*), willow (*Salix*), poplar (*Populus*), raspberry (*Rubus*), birch (*Betula*), maple (*Acer*), cherry (*Prunus*), and a variety of herbaceous species and/or groups of species, such as grasses, sedges, and rushes. Stand-level biomass reductions of non-conifer vegetation (commonly 50–70% during the first year after treatment, but varying by vegetative group – Fig. 1) have consistently followed site-preparation and conifer release treatments in a variety of northern ecosystems (Newton *et al.* 1992; Pitt *et al.* 1992, 1993, 2000; Freedman *et al.* 1993; Raymond *et al.* 1996; Bell *et al.* 1997; Kelly *et al.* 1998; Sullivan *et al.* 1998a; Vreeland *et al.* 1998; Gagné *et al.* 1999; Lautenschlager *et al.* 1999; Lindgren and Sullivan 2001). However, operationally effective conifer release treatments generally eliminate few, if any, of the species from treated sites (Morrison and Meslow 1983; Newton *et al.* 1989; Santillo *et al.* 1989; Lautenschlager 1990,1993a; Horsley 1994; Bell and Newmaster 1998;

Table 1. Overview of studies that documented effects of herbicides on vegetation in northern forested ecosystems

Author and publication date	Location	Herbicide(s) or treatments studied	Treatment was – years after cutting or planting	Post-treatment years studied	Pre-treatment data collected	Survey method	Data collected	Major findings
Bell *et al*. 1997	Northwestern Ontario	Glyphosate, triclopyr, brushsaw cutting, machine cutting, control	3–7 after planting	1	Growing season before treatment	Visual estimates	Cover %	Post-treatment cover of deciduous tree and shrub groups was lower in herbicide-treated plots than in brushsaw- and machine-cut plots. Forb and grass/sedge cover varied greatly among treatments. Brushsaw and and machine treatments reduced cover of deciduous trees; triclopyr reduced cover of deciduous trees and shrubs; glyphosate reduced cover of deciduous trees, shrubs, and ferns. Cover of all vegetation groups increased in control plots. Of all treatments used, glyphosate reduced woody and herbaceous vegetation the most.
Boateng *et al*. 2000	Northeastern British Columbia	Glyphosate, control	Planted less than 1 year after site-preparation; spot spray – 3 months after planting	10, 12	None	Visual estimates, average height by species	Cover %, height and diameter of planted spruce	The simulated broadcast spray reduced the dominance of tall shrubs and increased structural diversity and herb species richness. Twelve years after the spot-spray treatments no significant differences in plant community structure or species diversity were detected. Simulated broadcast- and spot-spray glyphosate treatments increased the growth of planted white spruce (*Picea glauca*) seedlings without eliminating deciduous tree or shrub species.
Freedman *et al*. 1993	Central Nova Scotia	Glyphosate, control	2–5 after planting	1, 2, 4, 6	Growing season before treatment	Visual estimates	Cover %, basal area, density	Glyphosate treatments caused large decreases in vegetation abundance, especially that of ferns, herbs, and deciduous species. Some plant taxa [raspberry (*Rubus idaeus*) and herbs] recovered by the end of 1 and others by the end of 2 years. Although glyphosate changed species relative abundance substantially, no plant taxon was eliminated. After 6 years, conifers were more abundant on sprayed than on control plots. Herbicide-treated clearcuts will develop into conifer-dominated stands.
Gagné *et al*. 1999	Northeastern Quebec	Glyphosate, brushsaw cutting, control	4 after cutting, 2 after planting	1, 2	Growing season before treatment	Visual estimates	Cover %	One growing season after treatment, deciduous cover was reduced 56% by brushsaw cutting and 80% by the glyphosate treatments but increased 270% in control plots. By 2 years after treatment, deciduous cover was 3 (brushsaw) and 10 (glyphosate) times less in treated than control plantations. During the second year, raspberry cover recovered slightly but was about 55% less in herbicide-treated than in brushsaw-cut and control plantations. After treatment, no differences in fungal fruiting body biomass were found among controls, herbicide-treated, or brushsaw-cut plantations.
Hamilton *et al*. 1991	Coastal British Columbia	Glyphosate, control	Not reported	1, 3	None	Visual estimates	Cover % of fruit-producing shrubs	Ground-based foliar and individual stem applications reduced fruit-producing shrub cover by an average of 63% 1 year after treatment and reduced fruit availability for at least 3 years after treatment.

Table 1. Continued

Author and publication date	Location	Herbicide(s) or treatments studied	Treatment was – years after cutting or planting	Post-treatment years studied	Pre-treatment data collected	Survey method	Data collected	Major findings
Horsley 1994	Northwestern Pennsylvania	Glyphosate (understory - before shelterwood cut), control	NA	1, 2, 4, 7	Growing season before treatment	Counts of all woody species by height class, herbaceous species as % cover	Counts and cover %	Fern (*Dennstaedtia punctilobula*; *Thelypteris noveboracensis*) cover was reduced from 57% before treatment to 7% 1 year after treatment, while maple (*Acer saccharum*) and beech (*Fagus grandifolia*) advance regeneration was reduced by 16%. By the fourth year after treatment, regeneration (stocking) of desirable hardwood species had doubled in treated plots but remained unchanged in control plots. The herbicide treatment and the shelterwood seed cut had no statistically significant effect on species richness of either woody or herbaceous species. Treatments did not affect woody species diversity. There was a trend toward increased diversity of less common species in glyphosate-treated areas, and the diversity of herbaceous species groups was higher during the 7 years after the glyphosate treatment.
Kelly and Cumming 1992, 1994	Northwestern Ontario	Glyphosate (3 rates), control	2–10 after site preparation and planting	1, 2, 4	Growing season before treatment	Browse surveys	Deciduous density	One and 2 years after treatment hardwood shrub and herbaceous cover were reduced by 56 and 36%, and 53 and 19%, respectively. Browse density continued to decrease up to 3 years after treatment, but began to increase again 4 years after treatment. One year after treatment browsing was twice as high in control plots compared with treated plots; 2 years after treatment, it continued to decrease in plots treated at the 2 highest rates. By 4 years after treatment, browsing in control plots was 3 times greater than in plots treated at the lowest rates and 6 times greater than in plots treated at the 2 highest rates.
Lautenschlager and McCormack 1989; Lautenschlager 1995	North-central Maine	Imazapyr, triclopyr, glyphosate, hexazinone, control	1 and 2 after cutting, 9 months before planting	1, 2, 3	None	Visual estimates and biomass, by species and species group	Biomass and biomass estimates by species and species groups, cover %	Total number of plant species and/or species groups growing in areas treated with triclopyr, glyphosate, or hexazinone were not reduced, and commonly increased when compared with controls, 1 and 2 years after treatment. Before and after treatments, competitive cover was significantly greater on better sites. Within 3 years after treatment, competitors developed substantial competitive cover and height, even following repeated (ground-based) attempts to reduce total competition.
Lindgren and Sullivan 2001	South-central British Columbia	Glyphosate (cut stump), brushsaw cutting, control	2–9 after planting	1, 2, 3, 4	Growing season before treatment	Visual estimates	Abundance, cover %, crown volume	In the first post-treatment year, both brushsaw cutting and cut-stump treatments significantly reduced crown volume index of deciduous trees. Due to prolific regrowth of stump sprouts, the brushsaw treatment effect did not last beyond the first post-treatment year. In contrast, the cut-stump treatment reduced sprouting and continued to significantly suppress deciduous growth for at least 4 years. Species richness, diversity, and turnover of the herb, shrub, and tree layers were not significantly different between treatments and controls. The structural diversity of the herb, shrub, and tree layers was also not significantly different between treatments and controls. By opening the canopy and decreasing the dominance of the deciduous tree layer, both brushsaw cutting and cut-stump treatments resulted in greater total structural diversity (herb, shrub, and tree layerscombined) relative to the controls.

Table 1. Continued

Author and publication date	Location	Herbicide(s) or treatments studied	Treatment was – years after cutting or planting	Post-treatment years studied	Pre-treatment data collected	Survey method	Data collected	Major findings
Lloyd 1994	North-central British Columbia	Glyphosate (2 rates),control (only sometimes in the same cutblock)	2–18 after burning or mechanical site preparation	3–8	Some available from pesticide use permit applications	Visual estimates	Cover %, height of common species in herb and shrub layers, browse use	Deciduous trees and shrubs were rare or lacking and their diversity and abundance were generally lower on herbicide-treated areas. Cutblocks treated at 5-6 L/ha when less than 6 years old lacked both structural and species diversity; they were dominated by grasses and red raspberry whereas untreated areas had a greater diversity of other berry-producing species. Deciduous trees and shrubs were extremely sparse in areas treated at 4 L/ha when less than 10 years old. No overall difference in percent cover of berry-producing shrubs [huckleberry (*Vaccinium* spp.), red raspberry, cranberry (*Viburnum edule*), thimbleberry (*Rubus parviflorus*), twinberry (*Lonicera involucrata*), prickly rose (*Rosa acicularis*), soopolallie (*Shepherdia canadensis*)] on treated and untreated sites was found, although berry production was much lower on recently treated areas.
Moola *et al.* 1998	Northwestern Ontario	Glyphosate (operational and annual), brushsaw cutting, control	4 after planting	2, 3, 4	Growing season before treatment	Visual estimates, measurements, counts, and berry collections	Cover %, average height, biomass	Both operational and annual glyphosate treatments reduced cover (67 and 97%, respectively) and fruit mass (by 69 and 80%, respectively) of the 2 common blueberry species [low sweet (*Vaccinium angustifolium*), and velvet-leaf (*V. myrtilloides*)] for up to 4 years after treatment. Low sweet blueberry was affected the most, and both species were affected more by the annual removal than by operational aerial release.
Newmaster *et al.* 1999	Northwestern Ontario	Glyphosate, triclopyr, control	NA	6 months, 1, 2	Growing season before treatment	Visual estimates	Cover %	Moss and lichen abundance and species richness decreased after herbicide treatments. In general, herbicide applications reduced the diversity of forest mesophytes to a few species of colonizers. Three groups were recognized: herbicide-tolerant, semi-tolerant, and sensitive mesophytes. Unfortunately, this study involved the use of application rates based on standard aerial rates despite work by Feng and Thompson (1989), Newton *et al.* (1990), Thompson *et al.* (1992), and Thompson *et al.* (1997) indicating that only about 75% of the active ingredient applied is deposited on foliage, and of this only 12.5% penetrates to 0.5 m (or below) where moss and lichens occur.
Newton *et al.* 1989; Newton *et al.* 1992	North-central Maine	2,4-D, 2,4,5-T, glyphosate, triclopyr, control	7 after cutting (natural regeneration)	1, 8	Reconstructed – based on stems killed by the treatment	Visual estimates, measurements around crop trees	Cover %, height to mid-point of competitor, % crown receiving direct sun	Glyphosate, triclopyr, or phenoxy herbicides were applied 7 years after clearcutting. One year after treatment, available browse (<1.5 m) was reduced by 17 to 52%. The high rate of glyphosate reduced non-coniferous cover by 43%, but by 1 year after treatment, available browse in plots was comparable to that in control plots, and by 8 years treated after treatment, it was 4 to 8 times greater than in treated plots. Unless excessive rates of herbicides are used, short-term browse reductions are minimal. None of the treatments examined (which included relatively high herbicide rates) eradicated any plant species.

Table 1. Continued

Author and publication date	Location	Herbicide(s) or treatments studied	Treatment was – years after cutting or planting	Post-treatment years studied	Pre-treatment data collected	Survey method	Data collected	Major findings
Pitt *et al*. 1993	South-central New Brunswick	Glyphosate (3 formulations), triclopyr, control	2 after cutting	2	Growing season before treatment	Horizontal point sampling	Crown area	Vegetation control ranged from 21% (low rate) to 80% (high rate). Control by triclopyr was equivalent at rates < 0.5 × label maximum to that achieved by a full strength triclopyr treatment, but when applied above 0.5 × label maximum, vegetation control from triclopyr averaged only 59% of the control from similar glyphosate treatments.
Pitt *et al*. 1992	Southwestern New Brunswick	Glyphosate (4 rates), control	2 after planting	1	Growing season before treatment	Visual estimates	Cover %	One year after treatment, percent cover reduction of red maple (*Acer rubrum* - lowest), white birch, raspberry, elderberry (*Sambucus racemosa*), aspen, and pin cherry (*Prunus pensylvanica* - highest) increased with active ingredient rate (0.25, 0.5, 0.75, 1.0 kg ai/ha). The highest rates provided nearly 100% control of pin cherry and aspen, 80% control of elderberry and raspberry, and 50% control of white birch and red maple.
Pitt *et al*. 2000	Central Ontario	Glyphosate, triclopyr (basal-bark), brushsaw cutting, control	3–5 after planting	1, 2, 3, 4, 5	Growing season before treatment	Visual estimates of cover, average height (trees and tall shrubs)	Jack pine height and diameter, non-crop cover %, average height by species	During the 5 years of observation, cover of herbaceous plants was highest (30–50%) in the aerial spray plots. Deciduous tree, shrub, and fern species remained common, although total cover and height were low (≤35% and 1 m, respectively). By the end of the fifth year, deciduous trees and tall shrubs dominated untreated sites (> 70% cover). Aspen (primarily *Populus tremuloides*) were reduced at least 75% by all treatments; and reduced the most (97%) by aerial glyphosate and annual removal treatments. Other deciduous tree and tall-shrub species were reduced by all treatments; they were reduced least by brushsaw and most by annual release; operational aerial release was intermediate.
Raymond *et al*. 1996; Eschholz *et al*. 1996	North-central/ northwestern Maine	Glyphosate, control	Unclear, 5–8 after planting	1, 2 for those with pre-treatment data, 7–11 for a "chronose-quence" analysis	Winter browse, 6 months before treatment	Counts	Current annual growth of live twigs	From pre-treatment to 2 years after treatment available winter browse (deciduous species) decreased 70% on treated clearcuts relative to untreated controls, but was not different 7–11 years after treatment. One and 2 years after treatment, moose used treated areas 57 and 75% less than controls; by 7–11 years after treatment, moose tracks, pellet groups, foraging activity, and beds were more abundant in treated clearcuts, where conifers were more abundant and taller.
Roy *et al*. 1989	Central Ontario	Glyphosate, control	Not provided	Ripe berries coll-ected at 0, 9 hours and 1, 2, 13, 20, 33, and 61 days after treatment	None	Berries (blueberry and raspberry) collected	Berries and washwater collected and stored	Less than 10% of the glyphosate penetrated fruit during the first 9 hours after treatment, thereafter residue levels declined with time. Blueberries lost 50% of the herbicide residue within 20 days and raspberry lost 50% within 13 days. Residue levels 33 and 61 days after treatment were approximately 6 and 4%, respectively, of the initial peak. Because the spray solution was applied directly over foliage and fruit these experimental treatments likely led to greater glyposate residues than operational treatments.

Table 1. Continued

Author and publication date	Location	Herbicide(s) or treatments studied	Treatment was – years after cutting or planting	Post-treatment years studied	Pre-treatment data collected	Survey method	Data collected	Major findings
Santillo *et al.* 1989	North-central Maine	Glyphosate, control	4–5 after cutting and planting (included some natural regeneration)	1, retrospective for 2, 3	Growing season before treatment	Visual estimates, counts	Cover %, selected stem density	One year after treatment, species richness was 50% lower for shrubs and 30% lower for herbs in treated clearcuts. Two and 3 years after treatment herb (but not shrub) richness was lower in treated areas. More herb species (13) were reduced or eliminated by herbicide treatment than increased (5) or remained the same (3). Three years after treatment fireweed recovered but strawberry (*Frigaria virginiana*) did not. The dramatic first-year decrease in shrub and herb richness is unlike that reported in other studies, potentially because treated sites were treated twice because of concern that rain 1.5 hours after the first treatment washed glyphosate from the foliage.
Sullivan 1994	Central British Columbia	Glyphosate, control	9–21 after cutting	2, 3	One year before treatment	Visual estimates,	Cover %, crown volume index	Two to 3 years after treatment herb biomass and cover recovered to control levels. In a conifer-dominated released areas shrub and tree biomass and cover were little affected by the release treatment. In a "backlog conversion" treatment area, the dominant deciduous trees and shrubs were relatively slow to recover.
Sullivan *et al.* 1996	Southern British Columbia	Glyphosate, control	5–21 after cutting	2, 3	One year before treatment	Visual estimates	Cover %, crown index	Diversity of tree species was reduced in treatment blocks in the shrub-tree stage. Species abundance curves of overall plant volume communities showed little change in the herb stage and a decline in the first post-treatment year in the shrub and shrub-tree stages. There were similar patterns between control and treatment blocks in subsequent years. Conifer-release treatments of plantations have no substantial, incremental effects on wildlife habitat.
Sullivan *et al.* 1998a	Central British Columbia	Glyphosate, control	5–10 after cutting	1, 2, 3, 4, 5	One year before treatment	Visual estimates	Cover %, crown volume index	In the first year after treatment, species richness of shrubs was reduced and it remained lower on treated sites throughout the 5-year period. However, indices of shrub diversity were not different anytime during that 5-year period. Herbicide treatment initially reduced crown volume index of herbaceous vegetation, but by the second year after treatment, values quickly recovered to levels on the untreated areas. Herbicide treatments did not affect herbaceous species diversity. If appropriately designed and implemented, conifer release with herbicides may contribute to a diversity of stand structures and wildlife habitats.
Sullivan *et al.* 1998b; earlier results in Sullivan *et al.* 1996	Central British Columbia	Glyphosate, control	4 after planting	1, 2, 4, 5	Growing season before treatment	Visual estimates of cover % and height	Cover %, crown volume index	Herbicide application reduced crown volume of shrubs. Species richness of shrubs was reduced in the first year and remained lower on treated sites throughout the 5-year study period. Indices of shrub diversity, however, were unchanged over the 5 years. Herbicide treatment initially reduced herbaceous vegetation, but by the second year after treatment, those values were similar to those on controls. Herbicide treatments did not affect herbaceous species diversity.

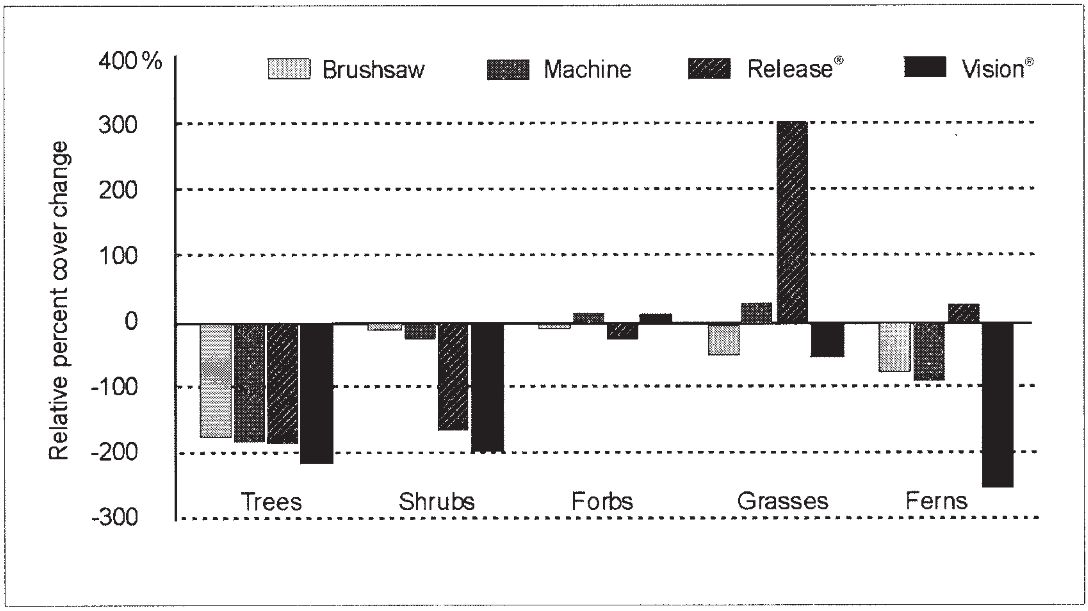

Fig. 1. Relative cover (adjusted for changes on controls) one growing season after treatment, by conifer release treatment type and vegetation group (N=4). Source: Bell *et al*. 1997.

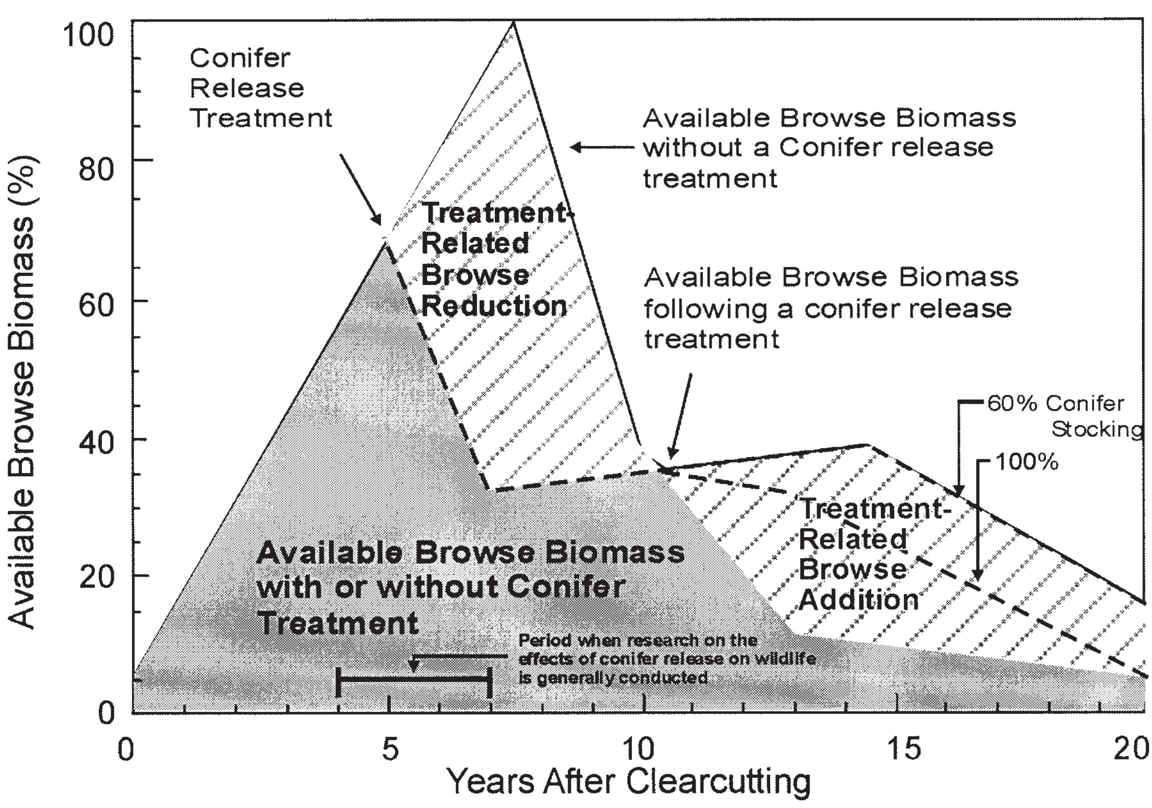

Fig. 2. Projected growth and available browse biomass with and without conifer release with herbicides. Source: Lautenschlager 1993b.

Boateng *et al.* 2000; Lindgren and Sullivan 2001). Indeed, plant species richness and related diversity indices often remain the same or increase on treated sites, because resident species generally remain and new species invade to occupy newly created niches (Swindel *et al.* 1984, Lautenschlager and McCormack 1989, Jobidon 1990, Freedman *et al.* 1993, Horsley 1994, Simard and Heinemann 1996, Lautenschlager *et al.* 1998, Sullivan *et al.* 1998a, Boateng *et al.* 2000, Lindgren and Sullivan 2001). Species are not eliminated because "(1) treatments are not designed to remove all competing vegetation but rather to reduce the level of competition; (2) treated areas often contain 'skips' (unintentionally unsprayed areas); (3) minimum effective volumes

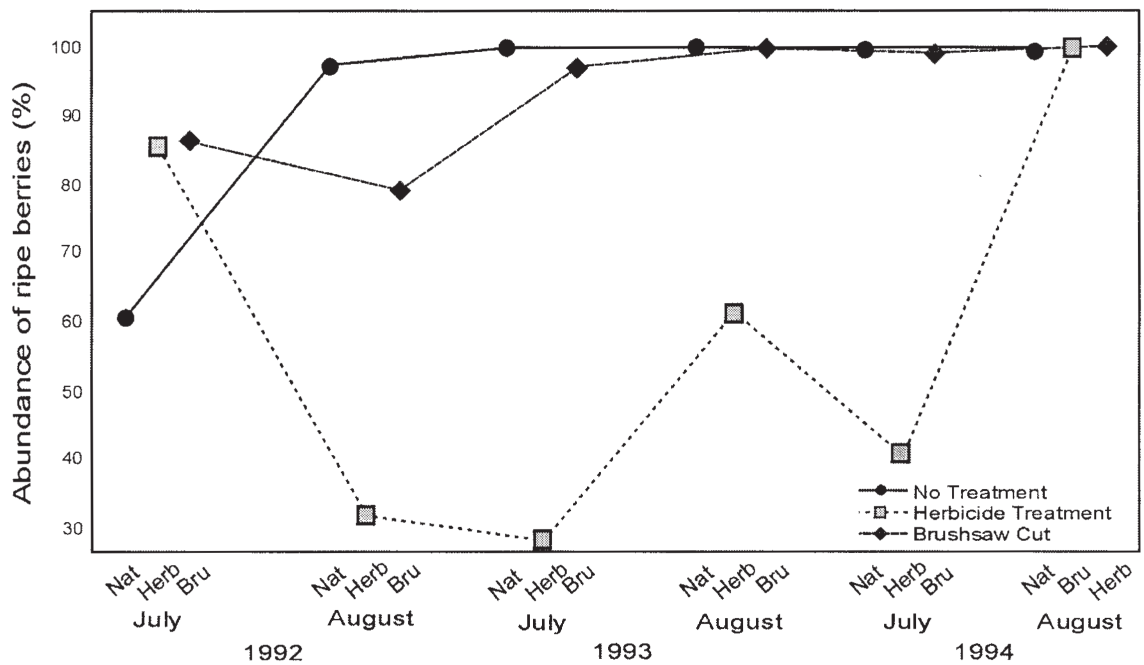

Fig. 3. Effects of no-treatment, herbicide (glyphosate) release, and brushsaw cutting on ripe berry abundance. Source: Gagné *et al.* 1999.

are applied; (4) low-growing vegetation often remains untreated when it is sheltered by taller vegetation" (Lautenschlager 1993a); and 5) increasingly, ground-based and aerial applications are focused on areas containing the densest competition, providing patch as opposed to broadcast control. That reduction in total control across treated areas will likely result in even fewer biotic differences, relative to controls, than have been found in the past and reported in this paper.

How long, however, do post-treatment vegetation reductions persist, following broadcast treatments? Newton *et al.* (1989) provided data that allowed Lautenschlager (1993a,b) to model changes in biomass availability of woody deciduous cover (browse) associated with post-clearcutting conifer release treatments (Fig. 2). Those data and models indicate that broadcast aerial treatments reduce non-conifer near-ground plant biomass below untreated controls for up to five years after treatment. At that time near-ground herbaceous and woody vegetation biomass on treated areas starts to exceed that on untreated controls, and provides more food and cover for some wildlife than vegetation on similar-aged untreated controls. In addition to differences associated with post-treatment successional time, reductions in and the reoccupation of treated areas by non-conifers seem to be linked to both site quality and conifer density (Lautenschlager 1993b).

Site quality influences the speed of recovery and biomass development on treated sites through time. All things being equal, vegetation recovers more quickly on richer than on poorer sites (Lautenschlager 1995). Although we know of no tests of effects of conifer density on browse recovery or availability, successfully released, poorly stocked conifer stands likely produce more non-conifer cover (potential browse) through time than do similar fully stocked stands.

Fruit Production

Concerns about the potential toxicity of herbicide treated plants that produce fruit used by wildlife and humans have been raised (Roy *et al.* 1989, Hamilton *et al.* 1991, Lloyd 1994). In addition, fruit production following treatment has been quantified (Moola *et al.* 1998, Gagné *et al.* 1999, Pitt *et al.* 2000). On richer sites, berry-producing shrubs, such as red raspberry (*Rubus idaeus*), are commonly the target of competition control (Newton *et al.* 1987, Roy *et al.* 1989, Lautenschlager 1990, 1995). As with other species, biomass reductions of fruit-producing species have consistently been recorded, but reductions seem to be short lived (Lautenschlager 1995, Gagné *et al.* 1999).

Roy *et al.* (1989) examined uptake and persistence of glyphosate in the fruit of wild blueberry (*Vaccinium* spp.) and red raspberry and found that, following an experimental treatment, less than 10% of the glyphosate contacting the fruit adhered to or penetrated that fruit. After the initial peak in the amount of active ingredient recovered from the fruit, herbicide residue levels declined gradually through time. They reported that glyphosate levels in treated fruit remained above the permissible maximum residue level (MRL) of 0.01 ppm established by Health Canada. However, because they removed the overstory that would normally intercept a significant part of any aerial spray solution (Thompson *et al.* 1997), their experimental treatment likely led to greater residues on fruit than would occur following operational treatments.

In addition, because glyphosate is a herbicide, it would not normally be applied to fruit, and hence MRLs that are established to reflect typical use of pesticides would not be set at all, or at very low levels. Indeed, the MRL of 0.01 ppm cited by Roy *et al.* (1989) is the default value used by Health Canada to reflect pesticide use that is not expected to result in any residue in a food commodity. In addition, risk assessment is not based on MRLs as suggested by Roy *et al.* (1989). Rather it is based on a reference dose (RfD), the dose or exposure level that is not considered to be associated with any adverse health effect even with lifetime daily dietary exposure. The RfD for glyphosate, based on information from the United States Environmental Protection Agency, is 2 mg/kg of body weight. When the highest residue levels reported by Roy *et al.* (1989)

are examined relative to a RfD for a 70 kg person eating 0.5 kg of blueberries or raspberries immediately after treatment every day of their life, the associated risk is actually 14 (raspberry) to 35 (blueberry) times lower than the RfD for glyphosate (L. Ritter, Toxicologist, University of Guelph, 2001, personal communication).

Hamilton *et al.* (1991) examined the effects of glyphosate applications on foliage of plants that produce fruit known to be consumed by grizzly bears (*Ursus horribilus)* in floodplain ecosystems in British Columbia. They concluded that ground-based foliar applications reduced the foliage of those shrubs by an average of 63% one year after treatment and influenced fruit availability for at least three years. In an unpublished report, Lloyd (1994) examined longer-term effects of operational aerial glyphosate treatments in north-central British Columbia on a variety of vegetation, including foliage of several fruit-producing species. Although only means are presented, it is clear that cover of fruit producing species varied widely on both the treated and untreated sites studied. However, treated and untreated sites had about the same mean cover percentages of berry-producing foliage seven to nineteen years after treatment. Cover of fruit-producing species in 14–19 year-old treated areas was dominated by *Rubus* spp., primarily red raspberry, while similar-aged untreated areas had a greater diversity of berry-producing species.

Moola *et al.* (1998) examined effects of brushsaw cutting, operational, and experimental (annually repeated) conifer release treatments with glyphosate on blueberries (*V. angustifolium* and *V. myrtilloides*) in regenerating jack pine stands in northwestern Ontario. They reported that "blueberry fruit production was highly variable in time and space, and consequently, these results are difficult to interpret—particularly … in the single Vision® sprayed plots" (Moola *et al.* 1998:846). However, they found that following a single operational treatment (aerial) with glyphosate, blueberry production (fresh biomass, primarily of *V. angustifolium*) was reduced 30, 39, and 69% at two, three, and four years after treatment, respectively. The annually repeated herbicide treatments essentially eliminated blueberry production. However, field foresters seldom use repeated treatments and do not view blueberries as particularly competitive. Thus, areas with extensive blueberry cover are rarely treated unless blueberries are associated with one or more taller competitive species, e.g., trembling aspen (*Populus tremuloides*), as was the case in this study.

Gagné *et al.* (1999) examined effects of brushsaw cutting and operational glyphosate treatments on vegetation, including soft mast production [primarily red raspberry but also currant (*Ribes* spp.), bunchberry (*Cornus canadensis*), yellow clintonia (*Clintonia borealis*), and red elder (*Sambucus racemosa*)] in northeastern Quebec. They found that, when compared with untreated controls, the abundance of ripe berries was reduced 2.5 to 3.0 times in brushsaw-cut and herbicide-treated areas within a month after an August treatment. In July of the following year, ripe berry abundance was 3.8 times less in herbicide-treated plots, than in untreated plots but it had increased in brushsaw-cut plots where it was similar to that in untreated plots. However, by the following month (August) berry abundance in herbicide-treated plots was only 1.6 times less than in untreated plots. Although there was a 2.4 times difference between herbicide-treated and the other treatment types in July during the second year after treatment, by the following month (two years after treatment), all treatments had similar soft mast abundance levels (Fig. 3).

Pitt *et al.* (2000) examined effects of operational aerial glyphosate release treatments and various ground-based alternatives on low-shrub species in central Ontario. They found that low-shrub [including sweetfern (*Comptonia peregrina*), blueberry, bush honeysuckle (*Diervilla lonicera*), and red raspberry] cover was reduced following the operational aerial herbicide treatment. In contrast, low-shrub coverage increased in control areas and in areas where conifer release was achieved via ground-based applications of glyphosate, triclopyr, and brushsaw cutting. Five years after treatment, blueberry cover was lowest (~2%) in aerial glyphosate-treated plots, intermediate (~8%) in control, basal bark (triclopyr), and mist blower (glyphosate) treated plots, and highest (~19%) in brushsaw-treated plots. At the same time, red raspberry recovered most rapidly following the aerial herbicide treatment; reaching 6% on the operational aerial herbicide-treated plots, but it remained low (< 2%) on control plots and plots that received ground-based herbicide, and brushsaw-cutting treatments.

Mosses, Lichens, and Fungi

Few studies have examined the effects of herbicides on mosses, lichens, or fungi. Bell and Newmaster (1998) provided field data documenting the consequences of operational treatments; Newmaster *et al.* (1999) provided results of a manipulative field experiment; and Boateng *et al.* (2000) documented effects of simulated broadcast- and spot-herbicide treatments on mosses and lichens.

Bell and Newmaster (1998) found that forest harvesting reduced moss species richness and abundance dramatically. Post-harvest herbicide release treatments further reduced species richness significantly and abundance slightly, but brushsaw cutting did not. Reductions in richness and abundance, however, were no longer statistically different three years after the operational treatments were applied. Boateng *et al.* (2000) found that moss and lichen richness and diversity were reduced slightly, but not significantly, 10 and 12 years after treatment.

Newmaster *et al.* (1999) examined moss and lichen abundance and species richness for two years following experimental treatments with herbicide spray solutions that ranged from 0–5.0 kg active ingredient (a.i.)/ha (glyphosate) and 0–6.7 kg a.i./ha (triclopyr). They reported that moss and lichen abundance and richness were reduced dramatically as the rate of both active ingredients increased. However, the rates chosen were dramatically greater than these plants would experience during operational treatments. Herbicide deposit is site- and application-technology specific; however, only about 75% of the a.i. applied during an operational treatment is generally recovered from a treatment site [Feng and Thompson (1989); Newton *et al.* (1990); Thompson *et al.* (1992, 1997)]. Therefore, only 12.5% of the total a.i. applied (9% of the a.i. intended for the site) is generally recovered from 0.5 m or lower, the stratum where mosses and lichens occur. So, at the rates mosses or lichens actually receive during operational aerial treatments ($\leq$ 0.2 kg a.i./ha), the work by Newmaster *et al.* (1999) shows no, or nearly no, effect at six months, one year, or two years after treatment.

Huston *et al.* (1998a, b) documented responses of below-ground biotic components to cutting, site preparation and planting, and those treatments followed by conifer release. They found that soil microbial processes and fungal community structure

Table 2. Overview of studies that documented effects of herbicides on terrestrial invertebrates in northern forested ecosystems

Author and publication date	Location	Herbicide(s) or treatments studied	Treatment was –years after cutting or planting	Post-treatment years studied	Pre-treatment data collected	Survey method	Data collected	Major findings
Addison 1996 (unpublished) cited in Lautenschlager *et al.* 1998	Northwestern Ontario	Glyphosate, triclopyr, brushsaw cutting, machine cutting, control, unharvested	3–7 after planting	2	None	Soil cores followed by laboratory separation	Abundance by species/ unit area	The author found: 1) 83 750 individual collembola/m^2 (representing a variety of species), with more collembola on unharvested than on recently clearcut (control or released) plots; 2) mite density of 175 000/ m^2; and forest earthworms in all clearcut plots, regardless of treatment; but not in the unharvested forest.
Duchesne *et al.* 1999	Northwestern Ontario	Glyphosate, triclopyr, brushsaw cutting, machine cutting, control, unharvested	3–7 after planting	2	Collected by Ward *et al.* 1998) – see Ward *et al.* below	Intensive sampling with pit fall traps	Abundance by species	Total carabid catches were statistically unaffected by the harvest or any of the post-harvest conifer release alternatives used. Two years after treatment, species richness and Shannon-Weiner diversity index increased after clearcutting and again after conifer release. The greatest diversity was recorded where competition control was most successful, in herbicide-treated and brushsaw-cut plots.
Gagné *et al.* 1999	Northeastern Quebec	Glyphosate, brushsaw cutting, control	4 after cutting, 2 after planting	1, 2, 3	Growing season before treatment	Foliar-active, by “beating” plants above plastic sheets; surface-active by pit fall traps	Relative abundance	Arthropod percentages collected were: Diptera (19%), arachnids (18%), Collembola (17%), Hemiptera (16%), Homoptera (15%) and Coleoptera (9%). Pre- and post-treatment differences in abundance were detected. During the first post-treatment spring foliar arthropods were not found in the herbicide-treated areas but were found in naturally regenerating cutblocks and brushsaw-cut plantations. During the following years, arthropod abundance was not significantly affected by release treatments. Regardless of treatment, foliar and ground arthropod numbers varied considerably through time.
Hawkins *et al.* 1997	Northwestern Ontario	Glyphosate, triclopyr, brushsaw cutting, machine cutting, control, unharvested	3–7 after planting	1	Growing season before treatment	Repeated counts of individuals by species from: under cardboard sheets, and soil cores	Abundance by species	During the summer before treatment mean surface-active gastropod abundance reached a maximum of 21/m^2 but remained fairly stable at about 10/m^2 throughout the first post-treatment summer. Differences were due to a decrease in surface-activity associated with reduced rainfall. The lack of difference following treatments was attributed to rapid re-establishment of the herbaceous layer, which seemed to provide favourable habitat. Average gastropod densities were higher in nine-year-old regenerating spruce plantations (15.5/m^2) than in the 70-year-old mixed-wood forest (9.4/m^2), and species richness was also slightly greater (20 vs. 18) in plantations.

Table 2. Continued

Author and publication date	Location	Herbicide(s) or treatments studied	Treatment was –years after cutting or planting	Post-treatment years studied	Pre-treatment data collected	Survey method	Data collected	Major findings
Kostyk *et al*. 1997	Northwestern Ontario	Glyphosate, triclopyr, brushsaw cutting, machine cutting, control	3–7 after planting	2	None	Spruce classified as light, moderate, or severely damaged	Damage to spruce by damage class	Most trees were lightly defoliated by the yellowheaded spruce sawfly and the eastern spruce budworm; however, damage was not severe. Hot spots of defoliation occurred throughout the study area but were restricted to roadsides and open slopes. Herbicide-treated areas did not attract more defoliating insects, despite the fact that non-crop vegetation cover was significantly lower than in control and brush-cut areas. Severe defoliation was only observed near large areas of completely bare ground where conditions were well suited for sawfly reproduction.
Prezio *et al*. 1999	Northwestern Ontario	Glyphosate, triclopyr, brushsaw cutting, machine cutting, control	3–7 after planting	2, 3	Collected by Hawkins *et al*. (1997)	Repeated counts under cardboard sheets, and from soil cores	Abundance by species	Two and 3 years after treatment, surface active gastropod densities (about 2% of the total gastropod density) were 50–60% greater in control areas than those in cut or herbicide-treated areas. Surface-active density reductions were most likely due to the drier near-surface (above- and below-ground) microclimate on cut and herbicide-treated sites. Gastropod surface activity on cut plots may be recovering more quickly than that in herbicide-treated plots.
Santillo *et al*. 1989	North-central Maine	Glyphosate, control	4–5 after cutting and planting (included some natural regeneration)	1 plus "chrono-sequence for 2, 3	None	Sweep-netting and pit-fall trapping	Abundance by order	Percentage of total captures, by order, 1 and 3 years after herbicide treatment and 6 years after cutting were as follows: Homoptera (4.3, 24.5, 21.5), Heteroptera (0.7, 1.4, 9.5), Coleoptera (20.2, 16.1, 15.9), Diptera (5.6, 9.2, 3.6), Lepidoptera (2.0, 1.9, 1.7), Orthoptera (5.8, 3.3, 4.2), Hymenoptera (35.9, 22.8, 23.9), Aranedia (26.0, 20.2, 19.4). Herbivorous insect captures changed with post disturbance time; compared with those captured 6 years after cutting (control), 25 and 89% fewer were captured 3 and 1 years, respectively, after the herbicide treatments were applied.
Ward *et al*. 1998	Northwestern Ontario	Glyphosate, triclopyr, brushsaw cutting, machine cutting, control	3–7 after planting	1	Growing season before treatment	Intensive sampling with pit-fall traps	Abundance by species	Homoptera was the only order to show statistically significant treatment-related responses, with lowest densities in glyphosate plots and highest densities in brushsaw-cut and control plots. Machine cut and triclopyr plots were intermediate but closer to the means for brushsaw-cut and control plots. One year after treatment, the Shannon-Weiner diversity index indicated that carabid diversity was lowest after brushsaw and machine cutting treatments, intermediate in herbicide-treated areas, and highest in control plots.

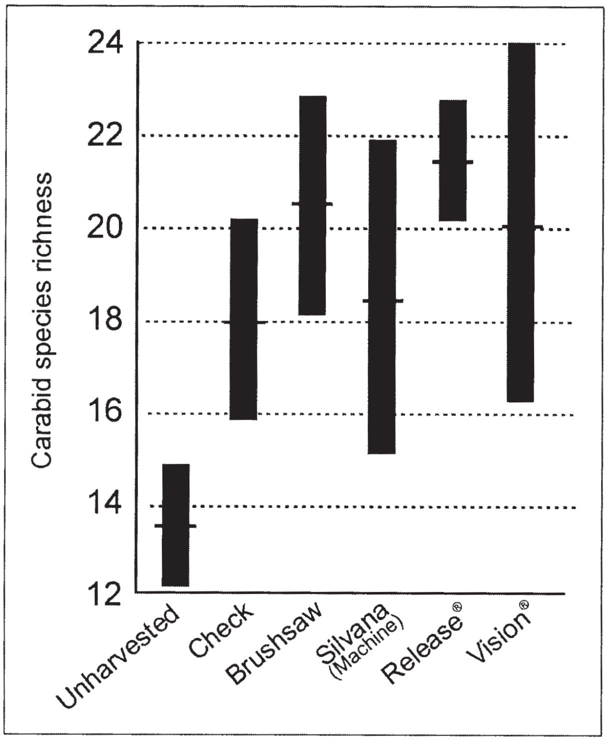

Fig. 4. Mean (± standard deviation, N=4) carabid species richness two years after conifer release. Source: Duchesne *et al.* 1999.

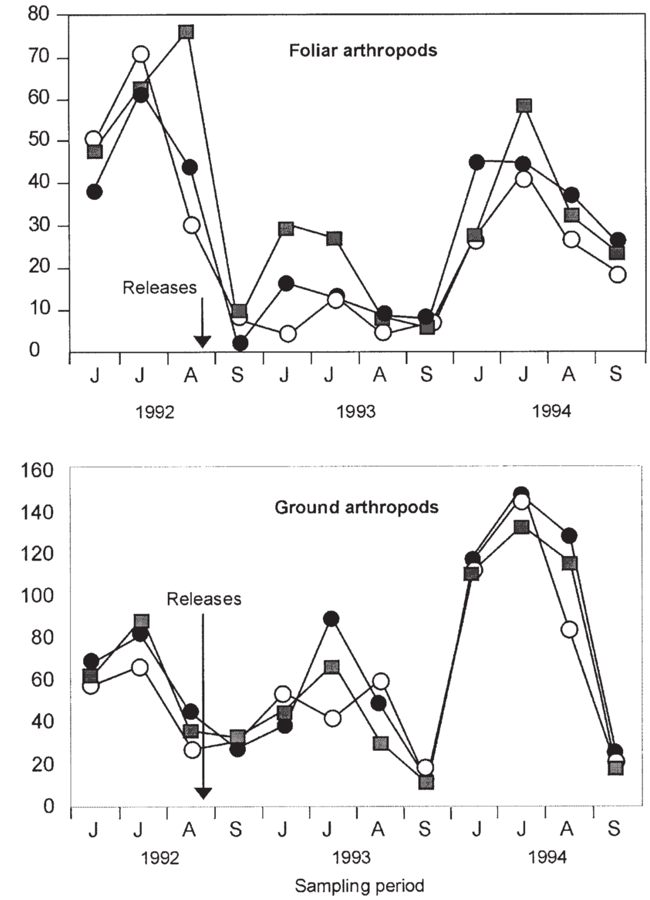

Fig. 5. Relative abundance of foliage and ground arthropods in naturally regenerating cutblocks (■), herbicide- (glyphosate) treated plantations (○), and brushsaw-cut plantations (●) by time period. Source Gagné *et al.* 1999.

(richness, diversity, composition) were similar in unharvested, clearcut, and clearcut then released [herbicide (glyphosate, triclopyr) or brushsaw cut] stands. However, they noted that although total fungal abundance was not changed, isolation frequencies (the abundance measure used) in organic soil of two fungal species, *Mortierella vinacea* and *Paecilomyces carneus,* decreased when samples were collected two years after herbicide and brushsaw release treatments.

Terrestrial Invertebrates (Table 2)

Sullivan and Sullivan (2000) and Mihajlovich (2001) listed 74 studies that, at least in part, include the effects of herbicides containing glyphosate or triclopyr on terrestrial invertebrates. Most of those studies, however, dealt with agricultural treatments or simulation models. Only eight published studies (Santillo *et al.* 1989, Hawkins *et al.* 1997, Kostyk *et al.* 1997, Lautenschlager *et al.* 1998, Ward *et al.* 1998, Duchesne *et al.* 1999, Gagné *et al.* 1999, and Prezio *et al.* 1999) are useful for drawing conclusions about effects of conifer release on terrestrial invertebrates in managed northern forest ecosystems. Results from the Fallingsnow Ecosystem Project in northwestern Ontario (Lautenschlager *et al.* 1997a, 1998) are particularly useful because that project documented effects on most terrestrial ecosystem components, including: below-ground, surface-active, and selected foliage-dependent invertebrates to conifer release alternatives. Papers by Hawkins *et al.* 1997, Kostyk *et al.* 1997, Ward *et al.* 1998, and Duchesne *et al.* 1999, are all based on work conducted at Fallingsnow.

Addison (1996) documented soil fauna abundance at Fallingsnow by examining soil samples collected two years after treatments were applied. She found 83 750 individual collembola/m^2 (representing a variety of species), more collembola in unharvested than in recently clearcut (both control and released—regardless of treatment type) plots, and mite density of 175 000 individuals/m^2 in clearcut control and released plots. Forest earthworms were found in all clearcut plots, regardless of the alternative release treatment applied, but earthworms were not found in the unharvested forest plots.

Santillo *et al.* (1989) provided experimental and retrospective information about surface-active and near-ground insect responses one and three years after operational glyphosate treatments. They found increasing abundance of insects through post-disturbance time with 446 captures one year after herbicide treatment, 644 three years after treatment, and 900 on the untreated control (an area harvested six years previously).

Ward *et al.* (1998) examined treated plots before and the year after treatments and concluded that conifer release [using herbicides (glyphosate and triclopyr), brushsaw, and machine cutting treatments] had little effect on most insect groups during the first year after treatment. Homoptera was the only order affected by any of the conifer release alternatives studied, with lowest densities in the glyphosate plots and highest densities in the brushsaw-cut and control plots.

Duchesne *et al.* (1999), used pre- and one-year post-treatment data collected by Ward *et al.* (1998) and re-examined those plots plus plots in the adjacent unharvested forests, two years after treatment. They found total Carabid catches were not sig-

Table 3. Overview of studies that documented effects of herbicides on amphibians and reptiles in northern forested ecosystems

Author and publication date	Location	Herbicide (s) or treatments studied	Treatment was – years after cutting or planting	Post-treatment years studied	Pre-treatment data collected	Survey method	Data collected	Major findings
Berrill *et al.* 1994	Laboratory study in central Ontario	Fenitrothion, (an insecticide), triclopyr, hexazinone, control	NA	NA	None	Laboratory exposure	Hatching success for tadpoles, mortality, swimming ability, total body length 1 week after exposure	Hexazinone, at high rates, had no effects on embryos or tadpoles. Exposure to triclopyr and fenitrothion did not affect hatching success of embryos and subsequent avoidance behaviour of any species. Newly hatched tadpoles of all species were very sensitive to 2.4 and 4.8 ppm triclopyr and to 4.0 and 8.0 ppm fenitrothion, either dying or becoming paralyzed following exposure. Tadpoles initially affected by exposure to lower concentrations of fenitrothion or triclopyr usually recovered within 1 to 3 days. The following tadpole sensitivity was observed: Bullfrog > green frog > leopard frog.
Bogart *et al.* 1995; Bogart (unpublished report, 1997)	Northwestern Ontario	Glyphosate, triclopyr, brushsaw cutting, machine cutting, control	3–7 after planting	1, 2	Growing season before treatment	Plot searches under placed and natural structures, captures in on-site pools, listening	Abundance by species, size, and age	A single reptile species (the garter snake) and six amphibian species were found. However, amphibian and reptile abundance was limited in the clearcut blocks (upland areas removed from wetland refuges). Only spring peepers and wood frogs were common in study blocks, and no treatment-related population changes for these species were observed.
Cole *et al.* 1997	Oregon Coast Range	Clearcut and burned, clearcut and burned followed by glyphosate, uncut (control)	Summer before cutting and burning two years before glyphosate was applied	1, 2	Growing season before treatment	Pit fall traps	Capture rates by species	No changes in capture rates after cutting were observed. Capture rates of ensatina (*Ensatina eschscholtzii*) and Pacific giant salamander (*Dicamptodon tenebrosus*) decreased after logging. Capture rates of western redback salamander (*Plethodon vehiculum*) increased the first year after clearcutting, but effects on populations were unclear. Clearcutting did not significantly alter capture rates of rough-skin newt (*Taricha granulosa*), Dunn's salamander (*P. dunni*), and red-legged frog (*Rana aurora*). Capture rates for rough-skin newt and red-legged frog were higher in uncut red alder stands than in regenerating Douglas-fir (*Pseudotsuga menziesii*) stands. LD_{50} values for glyphosate, based on intraperitoneal-injection were >1000 mg/kg for the amphibians examined; leading to the conclusion that effects of glyphosate spraying, if any, would be indirect.
Lautenschlager *et al.* 1998 – Bogart 1997	Northwestern and central Ontario	Glyphosate, triclopyr, brushsaw cutting, machine cutting, control	3–7 after planting	1, 2	Growing season before treatment	Plot searches under placed and natural structures, captures in on-site pools, listening	Abundance by species, size, and age	Some developmental abnormalities were encountered among wood frogs (*Rana sylvatica*) from 1 of 4 glyphosate treated areas. Further laboratory and field work indicated that those abnormalities exist naturally at low frequency in this species across its northern range.

nificantly affected by timber harvesting or the post-harvest conifer release alternatives used. Indeed, by two years after treatment, species richness, and diversity indices (Shannon-Weiner and Simpson) were consistently higher (although not always statistically significantly so) on clearcut plots and higher still on released plots. The greatest diversity was recorded where competition control was most successful: in herbicide-treated and brushsaw-cut plots (Fig. 4).

Gagné *et al.* (1999) had pre-treatment and arthropod response data for two years after treatment. They found that foliar and surface-active arthropod abundance decreased one year after treatment (clearcut followed by glyphosate or brushsaw). During the second year after treatment, abundance of foliar and surface-active arthropods and arachnids varied considerably throughout the study area, but was statistically unaffected by release (Fig. 5). However, as would be expected, foliar arthropods were less abundant (although not statistically so) during that time in herbicide-treated sites than in older naturally regenerated sites and brushsaw-cut plantations.

Kostyk *et al.* (1997) and Woodcock (1997) examined the responses of defoliating insects to several conifer release alternatives. Kostyk *et al.* (1997) found that many of the planted conifers, examined two years after treatment, were lightly defoliated by the yellowheaded spruce sawfly (*Pikonema alaskensis*) and eastern spruce budworm (*Choristoneura fumiferana*). However, herbicide-treated areas had no more insects or related damage than did brushsaw-cut or control areas, despite the fact that non-crop vegetation cover was significantly lower in herbicide-treated areas.

While documenting songbird responses to the same alternative treatments, Woodcock (1997) and Woodcock *et al.* (1997) documented abundance of defoliating insects in the regenerating spruce. Two years after release treatments, spruce budworm biomass (g/tree) was greater in spruce trees growing on control plots than in brushsaw-cut or herbicide-treated plots. However, budworm populations were similar among treatment types by three years after release (Lautenschlager *et al.* 1998).

Hawkins *et al.* (1997), Prezio (1997) and Prezio *et al.* (1999) produced the first publications examining effects of herbicides on terrestrial gastropods. Hawkins *et al.* (1997) collected 21 gastropod species (two slug and 19 snail) and reported that, during the first growing season after release treatments, neither density nor species richness was affected by the alternatives tested. In addition, surface-active densities in clearcuts (nine to sixteen/m^2) were consistently greater than those in adjacent unharvested forests (seven to nine/m^2) (Hawkins *et al.* 1997), a trend that continued through the next two years (Prezio 1997). Prezio *et al.* (1999) found that by three years after release, densities of surface-active gastropods were lower on herbicide-treated than on control plots. However, three and four years after treatment, soil-dwelling gastropod abundance was similar in soils collected from herbicide-treated (377/m^2) and control plots (258/m^2) (Prezio 1997).

Amphibians and Reptiles (Table 3)

Published work examining effects of conifer release with herbicides on amphibians and reptiles is limited to laboratory studies with frog embryos and tadpoles (Berrill *et al.* 1994), studies in the Oregon Coast Range (Cole *et al.* 1997), and field and laboratory work in Ontario (Bogart *et al.* 1995, Lautenschlager *et al.* 1998).

In the laboratory, Berrill *et al.* (1994) examined responses of embryos and tadpoles of the leopard frog *(Rana pipiens)*, green frog (*Rana clamitans*), and bullfrog (*Rana catesbeiana*) to fenitrothion (an insecticide) and two active ingredients (hexazinone, triclopyr) found in herbicide products. Hexazinone had no effect on embryos or tadpoles even at exposure levels dramatically higher than amphibians would experience in the wild. However, newly hatched tadpoles of all species were very sensitive to 2.4 and 4.8 ppm triclopyr; following exposure they either died or were paralyzed. Tadpole species sensitivity to triclopyr was bullfrog> green frog> leopard frog. However, because conifer release treatments in northern forest ecosystems occur during late summer, areas with water are not treated, and triclopyr breaks down relatively quickly, tadpoles in the wild are unlikely to be exposed to triclopyr.

In the Oregon Coast Range, Cole *et al.* (1997) examined effects of cutting, burning, and both treatments followed by a fall glyphosate application (1.3 kg a.i./ha). They also determined LD_{50} values for common amphibians [ensatina (*Ensatina eschscholtzii*), western red-back salamander (*Plethodon vehiculum*), Pacific giant salamander (*Dicamptodon tenebrosus*), rough-skin newt (*Taricha granulosa*), and tailed frog (*Ascaphus truei*)]. Intraperitoneal-injection LD_{50} values were >1000 mg/kg for those species, and based on a dose acquisition model, oral and dermal absorption of glyphosate after field application was predicted not to exceed 1.2 mg/kg for any of these species. Therefore, the authors concluded that effects of conifer release, if any, would be indirect (habitat changes) rather than direct (toxic). In addition, capture rates suggested no effects of a glyphosate application on amphibian abundance or species richness.

In northwestern Ontario, Bogart *et al.* (1995) found only a single reptile species, the relatively common garter snake *(Thamnophis sirtalis)*, and six amphibian species in studied blocks. During the growing season following conifer release treatments, 11 garter snakes from study blocks and 16 from adjacent areas were captured, and their reproductive conditions noted. Six (55%) of the study block snakes were gravid, while only one (6%) of the snakes from adjacent areas was gravid. Snakes have extensive home ranges; thus, they commonly moved in and out of study blocks as well as among treatment plots within blocks. However, even this small sample suggests that habitat quality for snakes in areas treated with herbicides was not reduced and may have increased following treatment (Bogart *et al.* 1995).

Amphibian abundance in the study by Bogart *et al*. (1995) was limited because experimental blocks were upland areas removed from extensive wetland refuges. Although blue-spotted salamander (*Ambystoma laterala*), American toad (*Bufo americanus*), spring peeper (*Pseudacris crucifer*), striped chorus frog *(Pseudacris triseriata*), tetraploid grey treefrog (*Hyla versicolor*), and wood frog (*Rana sylvatica*) were found in treatment blocks, only spring peeper and wood frog were common. No treatment-related population changes for these species were observed during the first two years after treatment (Lautenschlager *et al.* 1998). However, occasional developmental abnormalities were observed among wood frogs collected from one glyphosate-treated plot. Further work found that those abnormalities occurred regularly, although infrequently, in this species across its northern range (Lautenschlager *et al.* 1998).

Table 4. Overview of studies that documented effects of herbicides on songbirds in northern forested ecosystems

Author and publication date	Location	Herbicide (s) or treatments studied	Treatment was – years after cutting or planting	Post-treatment years studied	Pre-treatment data collected	Survey method	Data collected	Major findings
Easton and Martin 1998	South-central British Columbia	Glyphosate, brushsaw cutting, control	2–7 after planting	1,2,3	Growing season before treatment	Point counts and nest searches	Individuals seen or heard within 75 m radius of plot centre	Deciduous trees on brushsaw cut sites grew back, but those on sites that were cut then herbicide-treated did not. After herbicide treatment, songbird densities increased but bird species richness declined; common species dominated treated areas. After brushsaw cutting, species richness, abundance, and evenness increased. Turnover of bird species was highest in the herbicide-treated sites. Residents, short-distance migrants, ground gleaners, and conifer nesters increased significantly in herbicide-treated areas. Deciduous nesters and foliage gleaners increased in control and brushsaw-cut areas. Warbling viero (*Vieo rgilvus*), a deciduous specialist, may be particularly susceptible to brushsaw cutting followed by a herbicide stump treatment. Although treated areas had similar increases in total number of birds, nesting success of open-cup nesting species was significantly lower in the herbicide-treated than in brushsaw-cut areas. Bird communities became more homogeneous after herbicide treatment, but showed little change after brushsaw cutting.
Woodcock *et al*. 1997, 1998	Northwestern Ontario	Glyphosate, triclopyr, brushsaw cutting, control	3–7 after planting	1, 2, 3, 4	Growing season before treatment	Point counts, territory mapping, mist netting	All birds heard, seen, and captured were recorded and sex and age noted for captured birds	Following release treatments, males continued to establish and maintain territories in treated areas, while females of some species abandoned previously occupied territories. During the first year after release, densities of male alder flycatcher (*Empidonax alnorum*), red-eyed vireo (*Vireo olivaceus*), song sparrow (*Melospiza melodia*), and white-throated sparrow (*Zonotrichia albicollis*) did not differ significantly among treatments. During both the first and second year after release, chestnut-sided warbler (*Dendriuca oebstkvabuca*) densities decreased in cut and herbicide-treated plots. However, by 4 years after treatment densities of these warblers decreased in control plots and increased to pre-treatment levels in cut plots and to about half pre-treatment levels in herbicide-treated plots. In treated plots, woody vegetation was suppressed, and the presence of developing grasses/sedges led to increases in seed-eating species (sparrows and finches), which were most abundant in glyphosate-treated plots.

Songbirds (Table 4)

With the exception of work by Woodcock *et al.* (1997, 1998) and Easton and Martin (1998), little new data have been added to the literature documenting effects of herbicides used for forest management on songbird populations. Unlike much previous short-term research, Woodcock *et al.* (1998) examined bird populations pre-treatment and for four years after treating 3.3–12.5-ha plots on four replicated blocks via brushcutting (brushsaws, large cutting machine), two herbicides (glyphosate, triclopyr), and nothing (control). Spot mapping, territory mapping, and mist netting were used to document effects by gender as well as reproductive output.

Woodcock *et al.* (1997) recorded 20 to 38 (block-dependent) species, but only 11 species were common enough for statistical comparisons. Results, based on territory mapping, indicated that densities of most, including alder flycatcher (*Empidonax alnorum*), red-eyed vireo (*Vireo olivaceus*), song sparrow (*Melospiza melodia*), and white-throated sparrow (*Zonotrichia albicollis*) did not differ among treatments during the first year after release. However, chestnut-sided warbler (*Dendroica pensylvanica*) densities varied among treatments during both the first and second year after treatment (higher in control plots and lower in treated plots; lowest in brushsaw-cut plots). By four years after treatment, chestnut-sided warbler numbers were decreasing in control plots (likely because habitat quality decreased as succession proceeded), were increasing towards pre-treatment levels in cut (brushsaw, machine) plots, and were about one-half pre-treatment levels in herbicide-treated plots (Lautenschlager *et al.* 1998).

In general, during the first few years after treatment, songbird species dependent on hardwood foliage (parulid warblers, vireos, and thrushes) were more common in control plots than in any of the treated plots. In treated plots, woody vegetation was suppressed, and in glyphosate-, and especially triclopyr-treated plots, the developing grasses/sedges that increased in abundance soon after treatment provided foods for seed-eating species (sparrows and finches) (Woodcock *et al.* 1997). The presence of a significantly higher proportion of high shrubs inside territories (~ 20–37%), compared with outside (~15%), seemed to have been the factor influencing area use by alder flycatcher, chestnut-sided warbler, mourning warbler (*Oporornis philadelphia*), Nashville warbler (*Vermivora ruficapilla)*, red-eyed vireo, and veery (*Catharus fuscescens*) (Woodcock *et al.* 1998). These species were reduced by treatments that removed high shrubs while early successional and more generalist species, white-throated sparrow, Lincoln's sparrow (*Melospiza lincolnii*), and song sparrow, increased following those treatments.

During their three-year study, Easton and Martin (1998) found that deciduous trees grew back on brushsaw-cut sites, but not on cut-stump (glyphosate-treated) sites. After the glyphosate treatment, songbird species richness declined, while abundance of common species, residents, short-distance migrants, ground gleaners, and conifer nesters increased significantly. Songbird species richness, abundance, and evenness also increased after brushsaw cutting. Turnover of songbird species was highest on the glyphosate-treated sites. Deciduous nesters and foliage gleaners increased in control and brushsaw-cut areas. Easton and Martin (1998) observed that warbling vireo (*Viero gilvus*), a deciduous specialist, seemed particularly susceptible when cut stumps were treated with glyphosate. Although increases in the total number of birds were similar in brushsaw-cut and herbicide-treated areas, nesting success of open-cup-nesting species was significantly lower in the herbicide-treated than in brushsaw-cut areas. Bird community composition became more homogeneous after conifers were released by treating cut stems with glyphosate, while it changed little following brushsaw cutting.

Small Mammals (Table 5)

Studies documenting responses of small mammals to forest herbicide treatments have been conducted throughout the boreal and boreal mixedwood forests of northern North America (Sullivan and Sullivan 2000, Mihajlovich 2001). Lautenschlager *et al.* (1995), working in a regenerating jack pine forest in northwestern Ontario, found that red-backed vole (*Clethrionomys gapperi*) numbers were reduced for one year following brushsaw cutting and two years following an operational glyphosate treatment. Deer mouse populations seemed relatively unaffected by those treatments, while the least chipmunk (*Tamias minimus*), which at first was unaffected, became more common two years after the initial herbicide treatment on plots treated annually with glyphosate. Abundance of the eastern chipmunk (*Tamias striatus*), however, was reduced by all treatments.

In a different study in northwestern Ontario, Lautenschlager *et al.* (1997b) reported that abundance of most species occupying regenerating spruce stands was not reduced by any of the operational herbicide or cutting alternatives examined. During the first year after the treatments were applied, however, red-backed vole abundance was highest in control and lowest in herbicide-treated (glyphosate and triclopyr) plots. During the second year after treatment, their abundance on control and herbicide-treated plots was similar. Throughout the study, red-backed vole populations were consistently larger in adjacent unharvested forests (20/ha) than in recent cutovers, regardless of the release treatment used. In these regenerating forest plots, voles were most abundant in untreated control (13/ha), less abundant in brushsaw cut (10/ha) plots, and least abundant in herbicide-treated (6/ha) plots.

In south-central British Columbia, Runciman and Sullivan (1996) found no significant effects of brushsaw cutting or glyphosate cut-stump application on populations of deer mouse, yellow-pine chipmunk *(Tamias amoenus*), red-backed vole, or long-tailed vole (*Microtus longicaudus*). In a different British Columbia study, Sullivan and Boateng (1996) found that after treatment (broadcast burning or glyphosate) deer mouse populations were reduced for one to two months in the coastal study area, but those in the interior study area were unaffected. Meadow voles (*Microtus pennsylvanicus*) disappeared from burned blocks in the interior area, but Oregon voles (*Microtus oregoni*) persisted in the burned block in the coastal area. Red-backed vole abundance was reduced in both areas, while chipmunks *(Eutamias townsendii, E. amoenus*) seemed unaffected by either treatment. Neither burning nor glyphosate treatment affected species diversity of the small mammal communities studied. The authors concluded that small mammal abundance was likely affected more by broadcast burning than by herbicide treatment.

In coastal British Columbia, Sullivan *et al.* (1997) examined two areas sprayed with glyphosate in June and September. They reported that average deer mouse abundance was reduced during the remainder of the growing season following the

Table 5. Overview of studies that documented effects of herbicides on small mammals in northern forested ecosystems

Author and publication date	Location	Herbicide (s) or treatments studied	Treatment was – years after cutting or planting	Post-treatment years studied	Pre-treatment data collected	Survey method	Data collected	Major findings
Cole *et al.* 1998	Oregon Coast Range	Clearcut and burned, clearcut and burned followed by glyphosate, uncut (control)	Burning and glyphosate used as site preparation treatments 1 year before planting	1, 2	One year before treatment	Pit fall and live traps	Captures by species	For the 6 species analyzed capture rates did not differ between areas logged/burned and those logged/burned and then sprayed with glyphosate. Differences in vegetation between sprayed and unsprayed areas were minor relative to the major changes caused by logging and burning.
Gagné *et al.* 1999	Northeastern Quebec	Glyphosate, brushsaw cutting, control	4 after cutting, 2 after planting	1, 2, 3	Growing season before treatment `	Intensive live- and pit trapping	Abundance, health, and fall population dynamics by species, foods eaten	Treatments did not affect species composition markedly. Deer mouse (*Peromyscus maniculatus*), red-backed vole (*Clethrionomys gapperi*), and common shrew (*Sorex cinereus*) were the most common (81% of total captures). During the 2 years after release, red-backed vole abundance decreased significantly in herbicide-treated plantations, but slowly increased in naturally regenerating cutblocks and brushsaw-cut plantations. Deer mouse abundance varied throughout the study. By 3 years after release, mouse abundance increased slightly in treated plantations but not in naturally regenerating cutblocks. Common shrew populations were not affected by treatment. Meadow voles (*Microtus pennsylvnicus*) were uncommon, but abundance of this vole increased soon after treatment, 1993 and 1994, and then decreased in 1995.
Lautenschlager *et al.* 1995	Northwestern Ontario	Glyphosate (operational and annual repeated), brushsaw cutting,	5 after cutting and planting (included some natural regeneration)	1, 2	Growing season before treatment	Intensive live-trapping, mark and release	Abundance, health, population dynamics by species	Red-backed vole, deer mouse, least chipmunk (*Tamias minimus*), and eastern chipmunks (*Tamias striatus*) accounted for 98, 95, and 92% of the total small mammals captured in 1992 (pre-treatment), 1993, and 1994, respectively. During the first and second year after treatment red-backed vole abundance was reduced but by 1994 vole abundance began increasing again in the operational glyphosate-treated plots. None of the treatments seemed to affect deer mouse abundance. Least chipmunk abundance was initially unaffected, but soon became greatest on the annual removal plots. Eastern chipmunk abundance was reduced by all conifer release treatments.

Table 5. Continued

Author and publication date	Location	Herbicide (s) or treatments studied	Treatment was – years after cutting or planting	Post-treatment years studied	Pre-treatment data collected	Survey method	Data collected	Major findings
Lautenschlager *et al.* 1997b, 1998	Northwestern Ontario	Glyphosate, triclopyr, brushsaw cutting, machine cutting, control, unharvested	3–7 after planting	1, 2, 3, 4	Growing season before treatment	Intensive live-trapping, mark and release	Abundance, health, and population dynamics	Shrew (primarily *Sorex* spp.) densities were unaffected by release. During the first year after release, red-backed vole densities were highest in control plots and lowest in glyphosate and triclopyr-treated plots but by the following year statistically significant differences disappeared. During the first 2 post-treatment years, deer mouse abundance was highest in machine cut plots; eastern chipmunk abundance was highest in glyphosate- and triclopyr-treated plots; and meadow vole abundance was highest in triclopyr-treated plots. Three and 4 years after treatment, small mammal populations had recovered from initial changes. During all years, however, red-backed voles maintained consistently larger populations in the unharvested forest (20/ha) compared with 13/ha in control, 10/ha in machine and brushsaw-cut, and 6/ha in herbicide released plots.
Runciman and Sullivan 1996	South-central British Columbia	Glyphosate, brushsaw cutting, control	2-7 after planting	1, 2	One year before treatment	Intensive live-trapping	Abundance, population dynamics	Neither brushsaw cutting nor cut-stump glyphosate-treatments significantly affected the population size of deer mouse, yellow-pine chipmunk (*Tamias amoenus*), red-backed vole, or long-tailed vole (*Microtus longicaudus*). Meadow vole response was variable. Throughout this study sex ratios, body weights, reproduction, recruitment, and survival of deer mouse remained similar in treated and control plantations.
Sullivan and Boateng 1996	Coastal and interior British Columbia	Glyphosate, broadcast burning, control	1 after cutting, 1 after burning and planting	1	One year before harvest, 2 years before treatment	Intensive live-trapping	Abundance by species	In the coastal study area, deer mouse populations declined for 1-2 months after treatment. On the interior sites, they seemed unaffected by treatment related habitat changes. Voles (*Microtus*) disappeared from burned blocks in the interior area but persisted in burned blocks in the coastal area. (Red-backed vole, however, did not persist.) Chipmunks seemed unaffected by burning or herbicide treatments, and neither treatment seemed to affect species diversity of the small mammal communities studied. Broadcast burning alters habitat more than herbicide treatment.

Table 5. Continued

Author and publication date	Location	Herbicide (s) or treatments studied	Treatment was – years after cutting or planting	Post-treatment years studied	Pre-treatment data collected	Survey method	Data collected	Major findings
Sullivan *et al.* 1997	Coastal British Columbia	Glyphosate (2 rates), control	8, 19 after planting	9, 11	One year before treatment	Intensive live trapping	Abundance and population dynamics by species	Average deer mice abundance was reduced during the first year after both June and September glyphosate treatments. Average abundance of Oregon vole (*Microtus oregoni*) was higher on glyphosate treated areas 9 and 11 years after treatment. Townsend chipmunk (*Eutamias townsendii*) was less abundant in treated than control areas 9 years after treatment but were absent from both control and treatment areas 11 years after treatment. There was a slight decrease in shrew (*Sorex* spp.) average abundance in treated vs. control areas following the June glyphosate treatment. During the decade following the glyphosate treatments reproduction, survival, and growth of deer mouse and Oregon vole was not affected and species richness and diversity changed little.
Sullivan *et al.* 1998a	Central British Columbia	Glyphosate, control	5–10 after cutting	1, 2, 3, 4, 5	One year before treatment	Intensive live trapping	Diversity	Diversity of plant and small mammal communities was maintained following treatment, hence treated sites may not lower forested landscape diversity.
Sullivan *et al.* 1998b	Central British Columbia	Glyphosate, control	5–10 after cutting	1, 2, 3, 4, 5	One year before treatment	Intensive live trapping	Population dynamics	Higher average abundance of red-backed vole ($P=0.03$) and shrews (*Sorex* spp.; $P=0.001$) were present on control than treatment sites. Average abundance of meadow voles ($P=0.69$) and deer mice ($P=0.20$) were similar on control and treatment sites throughout the study. Short-tailed weasels (*Mustela erminae*) and long-tailed weasels (*Mustela frenata*) were commonly captured on both control and treated sites. Body mass, total biomass, and proportion of adult male and female red-backed vole and deer mouse in breeding condition did not differ by treatment. However, red-backed vole had a higher ($P=0.02$) number of successful pregnancies than did deer mouse ($P=0.18$) in controls than treatment populations during post-treatment years. Mean Jolly-Seber estimates of survival of red-backed vole ($P=0.01$) but not deer mouse ($P=0.70$) were higher for treatment than control populations. Observed demographic effects from herbicide treatment were well within the mean values of natural fluctuations of these variables.

Table 5. Continued

Author and publication date	Location	Herbicide (s) or treatments studied	Treatment was – years after cutting or planting	Post-treatment years studied	Pre-treatment data collected	Survey method	Data collected	Major findings
Sullivan *et al.* 1998c	South-central British Columbia	Glyphosate, control	In 5 and 15 year old apple orchards	1, 2, 3	Growing season before treatment	Intensive live trapping	Population dynamics	Average abundance of montane voles (*Microtus montanus*) declined by 53% and 73% on treatment compared to control blocks after the first herbicide application. Vole populations were consistently reduced in response to the herbicide treatment; average abundance ranged from 2.8-28.0 times higher on control than treatment blocks. Average abundance of deer mice (*Peromyscus maniculatus*) ranged from 1.3 to 11.1 times higher, and that of northwestern chipmunks (*Eutamias amoenus*) ranged from 1.8 to 13.3 times higher, on treatment than control blocks. There were no significant differences in biomass of small mammals between control and treatment populations in summer and winter in two of the three orchards studied.

June treatment, and during the following year's growing season after the September treatment. When compared to untreated areas, average Oregon vole abundance was higher in the glyphosate-treated blocks both nine and 11 years after treatment. Townsend chipmunk was less abundant in treatment than control areas nine years after treatment, but was absent from both control and treatment areas 11 years after treatment. Average shrew (*Sorex* spp.) abundance decreased slightly during the year after the September glyphosate treatment but not the June treatment; by nine and 11 years after treatment, shrew numbers were as great or greater on treated than control areas. During the decade following treatment, glyphosate did not adversely affect reproduction, survival, or growth of deer mice and Oregon voles in coastal forests, and species richness and diversity changed little.

In a study in sub-boreal spruce forests Sullivan *et al.* (1998a) reported that a single glyphosate treatment generally did not lower small mammal diversity in a forested landscape, but Sullivan *et al.* (1998b) reported that a single treatment reduced abundance of shrews and red-backed voles, while meadow vole and deer mouse populations were unaffected. Although body mass, total biomass (all species), and the proportion of adults in breeding condition did not differ between control and glyphosate-treated areas, female red-backed voles were gravid in control plots more often than in glyphosate-treated plots (Sullivan *et al.* 1998b). Weasels (*Mustela* spp.) were commonly captured in both glyphosate-treated and control plots, suggesting that populations of these carnivores were unaffected by a glyphosate treatment.

Sullivan *et al.* (1998c) reported average abundance of montane vole (*Microtus montanus*) declined 53% to 73% in treatment compared to control blocks after glyphosate broadcast and strip-treatments were applied to apple orchards. However, deer mouse and northwestern chipmunk populations were either unaffected or increased significantly following these treatments. Interestingly, this compensatory response —fewer voles but more mice and chipmunks—resulted in orchards having similar total small mammal biomass in treated and control areas. Compensatory response has not been discussed by other authors, but it also may occur in other habitats including forests.

Sullivan *et al.* (1998b) assessed the biological significance of variations in red-backed vole and shrew populations between control and treated areas. The mean changes in abundance and 95% confidence intervals were considerably smaller for the control/treatment comparison than for annual changes in control populations. Gagné *et al.* (1999) also found that a glyphosate treatment did not affect small mammal species composition markedly. However, during three years after treatment, red-backed vole numbers decreased in herbicide-treated plots but increased in plots located in naturally regenerated and brushsaw-cut plantations. In a three-year study, Cole *et al.* (1998) found that applying glyphosate after cutting and burning did not affect capture rates of the common small mammals, including shrews. Small mammal responses to cutting and burning depended on species-specific habitat preferences.

In a minimally replicated, partially retrospective study, Santillo *et al.* (1989) reported that for three years after treatment, insectivores (primarily the common shrew) were less abundant on glyphosate-treated than control plots. Sullivan *et al.* (1998b) and Gagné *et al.* (1999) also found fewer shrews (*S. monticolus* and *S. cinereus*) in glyphosate treated regenerating forest habitats. However, such differences were not observed when shrews were caught both before, and for two years after a variety of conifer release alternatives were applied in regenerating spruce plantations (Lautenschlager *et al.* 1997b) or in Douglas-fir plantations (Sullivan *et al.* 1997). Although results from these and previous studies differ, it seems that shrew abundance sometimes decreases slightly following conifer release treatments. Those reductions are likely caused by cover reductions, associated microclimate changes (increased near-ground temperatures and decreased relative humidity) (Reynolds *et al.* 1997), and/or changes in available food (Gagné *et al.* 1999).

Studies reviewed previously (Lautenschlager 1993a) have consistently found increases in mouse and chipmunk (except eastern chipmunks) abundance and decreases in red-backed vole numbers for as long as two years after treatment. By the third year after treatment, most populations in herbicide-treated plantations have recovered. Complete recovery seems to occur more quickly on richer than on poorer sites (comparing results from Lautenschlager *et al.* 1997b and Lautenschlager *et al.* 1995, respectively). Species-specific responses of small mammals to treatment have been attributed to changes in near-ground humidity associated with vegetation reductions, although changes in microclimate and vegetation (food and cover) are difficult to separate.

Direct Effects of Herbicide Use

Small mammals may ingest treated vegetation (seeds, fruits, vegetative parts) or invertebrates that contain residues or be contacted directly by a herbicide during application. However, significant direct contact seems unlikely because many small mammals forage and rest in or below the leaf litter on the forest floor and the bulk of the spray solution is intercepted by the vegetation above that strata, overstory trees, shrubs, and herbs (Thompson *et al.* 1997). Nevertheless, low-level herbicide residues have been found, at levels below those associated with vegetation, in omnivorous and herbivorous mammals soon after treatment (Newton *et al.* 1984). Therefore, forest herbicide treatments could directly affect small mammal demographic parameters.

Few studies, however, have examined the direct effects of herbicides on small mammals. Wahlgren (1979) reported that glyphosate had no adverse effects on reproductive parameters in laboratory mice. Similarly, Newton and Dost (1981, 1984) reported that glyphosate did not affect reproduction in laboratory rats. In field studies, glyphosate had no effects on demographic parameters of a deer mouse population in the first year after treatment (Sullivan and Sullivan 1981), and it did not bioaccumulate in mammals (Newton *et al.* 1984). Sullivan (1990b) assessed growth and survival in control and treatment populations of deer mice and Oregon voles over a five-year period in a coastal coniferous forest and found no direct effect on metabolic or general physiological processes associated with the development of young small mammals. Physiological changes that might have resulted from glyphosate exposure or ingestion were not apparent in demographic attributes at the population level. In a study in an interior cedar-hemlock forest, reproduction, recruitment, body weights, and survival of deer mice were similar in control and glyphosate treatment areas in the two post-treatment years (Runciman and Sullivan 1996).

Sullivan *et al.* (1998b) investigated potential long-term direct effects of glyphosate in sub-boreal spruce forests. They found that deer mouse and red-backed vole populations in control and treatment areas had similar body mass, total biomass, and proportion (adult males and females) in breeding condition. During the post-treatment years, red-backed voles in control areas had a higher average number of successful pregnancies than those in treated areas. However, estimates of red-backed vole survival were higher in treatment populations, potentially explaining increased vole pregnancies in control areas. The magnitude of observed demographic effects from herbicide treatment on these small mammal species were well within the mean values of natural fluctuations of these variables (Sullivan *et al.* 1998b).

In an unpublished report, McComb *et al.* (1997) compared intraperitoneal LD_{50} for glyphosate in four wild mammal and five wild amphibian species with lab mice (*Mus musculus*). They concluded that rats seem to be adequate models for seven of the nine species. LD_{50}s were >800 mg/kg, or about 165 times higher than a dose likely to be received by these species after field applications. Rough-skin newts (*Taricha granulosa*) and Townsend chipmunks (*Tamias townsendii*) given sub-lethal doses of glyphosate were marked with radio transmitters and released into unsprayed habitat. Individuals of both species had the same survival and movement patterns as those given a control dose.

Mid-Sized and Large Mammals (Table 6)

Snowshoe Hare

The snowshoe hare (*Lepus americanus*) is a common mid-sized mammal occupying early- to mid-successional boreal and boreal mixedwood forests across northern North America. In Europe, the "blue" or mountain hare (*L. timidus*) also prefers forested areas (Walker *et al.* 1968) and occupies a similar niche to the snowshoe hare. Hares are an important food source for a variety of terrestrial and avian carnivores (Walker *et al.* 1968, Kurta 1995) that may occupy or be found near treated sites. Understory vegetation density, softwood or hardwood, rather than food supply seems to limit hare populations (Wolff 1980, Litvaitus *et al.* 1985). However, "dense softwood understories support hare densities greater than do (similar aged) hardwood stands because softwoods provide hare with superior cover from predators and climatic extremes" (Litvaitus *et al*. 1985). So, although successful conifer release treatments should improve snowshoe hare habitat in the short- and longer-term, the possibility exists that they could reduce the carrying capacity of treated sites for hare.

Hjeljord *et al.* (1988) and Hjeljord (1994) reported that hare use of treated areas decreased during the first year after a glyphosate treatment, but during the next eight years hare use did not differ from their use of untreated controls. Litvaitus *et al*. (1985) stated that northern conifer forests are colonized by hare six or seven years after cutting and reach peak population levels 14–18 years later. Sullivan (1994, 1996) documented effects on snowshoe hare populations of conifer release of areas that were unsuccessfully regenerated, from one to two decades previously (backlog areas). He concluded that: 1) herbicide-induced alteration in these areas did not affect abundance, reproduction, growth, and survival of snowshoe hare, and 2) backlog areas, 14–21 years after harvest, particularly those with a high component of coniferous species, maintained a vegetative structure sufficient to support hare populations (and presumably associated carnivores) regardless of treatment.

Although limited studies reviewed by Lautenschlager (1993a, b) have suggested that conifer release treatments applied to young regenerating stands can reduce their carrying capacity for hare, previous research as well as recent work by Potvin *et al*. (1999) and de Bellefeuille *et al.* (2001) found that snowshoe hare avoid recently clearcut areas. Seemingly because of that, de Bellefeuille *et al.* (2001) found no difference in hare use between treatments [naturally regenerated (controls) and plantations released with either brushsaws or glyphosate herbicide] applied to early successional conifer stands in south-central Quebec. Therefore, research findings suggests that neither treatments designed to promote conifer survival and growth (applied soon after establishment) nor treatments designed to release conifers planted 10–20 years previously are likely to reduce stand-level hare populations.

Still, because of the large number of variables involved, stand- and landscape-level responses may be dramatically different, particularly for a cyclic animal like snowshoe hare. When snowshoe hare populations are high, dispersing individuals would likely use most available habitats regardless of quality, and when populations are low, they would likely occupy only the most preferred habitat. In many northern landscapes dominated by recent clearcuts preferred habitat seems to develop starting 10–15 years after clearcutting (Litvaitus *et al.* 1985, Potvin *et al.* 1999) and to be associated with two- to five-meter tall regenerating softwood stands (de Bellefeuille *et al.* 2001). Because conifer release treatments are designed to ensure the development of these and older conifer stands it seems likely that the most effective treatment (herbicide) is likely to benefit snowshoe hare populations, and those of associated carnivores, to a greater extent than no treatment.

Deer and Moose

Earlier reviews that examined information about the effects of herbicide treatments on deer and moose focused on studies of browse availability and habitat use (Lautenschlager 1986, 1991, 1992, 1993a,b). In general, deer seem unaffected by herbicide treatment while moose consistently reduce their use of treated areas during the first three to five years after treatment (Lautenschlager *et al.* 1999). Several recent studies confirm these results.

Trichet *et al.* (1987) concluded that although bramble (*Rubus fruticosus*), a staple winter food of roe deer (*Capreolus capreolus*), was controlled by a herbicide application, the treatment did not change the intensity of area use and browsing pressure became somewhat greater in treated plots. Where bramble was successfully controlled deer densities remained high because deer ate other shrubs. Once brambles recovered (four to five years after treatment), deer demonstrated no preference for either glyphosate-treated or control areas.

Gourley *et al.* (1990) reported that anti-browsing treatments (structural and chemical, e.g., protective netting, and a repellent, Deer Away®) provided no growth advantage to planted Douglas-fir, while some of the treatments actually reduced Douglas-fir growth. In contrast, competition control with glyphosate consistently improved Douglas-fir growth, and by the fifth post-treatment year, planted fir averaged twice the biomass of control trees regardless of the degree of browsing by black-tailed deer (*Odocoileus hemionus*) and elk (*Cervus canadensis*).

The influence of conifer release with glyphosate on summer forage for white-tailed deer (*O. virginianus*), one and seven to ten years after treatment, was evaluated by Vreeland *et al.* (1998) in northwestern Maine. They found that the abundance of leaves of deciduous trees and shrubs was 3.4 times greater on untreated than treated sites one year after treatment, but similar seven to ten years after treatment. Forb abundance was similar on treated and untreated sites one year after treatment, but 2.0 times greater on treated sites seven to ten years after treatment, when total forage availability was 1.2 times greater on glyphosate treated sites. They concluded that although glyphosate initially reduced the abundance of deciduous trees and shrubs, the longer-term positive effect on forbs may result in little net change in overall habitat value for deer.

Collectively, these studies and an earlier study by Sullivan (1985), suggest that deer use of regenerating conifer stands is not reduced by release treatments. That is probably because deer feed extensively on herbs (Crawford *et al*. 1993), which generally increase in abundance following herbicide treatments.

Much of the recent research into effects of herbicide treatments on moose has examined forage quality (Cumming *et al.* 1995, Raymond *et al.* 1996, Raymond and Servello 1997). Results have indicated that dormant-season forage quality is not affected by conifer release with herbicides. Cumming *et al.* (1995) also reported no differences in digestible protein (DP) or digestible dry matter (DDM), for growing season forage, between herbicide-treated and control plots four and eight years after treatment. However, their data indicate that in treated portions of their eight-year-old study area, DP of trembling aspen was 6% higher, willow (*Salix* spp.) was 26% higher, and red raspberry was 51% higher. Forage quality was similar among treatments (varying glyphosate rates) in a four-year-old study area of lower site quality.

Interestingly, earlier work by Morgan and McCormack (1973) found that two years after balsam fir (*Abies balsamea*) transplants were treated with simazine to control surrounding competing vegetation, treated transplants had approximately twice the crude protein and higher ash and moisture levels than did control and fertilizer-treated transplants. This increased nutrition could make treated plants more susceptible to browsing (Morgan and McCormack 1973). However, in Oregon, Gourley *et al.* (1990) found that five years after glyphosate treatment, planted Douglas-fir volume production was actually 33–50% greater than on untreated plots, regardless of treatments designed to reduce deer and elk browsing.

Raymond *et al.* (1996) found that, one to two years after glyphosate treatment, biomass and percent of available deciduous browse eaten by moose were reduced significantly relative to untreated controls. However, seven to eleven years after treatment, both were four to five times greater on treated than untreated clearcuts. Dormant season digestible energy and protein content of moose diets on clearcuts were not significantly affected by treatment. The authors concluded that initial forage reductions may decrease the suitability of clearcuts for moose, but this effect decreases during the next five to nine years as browse availability decreases naturally on untreated sites.

Raymond and Servello (1997) studied red maple (*Acer rubrum*) dormant-season twigs and found that neutral and acid detergent fibre concentrations were 18% less and lignin-cutin was 8% greater in twigs from herbicide-treated areas than those from untreated areas. Predicted digestible dry matter and digestible energy values were 7% greater in glyphosate injured (but not killed) than uninjured twigs. Crude protein concentrations

Table 6. Overview of studies that documented effects of herbicides on large mammals in northern forested ecosystems

Author and publication date	Location	Herbicide (s) or treatments studied	Treatment was – years after cutting or planting	Post-treatment years studied	Pre-treatment data collected	Survey method	Data collected	Major findings
Cumming *et al.* 1995	Northwestern Ontario	Glyphosate, control	3–7	4, 8	None	Vegetation collected from treatment and control areas	Quality of leaves (summer), twigs (winter) of aspen, hazel, raspberry, and willow	Forage quality varied significantly among blocks and species. Digestible protein varied between study areas in summer, but no significant differences were detected between treated and control plots either 4 or 8 years after treatment. Summer forage from treated portions of the 8-year-old study area had consistently higher values for digestible protein. Still, results suggest that any long-term effects of conifer release with glyphosate are more likely to be quantitative than qualitative.
de Bellefeuille *et al.* 2001	South-central Quebec	Glyphosate, brushsaw, control	12 cutting, 2 planting	1, 2, 3	2	Vegetation and area use (pellet counts and telemetry)	Summer and winter foods and habitat use	Clearcut sites in the area require 10 years to reach the sapling stage, which is preferred by snowshoe hare. The sites studied were in the seedling stage 7–9 years after cutting and hares avoided them year round because of inadequate cover. Therefore, conifer release treatments (glyphosate, brushsaw) did not affect habitat use by hare. The unharvested forest and forest edge was the focus for the bulk of hare use during what seemed to be a low in the local snowshoe abundance cycle.
Eschholz *et al.* 1996	Northwestern Maine	Glyphosate, control	5–8	1, 2; 7-11	Vegetation – growing season before treatment	Aerial and ground surveys of tracks, pellet groups, and beds	Winter exam of numbers of tracks pellet groups and beds	One and 2 years after treatment, tracks of foraging moose were 57 and 75% fewer in glyphosate-treated than in control areas, respectively. Counts of beds, tracks, and pellet groups also decreased after the glyphosate treatment. By 7–11 years after treatment, tracks of foraging moose and beds were greater in glyphosate-treated, where conifers were 2 times more abundant, than in untreated clearcuts. The increased use of older treated clearcuts seemed associated with increased foraging where conifer cover was abundant.
Gourley *et al.* 1990	Oregon Coast Range	Protection from browsing (physical - several approaches; chemical repellents; none) with and without glyphosate weed control	Unknown	5	Seedling size at planting	Visual examination of individual trees by treatment type	Damage (browsing, treatment), mortality (seedling or top), by treatment and location	After 5 years, none of the protective treatments provided growth advantages, some caused growth losses. In contrast, weed control, with or without additional protective measures, consistently improved growth. By the fifth year, weeded trees averaged twice the biomass of unweeded trees, regardless of browsing. Average tree size was largest in the herbicide-treated area lacking browsing barriers. Advantages of competition control were greatest on the poorest site. Competition control plus large transplant size seemed to effectively prevent most loss due to damage from deer browsing.

Table 6. Continued

Author and publication date	Location	Herbicide (s) or treatments studied	Treatment was – years after cutting or planting	Post-treatment years studied	Pre-treatment data collected	Survey method	Data collected	Major findings
Hjeljord 1994	Southern Norway	Glyphosate, control	Unknown	9	Unknown	Permanent plots examined annually	Hardwood cover, pellets (moose and hare)	Nine years after spraying there were fewer hardwood trees and associated shoots in treated areas. Ash (*Sorbus aucuparia*) almost disappeared from sprayed sites, while on control sites, heavy moose browsing prevented ash from growing taller. Therefore, 9 years after treatment, birch (*Betula* spp.) dominated both sprayed and control sites. During the first year after treatment, hare use of glyphosate-treated sites decreased but thereafter it did not differ from use of control sites. However, moose use of glyphosate-treated sites was lower for 8 of the 9 years studied.
Kelly *et al*. 1998 (summary); initially reported by Kelly and Cumming 1992, 1994	Northwestern Ontario	Glyphosate (3 rates), control @ Raith, glyphosate, control @ Obonga	4 planting (Raith), 1-9 planting (Obonga)	1, 2, 3, 4 (Raith); 1, 8 (Obonga)	Growing season before treatment, Raith only	Sample plots located systematically along transect lines	Available browse and pellet groups	At Raith, browse availability decreased, for 3 years following the herbicide treatments. During that time browse density was 3 times greater in control areas. Browse densities in treated areas began to increase 4 years after treatment; however total live stem density in control areas remained nearly double that in areas treated at the lowest glyphosate rate and about 3 times greater than that on areas treated at the two higher rates. Browsing in control area was 3 times greater than in areas treated at the lowest rate and 6 times greater than in areas treated at the 2 highest application rates. At Obonga, pre-treatment browse densities were twice as great on glyphosate-treated areas compared with control areas, but 1 and 8 years after treatment live stem density was similar on both areas. Comparative use, as measured by pellet groups, declined from 3 times more on glyphosate-treated areas before treatment to three-quarters of the use of glyphosate-treated areas 8 years after treatment.
Lautenschlager *et al*. 1999	Northwestern Ontario	Glyphosate, triclopyr, brushsaw cutting, machine cutting, control	3–7 after planting	2	None	Mid-July collection of aspen, hazel, and raspberry leaves	Analysis of forage samples via standard detergent techniques, tannins via bovine serum albumin	Two years after release, trembling aspen (*Populus tremuloides*) digestible dry matter, during July, was 5 to 11% greater in released plots than in control plots. However, release had no significant effect on forage quality of beaked hazel (*Corylus cornuta*) and red raspberry (*Rubus ideaus*). Moose winter use of the study area decreased during the first and second winter after release treatments were applied but has increased gradually since.

Table 6. Continued

Author and publication date	Location	Herbicide (s) or treatments studied	Treatment was – years after cutting or planting	Post-treatment years studied	Pre-treatment data collected	Survey method	Data collected	Major findings
Raymond *et al.* 1996	West and west-central Maine	Glyphosate, control	5–8	1, 2; 7-11	Collected by (Eschholz *et al.* 1996)	Twig counts (on quadrats randomly located on transects systematically placed into treated and control areas), forage collection	Availability of deciduous and balsam fir; digestible energy and protein of collected browse	One to 2 years after treatment biomass and percent of available deciduous browse eaten by moose were significantly reduced by the glyphosate treatment, but 7–11 years after treatment biomass and browse eaten were 4–5 times greater on treated than untreated clearcuts. Digestible energy and protein content of browse eaten in clearcuts was not significantly affected by the glyphosate treatment either 1–2 or 7–11 years after treatment. Initial reductions in browse availability decreased the suitability of treated clearcuts for moose, but this effect declined during the next 5–9 years as browse availability decreased naturally on untreated sites. Moose fed heavily in older treated clearcuts but the attraction seemed related more to cover than to browse availability or nutrition.
Raymond and Servello 1997	North-central Maine	Glyphosate, control	5–6 after cutting	1	NA	Herbicide treated areas containing injured red maple (*Acer rubrum*) and paper birch (*Betula papyrifera*) stems, similar stems selected from control areas	Forage quality via standard detergent techniques and adjusted based on fibre analyses and equations developed for white-tailed deer	For red maple, neutral and acid detergent fibre concentrations were 18% less and lignin-cutin was 8% greater in glyphosate injured twigs. Predicted digestible dry matter and digestible energy values were 7% greater in injured twigs. Crude protein concentrations were low in red maple overall, but were greater in injured twigs. In contrast, for injured paper birch twigs acid detergent fibre concentrations were 6 and 8% greater and digestible dry matter and digestible energy values were 8-11% less and lignin-cutin concentrations were greater. Injury in paper birch did not affect crude protein content. While measurable effects on nutritional quality of browse exist, absolute differences were generally small and may not represent important effects on diet quality of moose.

Table 6. Continued

Author and publication date	Location	Herbicide (s) or treatments studied	Treatment was – years after cutting or planting	Post-treatment years studied	Pre-treatment data collected	Survey method	Data collected	Major findings
Sullivan 1994, 1996	Central British Columbia	Glyphosate, control	9–21 after cutting	1, 2, 3	One year before treatment	Intensive live trapping	Abundance and population dynamics	Herbicide-induced alteration of optimum habitat did not affect snowshoe hare abundance. Post-harvest forest habitats (10–20 years), particularly those with a significant conifer component, may have sufficient and persistent vegetative structure to support hare populations regardless of herbicide treatment. The proportion of adult hares in breeding condition and number of successful pregnancies showed no consistent differences between control and treatment populations. Recruitment was generally similar, except for significantly more juvenile females entering the control population in one study area. In a second study area, total recruitment was significantly higher in the treatment area during the 3 post-treatment years studied. Survival in control and treatment populations differed little. Lack of significant differences in mean body mass and growth rates indicated that the herbicide treatment had little or no effect on young-hare and that comparable levels of hare biomass were available as prey for predators.
Tricket *et al.* 1987	Northeastern France	Glyphosate, control	NA	5	None	Visual analysis	Vegetation cover percentage, browse use	Herbicide treatment did not change the intensity of roe deer (*Capreolus capreolus*) use (6–10 animals/ha) of treated areas. Browsing pressure increased somewhat in treated plots. Where brambles (*Rubus* spp.) were reduced by 80%, and deer population densities were high, deer ate shrubs instead of brambles. However, this phenomenon did not persist long; by 4 to 5 years after treatment, brambles recovered and deer seemed not to distinguish between control and herbicide-treated plots.
Vreeland *et al.* 1998	Northwestern Maine	Glyphosate, control	6-8 after cutting and 6-14 after cutting	1; 7–10 retrospectively	None	Visual estimates of cover percentages	Cover percentages of leaves (trees, shrubs, forbs, ferns, and grasses	Leaves of deciduous trees and shrubs were 3.4 times greater on untreated than glyphosate treated sites one year after treatment, but similar on untreated and treated sites 7–10 years after treatment. Forb coverage was similar on untreated and treated sites one year after treatment, but 2.0 times greater on treated sites 7-10 years after treatment. Total summer forage availability was 1.2 times greater on glyphosate-treated sites than untreated sites 7–10 years after treatment. The positive response by forbs suggests that white-tailed deer summer forage is affected little by an operational glyphosate treatment.

were low in red maple overall but were greater in injured than uninjured twigs. Analysis of dormant-season paper birch (*Betula papyrifera*) twigs showed that injured twigs had neutral and acid detergent fibre concentrations that were 6 and 8% greater and digestible dry matter and digestible energy values that were 8–11% less in injured twigs. Lignin-cutin concentrations were greater in injured twigs, and crude protein content was not affected by injury. The authors concluded that while measurable effects on nutritional quality of browse existed, absolute differences generally were small and not biologically significant.

Two years after several conifer release alternatives were applied, Lautenschlager *et al.* (1999) examined DP and DDM of quaking aspen, hazel (*Corylus cornuta*), and red raspberry foliage collected during July. Only trembling aspen, which had the highest DDM and DP of the species examined, showed statistically significant differences among treatments. Aspen DDM was five to eleven percent and DP was 34–49% greater in released plots than in control plots (Lautenschlager *et al.* 1999). Although not statistically significant, DP also was consistently higher for hazel and red raspberry in released plots. However, the lack of statistically significant differences in DDM and DP among treatments for two of the three species examined suggests that, through time, biomass availability of forage species continues to be a realistic way to predict the effects of conifer-release treatments on forage (Lautenschlager *et al.* 1999).

Stand-level reductions in forage biomass availability (commonly 50–70% during the first year after treatment – Newton *et al.* 1987; Kelly and Cumming 1992,1994; Raymond *et al.* 1996, Kelly *et al.* 1998) and reductions in habitat use by moose have consistently followed conifer release treatments (Lautenschlager 1992, Lautenschlager *et al.* 1999). Most studies confirm that those reductions persist up to four years after treatment. However, Kelly *et al.* (1998) suggested that on some sites in northwestern Ontario, forage availability and habitat use reductions may continue through eight years after treatment. Eschholz *et al.* (1996), and Raymond *et al.* (1996), using a combination of designed and retrospective studies, reported that biomass of deciduous browse eaten by moose and habitat use during winter decreased soon after glyphosate release treatments, while seven to eleven years after treatment, availability increased in treated clearcuts. Raymond *et al.* (1996), who found heavy browsing in older treated areas, concluded, as did Lautenschlager (1986, 1993a, b) and Newton *et al.* (1989), that those areas were more attractive to moose than control areas. However, Raymond *et al.* (1996) suggested that the attraction likely was related more closely to the successful establishment of conifer cover than to the availability or nutritional content of the browse.

Studies from Maine (Newton *et al.* 1989, Eschholz *et al.* 1996, Raymond *et al.* 1996, Vreeland *et al.* 1998), however, may not be comparable to studies elsewhere in the North because much of that research has been conducted in naturally regenerated early-successional spruce-fir stands. Studies in other northern areas are commonly conducted in plantations, which tend to receive greater silvicultural attention and be released sooner than naturally regenerated stands. The biomass of competing vegetation in young naturally regenerated stands generally is older, greater, and more difficult to control. Thus, conifer release in plantations may not consistently lead to the longer-term increased area use by moose documented for naturally regenerated conifer stands.

Palatability, Forage Consumption, and Meat Quality

A concern of those who gather meat from wild sources is its potential contamination. Meat consumption could potentially pose a health risk to humans if wild game consumed herbicide-treated forage and retained significant percentages of the active ingredients in tissues normally consumed by hunters and their families.

Results to date indicate that animals do not avoid herbicide-treated forage. Sullivan and Sullivan (1979) fed captive black-tailed deer both control and glyphosate-treated forage and found that deer showed no preference. Campbell *et al.* (1981) found that when glyphosate was applied at silviculturally effective rates, black-tailed deer did not avoid treated foliage. Jones and Forbes (1984) reported that treating forage with glyphosate had no significant effects on use by domestic sheep (daily intake, mean meal size, or consumption rate). Lloyd (1989) reported that moose eat herbicide-damaged plants when damage is light or moderate but do not browse severely damaged or dead plants. Because large wild animals will consume treated forage, secondary effects on humans must be considered.

In a study of the fate of glyphosate in a forest ecosystem, Newton *et al.* (1984) concluded that exposure of mammalian herbivores, carnivores, and omnivores varied with food preferences. However, all species examined by Newton *et al.* (1984) had visceral and body contents of glyphosate at or below observed levels in ground cover and litter. This suggests that glyphosate does not accumulate in higher trophic levels. Brewster *et al.* (1991) documented metabolism of glyphosate in rats fed 10 mg/kg body weight and found that 35–40% of the administered dose was absorbed from the gastrointestinal (GI) tract; while 60–65% was initially eliminated via urine and faeces. They also reported that any residue in the body after seven days (approximately 1% of the administered dose) was associated with bones. Because there was little evidence of metabolism, Brewster *et al.* (1991) concluded that virtually no toxic metabolites of glyphosate were produced.

Legris and Couture (1991) examined flesh samples from snowshoe hare, white-tailed deer, and moose harvested inside or close to areas that had been treated with glyphosate approximately two months before sampling. Although 0.146 μg/g was found in one sample of moose flesh, the authors concluded that this was likely due to contamination, because the 31 other samples showed no detectable residues. Based primarily on data from snowshoe hare, they concluded that glyphosate ingested with vegetation was mainly eliminated through the urinary and faecal tracts, and that consuming meat or organs such as liver of animals that have fed in or near treated areas poses little risk to humans.

These findings, along with the recent registration by Health/Agriculture Canada of Roundup® (the formulated glyphosate product used in agriculture which is nearly identical to the product registered as Vision® for forestry use) for preharvest forage and cereal grain desiccation treatments (Roundup® label) demonstrate that there are no science-based health concerns associated with eating wild animals that may have consumed glyphosate-treated vegetation, domestic animals fed treated agricultural forage, or cereal grain following treatment.

Landscape-Level Considerations

After cutting, forests are generally regenerated, either naturally (seeds or sprouts) or artificially (planting). Clearcutting

Table 7. Annual average area of forest affected by different disturbance types in New Brunswick, Ontario, and British Columbia

Disturbance	New Brunswick	Ontario	British Columbia
Clearcut (ha)[1]	81 632.5	191 642.8	195 651.6
Fires (ha)[1]	6 116.4 (7% of cut)	188 348.4 (98% of cut)	49 561.3 (25% of cut)
Insects defoliation[1] (moderate to severe (ha)	459.3 (0.5% of cut)	17 651.8 (9.2% of cut)	728.5 (0.3% of cut)
Site Preparation[2] (Total – burn, mechnical, and other)	10 673.5 (13.1% of cut)	91 788.0 (47.9% of cut)	151 825.5 (77.6% of cut)
Weeding and cleaning[2]	12 572.8 (15.4% of cut)	78 984.0 (34.2% of cut)	29 380.0 (16.3% of cut)

[1]For 1985 to 1994.
[2]For 1993 to 1994.
Source: CCFM 1995b.

continues to be the most commonly used method of harvesting even-aged forests in Canada (CCFM 1995b, Potvin *et al.* 1999), and it has been recognized as "an acceptable timber management practice for the boreal forest" (Koven and Martel 1994). Herbicide use commonly follows clearcutting. Both cutting and herbicide use are stand-level treatments that affect vegetation (species, abundance, structure), and associated biotic and abiotic components on sites. Landscape consequences of stand-level treatments are the sum of those effects plus the result of the character, extent, and interactions with landscapes around them (context). Consequences for specific components and systems increase as treatment size and related influences increase (Allen and Hoekstra 1992), but are modified by context.

Extensive efforts, such as planting and tending, are often required to replace harvested forests with pre-harvest forest types. Historically, in northern ecosystems, regeneration efforts were non-existent; although they are now more common, they are often incomplete or insufficient (Lautenschlager 2000). As a result, and because of changes in wildfire frequency and intensity, the composition of northern forests has changed from conifer dominated to mixed-wood or intolerant hardwood dominated (Carleton 2000, Lautenschlager and Voigt 2001). The problem is not that those forests have been harvested, rather regeneration following harvesting seems to be unlike that which followed the natural disturbances. Serious effort is required if managers hope to maintain conifers across harvested northern landscapes. That effort, however, has commonly been insufficient. For example, in 1993 and 1994, only 22% of clearcut forested land in Canada was "weeded and cleaned" using herbicides (CCFM 1995b). Still, even those efforts have not always resulted in successful conifer re-establishment. Hearnden *et al.* (1992) examined areas that were clearcut between 1970 and 1990 in Ontario and found major conversions from previously conifer-dominated to hardwood-dominated stands, even after the clearcuts were planted or seeded with conifers and many were released with herbicides.

Carleton (2000) summarized the survey by Hearnden *et al*. (1992) and his own work in northeastern Ontario and concluded that selective logging has led to an increase in shade-tolerant tree species and a decline in pioneer conifers while clearcut logging has converted forests dominated by pioneer, fire-tolerant conifers to those dominated by pioneer, fire-tolerant, broadleaved tree species. Interestingly, this loss of conifers has been documented in Ontario, a province where herbicides are used extensively (Table 7). For instance, in 1994, Ontario treated nearly as many hectares with herbicides as all other Canadian provinces combined (CCFM 1995b). The loss of conifers across northern ecosystems would undoubtedly be greater if herbicides were not used; however, it has been documented wherever forests have been harvested in the north (Harvey and Bergeron 1989, Kuhnke 1989, Drapeau *et al.* 2000, Lautenschlager and Voigt 2001). A variety of approaches, including planting larger stock and planting immediately after harvesting as well as earlier release with an appropriate herbicide to ensure conifer survival and growth could reverse this trend in the future.

In addition to human-caused disturbances, like cutting and herbicide treatments, fires, insect damage, and disease affect stands and landscapes. Although commonly human-caused, fire is the natural disturbance cited as the major factor shaping landscape development in the north (Holling 1973, Heinselman 1981, Johnson 1992). However, the ecological consequences of many of the fires that burn today seem unlike those of fires that burned in the past. This may be because previously common low intensity ground fires are now often successfully suppressed and decades of suppression has led to an abundance of fuels, and related higher intensity fires. Fires presently affect differing percentages of forested land across Canada. Each year, fire occurs on an equivalent of approximately 25, 100, and 7% of the area harvested in British Columbia, Ontario, and New Brunswick, respectively (Table 7).

Compared with fire, insect defoliation, the other commonly cited natural disturbance agent affecting northern ecosystems, affects much less of the Canadian landscape. Although western pine beetle (*Dendroctus ponderosae*) is presently decimating parts of British Columbia and the eastern spruce budworm caused extensive damage to New Brunswick forests in the past, insect defoliation seems to have played less of a role in British Columbia and New Brunswick, recently, where an average of 0.3% and 0.5%, respectively, of the area clearcut annually is defoliated, than in Ontario, where 9% is defoliated (Table 7). Like the interaction between fire suppression and the destructiveness of today's fires, decades of forest harvesting coupled with insect and fire suppression have also likely altered the ecological consequences of present-day insect outbreaks at stand and landscape scales.

Clearly, vegetation responses to any disturbance, including silvicultural treatments, like cutting and conifer release must be documented at the stand level. But, meaningful conclusions come only from placing those responses into an increasingly broader-scale context (Flather and Sauer 1996, Bissonette 1997). Although a limited number of ecological studies have recently attempted to document landscape-level effects of forest management on key biotic components (e.g., Potvin *et al*. 1999, Mitchell *et al*. 2001), those studies seldom examine effects of clearcutting per se and have not examined effects of herbicide treatments. In addition, studies have seldom attempted to put effects of either clearcutting or conifer release with herbicides into context much beyond the local landscape. Therefore, studies that attempt to draw broader-scale conclusions relative to effects of herbicide treatments on biota are of interest.

After examining 156 cutblocks (totalling approximately 10 000 ha) harvested in north-central British Columbia between 1970 and 1988, Lloyd (1994), in an unpublished report, attempted to draw such conclusions. Of the blocks examined, two thirds were treated (or planned for treatment) in whole or in part with glyphosate. Therefore, one might conclude that about two thirds of the recently cut landscape of northern British Columbia, receives a herbicide treatment. However, the Canadian Council of Forest Ministers (1995b) *Compendium of Canadian Forestry Statistics* shows that in British Columbia and across Canada (the broader, and much broader context, respectively) the percentage of clearcuts treated with herbicides tends to be much lower. Indeed, British Columbia treated (weeding and cleaning) only about 16% of the forest land clearcut annually from 1984 to 1994 (Table 7). In addition, in the area examined by Lloyd (1994), during the last seven years, only about 22% of clearcuts were released, about a third (9%) with herbicides (Lautenschlager, unpublished notes). Therefore, in that area less than one quarter of the cut area is released and less than one tenth is released with herbicides.

At broad scales, Canadian forests continue to regenerate after a combination of human- and natural-caused disturbances, but the escalating loss of conifers from these ecosystems is socially and ecologically troubling. Even as our climate seems to change (Parker *et al*. 2000), many argue that efforts should be made to maintain functioning ecosystems similar to those that were found historically across landscapes (Brown *et al*. 2001). Such maintenance, however, will require developing replacement stands of appropriate species and structures that provide acceptable, potentially historical, forest cover patterns. Successful conifer re-establishment is based on an interaction among stocking, treatment efficacy, and site quality (Lautenschlager 1993a, b). At the stand level, complete success at re-establishing conifers has been unusual (Frisque *et al*. 1978, Kuhnke 1989, Hearnden *et al*. 1992, Carleton 2000). That establishment, however, it is often a legal requirement and may be the most rapid way to increase forest production in northern ecosystems (Lautenschlager 2000). Although there are any number of potential explanations for the loss of conifers from northern forests, herbicide use presently provides the most cost-effective, environmentally safe way to reverse that loss and accomplish restoration goals.

Discussion and Conclusions

Long-Term Trends

North American forests have developed and changed dramatically since the retreat of glaciers 10 000 to 12 000 years ago. Over the last few thousand years, those forests have experienced periods of dramatic warming and cooling (Miller and Woolfenden 1999). At broad scales, climatic forces influence the development of vegetation. That development is further influenced by a variety of local abiotic (climate, soil, fire, etc.) and biotic (plant, animal, disease, etc.) factors. During the last century, harvesting large trees was one of the major biotic influences on North American forests. However, human management of northern forests is not new. Natives used fire and other tools to manage vegetation and associated animals in these ecosystems for thousands of years (Day 1953, Pyne 1982, DeGraaf and Miller 1996). In addition, wildfires (both natural and human-caused), insect outbreaks, and diseases periodically changed the composition of large expanses of northern forests during that time (Holling 1973).

Therefore, the forests found in northern North America by early European settlers resulted from the previous climate (e.g., the Little Ice Age), repeated natural and human-caused disturbances, and potentially reduced human disturbance during the previous two centuries caused by introduced diseases that decimated native populations (Kay 1998). Stand-replacing wildfires provided favourable seedbeds for conifer establishment and growth, favouring stress-tolerant conifers and early-successional fruit-producing low shrubs over the less stress-tolerant, more nutrient-demanding hardwoods. By removing ground-level competition and smaller weaker conspecifics, the more common surface fires, which were both natural and native-set, tended to favour established larger conifers e.g., pines across much of the north and Douglas-fir in the Pacific Northwest.

As forest harvesting became increasingly common, post-harvest forest establishment and growth increasingly failed to track historical post-disturbance successional patterns. Specifically, hardwoods began to increase and prosper at the expense of conifers. Before the rise of conservation, few were concerned about those changes. However, as interest in basic management, wise use, conservation, and the maintenance of ecosystems across landscapes slowly emerged, managers attempted to ensure that ecosystems both provided products for human use and returned to their pre-harvest composition. It soon became evident, however, that conifers, even when planted, suffered without the more violent natural and human-caused disturbances and related site changes that previously allowed them to prosper. Historically, natural disturbances such as insect attacks or wildfires commonly allowed the development of advance conifer regeneration or prepared sites for early-successional species establishment and growth while sometimes minimizing competition. Planting without competition control was often unsuccessful because competing vegetation tended to reduce or eliminate the planted conifers.

Thus, silvicultural practices, including the use of herbicides, were developed to encourage growth of conifers after harvesting. Herbicide active ingredients mixed in water were sprayed over naturally regenerated conifers and conifer plantations to reduce non-conifer competition. This alone, or in combination with other silvicultural practices (e.g., site preparation), helped conifers become established, survive, and grow after harvest. Although these efforts contributed to conifer replacement in many treated stands, they were not always successful. In addition, many harvested stands remained untreated leading to an additional loss of conifers. The loss of conifers from northern landscapes, and their short- and long-term replacement by hardwoods, continues wherever northern landscapes are harvested.

Vegetation

Herbicide treatments have become a valuable tool of operational foresters because they can, relatively inexpensively and effectively, increase conifer survival and growth. Non-conifer vegetation is commonly reduced for one to four years following broadcast herbicide treatments; longer-term reductions of some species (e.g., blueberry) seem possible. Fungi, however, seem relatively unaffected by herbicides. Although moss and lichen reductions have been recorded, they are most dramatic followed experimental, as opposed to operational, treatments. The extent and length of non-conifer reductions, including reductions in browse and fruit-bearing species, depends on active ingredient, application rate, time, weather, and site. However, post-treatment vegetation changes, especially longer-term changes, are poorly documented and need more study. Short-term reductions are commonly species and/or vegetation group-specific, while longer-term changes often are linked to conifer stocking, site quality, and the ability (or lack thereof) of conifers to dominate treated sites. The duration of non-conifer reductions that do occur seemingly decrease as site quality increases. Although vegetation reductions following herbicide treatments are common, the literature illustrates large variability in vegetation abundance found following "identical" (chemical and rate) treatments (Lautenschlager 1993a). It is clear that herbicide treatments applied to regenerating stands do not reduce, and sometimes increase, stand and landscape level plant species richness (diversity). If conifers (planted or natural) dominate a site they may reduce the presence and abundance of other species. Still, site-level changes must be viewed from a landscape perspective at increasingly broader scales. Management practices that lead to large early-successional stands in the midst of older-successional stands may be desirable, while practices that simply add one more early-successional stand to an abundance of such stands may be less desirable (Hunter 1990).

Terrestrial Invertebrates

Below-ground and surface-active terrestrial invertebrates, insects, arachnids, gastropods, and microbial processes seem relatively unaffected by herbicide release treatments. Some components (carabid beetles) increase, while others (slugs and snails) have become slightly less active on the soil surface. As would be expected, foliar-dependent insects are reduced in abundance following successful treatments, but start to recover as broad-leaved plants re-invade or begin growing again on treated sites. As with plants, invertebrate species are seldom eliminated, and new species often arrive to occupy newly created niches. Available data suggest no reason for concern about the presence and condition of terrestrial invertebrates following herbicide treatments in northern ecosystems.

Amphibians and Reptiles

Although little information exists about effects of herbicide treatments on amphibians and reptiles, that which is available suggests that because of application timing, and the habitat preference and secretive nature of these animals, they, especially amphibians, are unlikely to be exposed, or absorb enough of any herbicide to lead to direct toxicity. To date, habitat changes caused by site preparation and conifer release treatments have not affected any of the species examined in the wild. The garter snake is the only reptile studied to date, and limited data suggest that it is common and reproductively active in and around released regenerating stands.

Songbirds

Abundance of species that prefer early successional deciduous cover generally decreases one to two years after conifer release treatments, whereas densities of species that avoid that cover tend to increase. Abundance of species that decrease soon after treatment often recovers during the following three years. Species-specific responses are linked to treatment-related habitat changes and not to herbicide treatments per se. Densities of some species have been reduced as much or more by brushsaw cutting as by herbicide treatments. However, population increases or decreases associated with herbicide treatments seem to last longer than those associated with brushsaw cutting.

Small Mammals

Changes following application of herbicides are related to habitat changes (vegetation composition and structure), and they affect small mammal abundance and species composition indirectly. However, depending on site quality, abundance of some species (red-backed vole and sometimes the common shrew) are reduced for one to three years after treatment. Under normal use scenarios, the active ingredients in the herbicides commonly used to manage northern forest ecosystems do not affect the general health (e.g., survival, growth, reproduction) of small mammals or any of the other animals examined. In studies where short-term control versus treatment differences in abundance were found, the magnitude of observed differences was well within the range of natural fluctuations. Even when herbicide treatments cause major changes in plant species abundance, plant and small mammal diversity seems relatively unaffected.

Mid-Sized and Large Mammals

Few studies have documented effects of site preparation and conifer release treatments on snowshoe hare; however, hares seldom use early successional plantations, the focus for most conifer release treatments, and seem to be unaffected by later treatments (10–20 years after regeneration is initiated). Hares should benefit from conifer release because that treatment is designed to aid the development of preferred, conifer-dominated, habitat. Deer also seem to be unaffected or to benefit from conifer release treatments. In contrast, treatments often reduce biomass of moose forage and habitat use of treated areas by moose for three to seven years. Though, for several years after treatment, forage quality (DP, DDM) in treated areas is equal to or superior to that in control areas. However, moose populations are commonly controlled more by hunting mortality than by habitat availability (Rempel *et al.* 1997), and moose in naturally regenerated conifer stands have consistently used older (≥ seven-year-old) treated areas more than similar-aged untreated areas. Although large- (deer and moose) mid-sized, and small-mammals consume glyphosate-treated foliage when it is encountered, residues are quickly eliminated through digestive processes and treatments should pose no threat to humans or carnivores.

Successional Time Comparisons

Although most of the studies reviewed were established to compare responses among treatments, successional time following treatments within and among studies often vary considerably, i.e., investigators compare stands of different successional ages and structures. Specifically, within-study controls are consistently successionally older than the treatment types to which they are compared. For example, Lautenschlager *et al.* (1998) applied treatments four to seven years after site preparation and planting; controls in that study were therefore successionally four to seven years older than treatment areas because, to varying degrees, the treatments reinitiated succession. Even by three years after treatment, Lautenschlager *et al.* (1998) compared treated areas where the bulk of vegetation was successionally three years old with controls that were successionally six to nine years old. Little wonder researchers find differences when such comparisons are made; the wonder is that they find so few.

Those involved in disturbance-related studies should consider examining their results in terms of successional time as well as among treatments. When results of the studies reviewed for this paper are examined through successional time, few or no differences among treatments on biotic components are observed. For instance, Santillo *et al.* (1989) reported "fewer invertebrates, especially herbivorous insects, on herbicide-treated clearcuts." In that study, total insect captures, one and three years after the glyphosate treatments, studied were 446 and 644, respectively, and 900 in the untreated control area. However, the *control* was clearcut six years before the study began and when plotted in successional time (one, three, and six years) after disturbance, total captures reported by Santillo *et al.* (1989) fit a nearly straight line, increasing through time. Keeping that in mind, as researchers examine differences between treated and untreated areas in the future, their conclusions should be based on changes through successional as well as chronological time.

Stand versus Landscape Changes

Most studies of environmental responses to herbicides have been conducted at a sub-stand level. Researchers commonly subdivided stands into smaller units to achieve statistical replication, but results from these small-scale versus truly operational-scale treatments have never been tested. In addition, forest management practices in general, and site preparation and conifer release with herbicides in particular, must be viewed relative to the landscape mosaic and the desired future forest conditions. What may be unacceptable in certain stands or areas may be desirable in others, depending on how it fits into present or developing forest landscape patterns and local needs (Lautenschlager *et al.* 2000). Herbicide treatments are commonly used to encourage conifer establishment, survival, and growth; yet at broad scales, across boreal and boreal mixedwood ecosystems, conifers have consistently been replaced by hardwoods since Europeans began harvesting in these ecosystems. Therefore, although concern about forest management treatments favouring conifers has been expressed, conifers have actually been losing their position of dominance in most northern ecosystems. Those interested in maintaining or restoring conifer ecosystems, in the future, likely will find herbicides useful for accomplishing their goals.

Considerations for the Future

Many members of the public viewing areas recently treated with spray solutions containing a herbicide product assume that effects on plants and animals are dramatic, long lasting, and negative. However, the scientific literature published to date provides no evidence for those assumptions. Rather, it shows that herbicide treatments affect plants both directly and indirectly and those changes to habitat (quantity and quality) affect animals indirectly. Therefore, depending on habitat requirements, populations of animal species may increase, decrease, or remain relatively unchanged following treatments.

Some of the problems identified by Lautenschlager (1993a) have been addressed by subsequent research, but longer-term work at appropriate scales, similar to that documenting responses of wildlife to clearcutting (Potvin *et al.* 1999), is still needed. Researchers documenting biotic consequences of silvicultural treatments also must identify if the silvicultural objective(s) of the treatment(s) were achieved; e.g., did conifer crop trees become established, survive, or grow better because of the treatment? If so, how much better and for how long? Both biotic and silvicultural consequences must be documented before the full effect of existing or proposed treatments can be determined. Addressing operational-scale questions, which according to Baskerville (1994) forestry researchers have seldom done, has become even more difficult with increased public concern about and demand for involvement in natural resource management decisions (Lautenschlager 1999c). In addition, operational realities associated with site-preparation and conifer release can and have changed over time.

This review will be most valuable for decisions in the future if the management practices examined continue. However, changes in management have been made and should be expected to continue. For instance, using patch as opposed to broadcast treatments has become more common and there is increasing interest in dividing landscapes into specific management zones, including zones dedicated to intensive silviculture (Lautenschlager 2000). Therefore, in the future, although the herbicide active ingredients will likely change little, treatments designed to increase fibre production may be applied sooner and more often and treatment areas may be at a higher density within designated zones. Unfortunately, we know little about the consequences of these or the combination of treatments, such as site preparation, fertilization, genetic improvement, and conifer release, identified by Lautenschlager (2000) on crop survival, growth, or the environment. To provide meaningful results for the future, researchers will need to document those consequences as new operational regimes emerge, are implemented, or change.

Still, economic realities suggest to some (Benson 1988, Oliver 1999, McKenney 2000) that management intensity in our cooler, less productive northern ecosystems may not increase substantially in the near future. If not, managers may simply strive to become more effective with existing treatments, potentially optimizing timing, improving delivery systems, and/or improving the effectiveness of existing active ingredients. Even those improvements, however, could pose problems for those hoping to use the synthesized information presented here to predict biotic consequences of improved treatments. However, this review should be useful for drawing conclusions about standard treatments and outlining expectations for restoration efforts, a use of herbicides that will likely become increasingly important as managers attempt to re-establish conifers across northern landscapes. Regardless of the management approach taken, in addition to study designs that document effects of operational treatments on environmental components of concern and translate fine-scale findings to broader-scale realities, increasingly social considerations will need to be integrated into research and management plans (Lautenschlager 1999c, Lautenschlager *et al.* 2000).

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