

INFLUENCE OF FOREST FERTILIZATION ON WILDLIFE AND BIODIVERSITY

Contract Report (1070-20RE17FHQ105)

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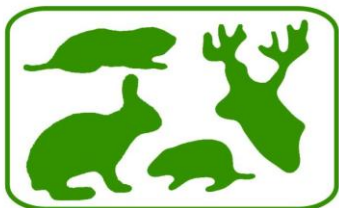
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1.0 Executive Summary

To help mitigate the impact of mountain pine beetle and wildfire disturbances to the timber supply in BC, forest fertilization reduces the time required by key stands to reach harvestable size and increase mid- and long-term harvest levels. Aerial application of fertilizer makes nutrients available to all trees, plants, and wildlife in a given ecosystem, and therefore may have direct and indirect effects on these systems. A scientific review of these potential effects was conducted with 122 published scientific studies covering vascular and non-vascular plants, amphibians, birds, mammals, terrestrial invertebrates, soil animals, and non-timber forest products associated with fertilization of stands in temperate and boreal forests.

Direct effects

Amphibians and domestic mammals appear to be the most sensitive to urea used in fertilization programs. The avoidance behaviour and/or mortality of amphibians in laboratory studies was species-dependent. We did not find any published field studies of the influence of forest fertilization compounds on amphibians. Low concentrations of urea (up to 3%) are used as a nitrogen supplement to ruminant feeds for domestic animal production. Ruminant animals, including wild ungulates such as deer, moose, elk, and caribou (reindeer), rapidly convert urea to ammonia and are susceptible to toxicity following ingestion of large amounts of urea. As acknowledged in the Forest Fertilization Guidebook in BC, fertilizer spills at storage or transfer facilities are probably the greatest potential wildlife hazard, and careful management should avoid any problems. Feeding on urea pellets by small mammals or ground-active birds (e.g., grouse) appears to be minimal as granules are unpalatable.

Indirect effects – understory plants

The majority of responses of understory herbs to nitrogen fertilization were an increase in abundance. In the interior of British Columbia (BC), mean abundance of total herbs, grasses, and fireweed all increased dramatically with repeated fertilization, up to 3-4 times compared with unfertilized stands. Some shrubs in repeatedly fertilized stands, such as Sitka alder, prickly rose, and willows eventually increased in abundance in long-term studies in BC and the Yukon. Dwarf shrubs such as twinflower, kinnikinnick, and various *Vaccinium* species declined, likely in response to competition from dominant herbs and increasing canopy cover from rapidly growing crop trees in fertilized stands. Abundance of bryophytes (mosses and lichens) followed the pattern of dwarf shrubs with the majority of studies reporting declines.

Species richness and diversity of understory herbs and shrubs declined or were unaffected in fertilized stands. In the long-term repeated fertilization studies in BC, mean species richness of herb and shrub layers were unaffected by fertilization, but species diversity was decreased. Competitive exclusion from a few dominant species was the likely explanation. Response in abundance of vascular plants to a single application of nitrogen showed either an increase or no change. This pattern was similar for responses in species richness and diversity whereby 8 and 10 records of no change were recorded, respectively. Repeated applications (2-5 and > 5) showed a trend to either no change or declines in responses of plant abundance and richness-diversity. In young lodgepole pine forest in BC at 6 and 11 years after the last of five repeated fertilizer applications, mean abundance and species diversity of herbs and shrubs in fertilized stands had returned to levels recorded in unfertilized stands.

Indirect effects – mammals

The common pattern of a shift in vegetation from dwarf shrubs and mosses-lichens to grasses and dominant herbs provided excellent habitat for *Microtus* voles in Canada and also Scandinavia. Overall for abundance of small mammal species, there were 6 increases, 15 no changes, and 6 decreases in responses to fertilization. Relative abundance of deer, moose, and hares, and forage quality as indexed by nitrogen concentration and sometimes crude protein, were usually increased by fertilization. Forest fertilization consistently improved forage production for livestock by the increased abundance of herbs and grasses for sheep and cattle. In the BC long-term study, fertilized stands received 2.1 times more cattle use than unfertilized stands, with no apparent negative effects on mule deer occupying the same range.

The red squirrel is by far the most important mammal in terms of feeding damage to young stands in BC. Black bears and porcupines also have the potential to feed on fertilized trees in sapling and pole-sized stands. The first task in managing proactively to avoid mammal damage in fertilized stands is a pre-fertilization survey to determine if the stands currently have significant amounts (e.g., $\geq 15\%$ of trees) of damage. A decision-making profile provides an assessment of the risk of squirrel damage based on 10 factors describing conditions that make young stands susceptible. A list of possible silvicultural practices to ameliorate bear damage is also provided.

Indirect effects – birds, insects, and soil mesofauna

Studies on the relationships between birds and fertilizers have tended to focus on the role of birds as predators of invertebrate herbivores in forest ecosystems. For non-conifer pest arthropods, forest fertilization may provide winter feeding habitat for

coniferous foliage-gleaning insectivorous birds in some cases. Five species of forest grouse showed no response to fertilizer treatments. The responses of soil animals (mesofauna) to nitrogen fertilization appear to be species- and dose-specific and ameliorated or accentuated by surrounding micro- and macro-habitat characteristics.

Indirect effects – NTFPs

In a long-term study in BC, 54 herb and shrub species were identified as potential NTFPs, with mean total abundance of plants and total herb NTFPs being significantly greater in fertilized than in unfertilized stands. In Scandinavia, nitrogen fertilization had variable and contradictory effects on *Vaccinium* berry crops with respect to site fertility. The decline in berry crops after fertilization on fertile sites may be related to the enhanced growth of grasses and forbs on those specific sites. However, fertilization apparently had no harmful effects on the nutrient concentrations of the berries.

A list of information and research needs is provided.

2.0 Introduction

The global demand for timber production and forest cover continues to increase to produce conventional wood products and biofuels, as well as sequester carbon in response to climate change (Sedjo 1999; Raunikaar et al. 2010). Concurrent with this demand are conservation strategies to increase the size of protected areas and strategically manage second-growth forests to conserve biodiversity (Sullivan et al. 2009; Hunter and Schmiegelow 2011). These conservation efforts need to be balanced with the unpredictable and large-scale losses of existing timber to natural disturbances from wildfire, insect epidemics such as mountain pine beetle (MPB), and potentially

widespread drought and heat-induced tree mortality owing to climate change (Agee 1993; Walton et al. 2009; Allen et al. 2010). Thus, enhanced wood production will become increasingly necessary to mitigate current and future wood supply shortfalls (Moore and Allen 1999; Park and Wilson 2007).

Sustaining wood and biomass production on a shrinking landbase while concurrently creating a diversity of forest habitat conditions to meet the goals of biodiversity conservation may be achieved with silviculture practices such as pre-commercial thinning (PCT), commercial thinning (CT), and fertilization (Moore and Allen 1999; Hartley 2002; Sullivan et al. 2013). These practices have been used successfully to increase biomass production in second-growth forests across northern Europe (Nabuurs et al. 2007; Bergh et al. 2008), the southeastern United States (US) (Allen et al. 1990; Fox et al. 2007), and coastal Douglas-fir (*Pseudotsuga menziesii* var. *glauca*) and interior lodgepole pine (*Pinus contorta* var. *latifolia*) forests in BC of the Pacific Northwest (PNW) of North America (Weetman et al. 1992; Brockley 2007a; Lindgren and Sullivan 2013a).

The Forests for Tomorrow (FFT) program within the BC Ministry of Forests, Lands and Natural Resource Operations (MFLNRO) was established in 2005 in response to the catastrophic disturbances caused by MPB and large wildfires with the aim of improving the future timber supply and mitigating impacts on other forest values. As part of the FFT program, forest fertilization contributes to the program by reducing the time required for key stands to reach a harvestable size, and thus increase the mid-term timber supply. Fertilization accelerates stand development and increases size of individual trees without sacrificing stand volume, and hence may be particularly useful

for addressing age-class imbalances and for increasing long-term harvest levels (Brockley 2005). Since 2005, approximately 120,000 hectares have been fertilized across the province. Aerial application of fertilizer makes nutrients available to all trees, plants, and wildlife in a given ecosystem. Thus, this practice may affect wildlife directly by exposure to nutrients in their concentrated form immediately after application, and indirectly through growth enhancement of understory plant species and potentially affect other organisms on the forest-floor. In addition, fertilization, by way of enhancing tree growth and vigour, may increase wildlife feeding damage to conifer saplings and pole-size trees.

MoFLNRO staff involved in the forest fertilization program receive enquires related to interactions between forest fertilization applications and non-timber resources. Over the last three years, inquiries have been made with regard to effects on bees, berries, bears, moose, cougars, amphibians, reptiles, butterflies, and grouse. Thus, a synthesis of peer-reviewed scientific literature summarizing the influence of forest fertilization on wildlife and biodiversity was conducted to identify recent research and summarize findings for staff.

This topic was originally reviewed by Rochelle (1981) and identified the effects of forest-grade urea on wildlife, particularly in the PNW. Sullivan and Rochelle (1992) followed up with a further review of fertilization-wildlife interactions that included information from other forested areas of North America and Europe. The current review will also follow this format and includes results of scientific studies (1990 to 2016) of the influence of fertilization on wildlife and biodiversity in forests primarily from North America and Scandinavia. The conservation of biodiversity is an integral part of the

management of forest ecosystems because it is an important ecological criterion of sustainability (Hunter 1990, 1999). Biodiversity may be defined as the diversity of life in all its forms and at all levels of organization in a given ecosystem (Hunter 1990). As such, it includes the full range of organisms from soil microbes and mycorrhizal fungi to large mammal and tree species that reside in forests, and these groups are often termed “non-timber resources”.

Thus, we provide an evaluation of the influence of forest fertilization on wildlife and biodiversity in the following categories: (i) direct and indirect effects across groupings of organisms; (ii) effects on understory vegetation and forage production for native wildlife species and domestic livestock; (iii) impacts to fertilized stands from feeding damage by wildlife; (iv) identification of topic areas needing additional research in relation to current forest fertilization practices in BC.

3.0 Methods

3.1 Database

The following electronic databases were searched for the period 1990 to 2016: specific journals including Forest Ecology and Management, Canadian Journal of Forest Research, Scandinavian Journal of Forest Research, and Google Scholar and Summon 2.0 search engines across a range of journals publishing papers in English. Additional studies were identified from reference lists of individual publications and from review papers. In a few cases, references not in English (e.g., English abstract only) but cited in review papers, were included and referenced via the author(s) of the review paper. Results of these studies were noted in the text, but not in the tabulated data since we

could not access the methods used. The Scandinavian literature has been heavily used as they have similar boreal forest ecosystems to northern North America and a long-term record of studies. To be included in this compilation, studies had to: (i) be published in peer-reviewed scientific journal publications or some credible government reports (e.g., USDA, FRDA); (ii) be conducted on one or more of these groups: vascular and non-vascular plants, amphibians, birds, mammals, terrestrial invertebrates, and soil animals; (iii) be conducted in temperate or boreal forest ecosystems with a history of experimental and/or operational fertilization programs; (iv) provide data on organism response variables to control (no fertilization) and fertilization treatments such that an “increase”, “decrease”, or “no change” result could be identified. Some studies may have focused on one group (e.g., understory vascular plants) or directly on one group (e.g., native ungulates) and secondarily on another group (e.g., understory plants as forage). Both “direct” (toxicity, e.g., via feeding or contact) and “indirect” (changes in habitat, e.g., understory vegetation, response of wildlife populations and habitat use, and use of forage plants by indigenous people) effects were included. Because of the broad survey of organisms in this account that were not covered in earlier reviews, some pre-1990 publications were included in this compilation.

We did not include responses of tree growth metrics to fertilization as this was not an objective and has been rigorously covered in other publications. Cycling of nitrogen, carbon, and other elements as nutrients in forest vegetation and soils was also beyond the scope of this review. Except for soil animals, the diverse world of soil microbial biomass, including mycorrhizal fungi, was not included as this topic would be a substantial review on its own. Nitrogen deposition and saturation studies with respect to

atmospheric pollution and other anthropogenic sources also were not included.

Similarly, we did not include organic-based (e.g., sewage, wastewater sludges, wood ash) fertilizers in this assessment as they are not part of the forest fertilization program in BC, nor as a widespread practice in any jurisdiction that we know.

Specific methodologies were sufficiently variable among studies, even for a given group of organisms, that it was not possible to conduct a formal meta-analysis (Arnqvist and Wooster 1995). Therefore, for each study within a group of organisms, we evaluated the response variables (e.g., presence/absence, abundance, cover, species richness, species diversity) and rated these responses as an increase (+), decrease (-), or no change (0). Abundance and cover were indices of biomass (Lindgren and Sullivan 2013b). Species richness was the total number of species sampled for each group or community and species diversity was usually measured by a variation on the Shannon-Wiener and Simpson indices (Krebs 1999).

Nitrogen (N) is the major element that is deficient in many forest soils (Tamm 1991; Brockley et al. 1992; Weetman et al. 1992). Urea ($(\text{NH}_2)_2\text{CO}$) is currently the only fertilizer widely used by the BC MoFLNRO for operational applications. This is due to its good response history, ease of storage, availability, environmental effects, and high nitrogen content (46%) which minimizes application costs per unit area (MoFLNRO 1995). It is commonly applied as forest grade urea (46-0-0) at a range of application rates from 175-225 kg N/ha, with one or more applications over the rotation of a given stand. Nitrogen may also be delivered via ammonium nitrate (NH_4NO_3), ammonium sulphate ($(\text{NH}_4)_2\text{SO}_4$), and other less common formulations. These latter formulations are more commonly used in Europe, and urea in North America. Other elements that

may be applied in combination with nitrogen (N) include sulfur (S), phosphorus (P), potassium (K), and boron (B), usually in minor amounts tailored to foliar analyses of trees (Brockley 2007a). Many operational and experimental studies had multiple applications of nitrogen, with and without additional elements. Operational applications were generally aerial and covered forests at a scale of 10s to 100s of ha. Experimental applications were manual and usually covered sample plots $\ll$ 0.50 ha.

A total of 122 peer-reviewed scientific publications contributed to the database in this compilation.

4.0 Results and Discussion

4.1 Direct effects of fertilization on wildlife

As noted in the two previous reviews, toxicity, palatability, and availability in the environment are all factors that influence the direct hazard of fertilizers (specifically urea) to wildlife species. As reported by Sullivan and Rochelle (1992), acute and chronic toxicity levels of urea measured in laboratory lethal dose (LD_{50}) tests indicated that domestic animals and amphibians to be the most susceptible to urea poisoning (Table 1). There are additional entries of acute oral toxicity (LD_{50}) for cattle at 510 mg/kg body weight, chronic oral toxicity levels for the rat (2,250 mg/kg) and mouse (6,750), and acute and chronic toxicity levels for reindeer (*Rangifer tarandus*) from Sweden at 1000 and 400 mg/kg, respectively (Nordkvist and Erne 1983; Agrium 2013).

Table 1. Acute (LD₅₀ mg/kg) and chronic oral toxicity levels of urea for the rat, mouse, and cattle. Minimum lethal oral dose (mg/kg) of ammonium nitrate for reindeer.

Species	Oral		Subcutaneous	Intravenous
	Acute toxicity	Chronic toxicity		
Laboratory rat	14,300	2,250	8,200	5,300
Laboratory mouse	11,500	6,750	9,200	4,600
Dog	-	-	3,000	3,000
Rabbit	-	-	3,000	4,800
Cattle	510	-	-	-
Goat or sheep	511	-	-	-
Reindeer	1,000	400	-	-
Pigeon	-	-	14,800	-
Frog	-	-	600	-

From Nordkvist and Erne (1983), Sax and Lewis (1989), and Agrium Material Safety Data Sheet (2013).

4.1.1 Toxicity

Toxicity occurs when urea is converted to ammonia and carbon dioxide by the enzyme urease. Urease is produced by bacteria found in the digestive systems of both ruminants and monogastric (simple stomach) animals, as well as in the soil (Rochelle 1981). If ruminants such as cattle and sheep take in large amounts of urea, then ammonia in excess of that which can be metabolized is liberated, thereby resulting in a rapid pH change in the rumen and the mortality of rumen microbes (Rochelle 1981). Toxic levels of ammonia become elevated in peripheral blood because the liver cannot detoxify excess ammonia.

4.1.2 Ruminants

It is important to note the relationship between urea toxicity and intake rate. For example, use of low concentrations of urea (up to 3%) as a nitrogen supplement to ruminant feeds serves as an inexpensive non-toxic source of protein for domestic animal production (Stanton and Whittier 2006). Non-protein nitrogen (NPN) compounds such as urea may be used by bacteria in the rumen of cattle and sheep and these compounds are broken down to ammonia during the normal fermentation process in the rumen. Monogastric animals (pigs and chickens) cannot make use of large concentrations of NPN compounds because of a lack of enzymes and bacteria to break down the NPN to ammonia and synthesize it into protein (Stanton and Whittier 2006).

Urea toxicity is highly dependent on the rate at which urea degrades to ammonia. Humans and monogastric animals do not rapidly convert urea to ammonia, and hence urea is of low toxicity following ingestion by these species. However, ruminant animals

rapidly convert urea to ammonia and are much more susceptible to toxicity following ingestion of urea. Accidental ingestion of granules of urea should be considered of low toxicity unless a large amount was ingested. Deer (*Odocoileus columbianus*), elk (*Cervus elaphus*), and moose (*Alces alces*) are all ruminants (Bunnell 1990; Renecker and Hudson 1990), and together with cattle constitute the risk group for ungulates in areas of forest fertilization in BC. A fourth native ungulate in BC is the woodland caribou (reindeer in Scandinavia) (*Rangifer tarandus*). In Sweden, nitrate concentrations appearing in plants soon after fertilization with 150 kg N/ha (ammonium nitrate) were not toxic to reindeer (Nordkvist and Erne 1983). However, urea-fertilized areas were avoided by reindeer for winter grazing which takes place through snow cover (Eriksson 1984, as cited in Nohrstedt 2001). Other than for reindeer, we could find no specific toxicity data with respect to urea for any of these large mammals, except for cattle. Thus, it may be reasonable to conclude that urea toxicity in these native ungulates is similar to cattle, goats, or sheep and might be in the vicinity of 500 mg/kg of body weight.

4.1.3 Availability in environment

Availability of urea in the forest environment from an operational application determines the potential hazard for wildlife. As reported in the earlier reviews, dissipation rates of urea in the field depend on application rate, vegetation density, soil moisture, and precipitation pattern (Postovit 1976). Therefore, field rate applications of fertilizer in closed canopy conifer plantations under conditions of high humidity, high soil moisture, and frequent rainfall should result in 18 to 36 hours of urea availability as a

food source. The normal application rate of urea pellets on the forest floor would not likely pose a toxicity risk to ruminants. If we consider that urea must be consumed for several days to produce reversible toxic symptoms, and it dissipates rapidly under field conditions, forest fertilization with urea is unlikely to adversely affect mammals or gallinaceous birds.

4.1.4 Palatability

In terms of palatability of urea to forest wildlife, there was no new information available beyond that reported in Rochelle's (1981) review. Briefly, acceptance of pelletized urea by deer mice (*Peromyscus maniculatus*) was negligible in laboratory and field trials and no toxic effects were observed (Postovit 1976). Urea in water solution presented to deer mice, where it could not be selected against, produced symptoms of intoxication at high concentrations (Postovit 1976). Toxic symptoms disappeared within one day when animals were fed normal water and roughage, whereas mice kept on urea solutions died. Concentrations of dissolved urea causing toxicity were probably higher than would be encountered on the forest floor of a fertilization program. Experiments with the western capercaillie (*Tetrao urogallus*) (Eurasian wood grouse) indicated that the birds did not swallow granules of N fertilizer even if they picked up the granules in their beak (Hogland et al. 1973, as cited in Nohrstedt 2001).

Fertilizer spills at storage or transfer facilities are probably the greatest potential wildlife hazard. Silver gulls (*Larus novaehollandiae*) were poisoned (ammonia toxicity) by a spillage of urea into water pools at a commercial shipping facility in Australia (Raidal and Jaensch 2006). Although not documented, there are several examples of

cattle having died after feeding on exposed piles of urea at forest fertilization sites in the Pacific Northwest. Cases of poisoned livestock on farms from accidental urea spills have been noted in the Midwest of the USA (Vough et al. 2006). These situations should be readily avoided with careful handling, storage, and prompt cleanup of spilled fertilizer.

4.1.5 Amphibians

The subcutaneous acute toxicity level (LD_{50}) of urea for the laboratory frog was 600 mg/kg (Table 1). Because amphibians absorb moisture and oxygen through their skin membranes, they could potentially come into direct contact with urea on the forest floor. Amphibians have two stages to their life cycle: the aquatic and the terrestrial. The terrestrial responses and tolerance levels to a forest application of urea, for example, may have an impact on the distribution and range of amphibians (Hatch et al. 2001). In a laboratory study, three species of forest-dwelling amphibians: western red-backed salamander (*Plethodon vehiculum*), southern torrent salamander (*Rhyacotriton variegatus*), and rough-skinned newt (*Taricha granulosa*) avoided urea at a concentration of 225 kg N/ha (Marco et al. 2001). In a 4-day experiment, western red-backed and southern torrent salamanders exhibited mortality at 450 kg N/ha after a 24-h exposure, but there was no mortality for rough-skin newts (Marco et al. 2001). Oldham et al. (1997) found that ammonium nitrate fertilizer was toxic to adult common frogs (*Rana temporaria*), but these investigators also noted that this fertilizer dissolved rapidly in the field, reducing the likelihood of exposure.

In another laboratory setting, the behavioural and mortality responses to urea at 50 and 100 kg N/ha was examined for juvenile terrestrial amphibians: Western toads (*Bufo boreas*), Cascades frogs (*Rana cascadae*), long-toed salamanders (*Ambystoma macrodactylum*), and rough-skin newts (Hatch et al. 2001). Juvenile Western toads and Cascades frogs avoided paper towels dosed with urea but did not avoid urea-dosed soil substrate. Western toads and Cascades frogs both suffered significant mortality when exposed to urea on a soil substrate for 5 days. Also, urea-exposed juvenile Western toads and Cascades frogs consumed significantly fewer prey items (crickets) compared with non-exposed control animals. Long-toed salamanders did not discriminate against the urea soil substrate, and neither long-toed salamanders nor rough-skin newts died or reduced prey consumption as a result of urea exposure (Hatch et al. 2001).

It is unclear as to the mechanism of urea toxicity in amphibians and why some species seem relatively unaffected. Urea application to the forest floor may increase the salinity of the environment causing osmoregulatory stress. Urea hydrolysis may increase soil pH thereby producing toxic ammonia that can easily cross cell membranes and disrupt metabolism as observed in bacteria (Kernaghan et al. 1995; Hatch et al. 2001; Marco et al. 2001)

4.1.6 Water quality

A brief overview of the potential effects of forest fertilization on water quality was derived from a comprehensive global review by Binkley et al. (1999). Their synthesis concluded that the greatest increases in streamwater nutrient concentrations arise from 1) direct application to streams; 2) use of ammonium nitrate forms of fertilizer; and 3)

application of high rates or repeated doses of fertilizer. As noted by Binkley et al. (1999), even in these situations, the impact may still be too small to degrade water quality. In general, the quality of water draining from forests is much better than that draining from agricultural lands, and this is true whether or not the forests are fertilized.

On a local scale, Pike and Perrin (2005) reviewed the effects of fertilization on forested watersheds in BC. They report on the results of case studies that formed the technical basis for Forest Fertilization Guidelines in BC (MoFLNRO 1995). Pike and Perrin (2005) concluded that unintentional nutrient transport to water bodies following forest fertilization is generally not enough to adversely affect aquatic ecosystem health or the quality of drinking water. Most studies reported increased post-fertilization levels of nitrogen elements for several days to months, but these increases remained well below water quality guidelines. The largest increases were at sites where fertilizer-free (buffers) zones were not used. Mandatory buffer zones around water bodies and restrictions on the percentage of a watershed that can be fertilized have ameliorated these issues. In addition, these buffers may also limit deposition of urea into water bodies with aquatic life-stages of amphibians and other aquatic organisms. As such, we did not include a review of studies of the effects of fertilization on aquatic vertebrates and invertebrates.

4.2 Indirect effects of fertilization on wildlife

Indirect effects arise from fertilization-induced changes in understory vegetation, and these include abundance, plant species composition (richness and diversity), vegetative cover, and increased growth, nutritive quality, and palatability of forage plants. The plant

community itself is a major component of biodiversity and also provides many of the physical attributes of habitat types for all species of wildlife (e.g., forage, cover, hunting grounds, nesting sites) (Carey et al. 1999; Sullivan et al., 2001). Understory vegetation also modifies the environmental conditions of these habitats with respect to both above- (air temperature, wind speed, humidity, and shading) and below-ground (soil temperature, moisture, and nutrient content) characteristics (Berch et al. 2006). The forest understory also contains many non-timber forest products (NTFPs) consisting of plants and fungi that may be used for traditional and cultural use by indigenous peoples throughout North America (Marles et al. 2000; Vance et al. 2001).

4.2.1 Abundance of understory plants

A total of 33 publications were included in our assessment of the influence of forest fertilization on abundance of understory layers of herbs, shrubs, and bryophytes (Appendix 1). Species richness and species diversity were also evaluated for herb and shrub layers where possible. Some studies included a combined layer of herbs and shrubs as “understory vegetation”. Overall, these studies were from Scandinavia (16), western NA (12), other parts of NA (3), Europe (1), and Australia (1). Forest ecological zones and associated overstory tree species were boreal in Scandinavia, and boreal and temperate in North America and elsewhere. In terms of number of applications, 11 studies had 1 or 2 and the others ranged from 3 to 28 applications of nitrogen. Overall, 25 of 33 studies had repeated applications of nitrogen fertilizer. Eight studies had aerial operational applications of fertilizer and 25 studies had experimental small plot-based manual applications. Duration of studies ranged from 1 to 30 years and application rates

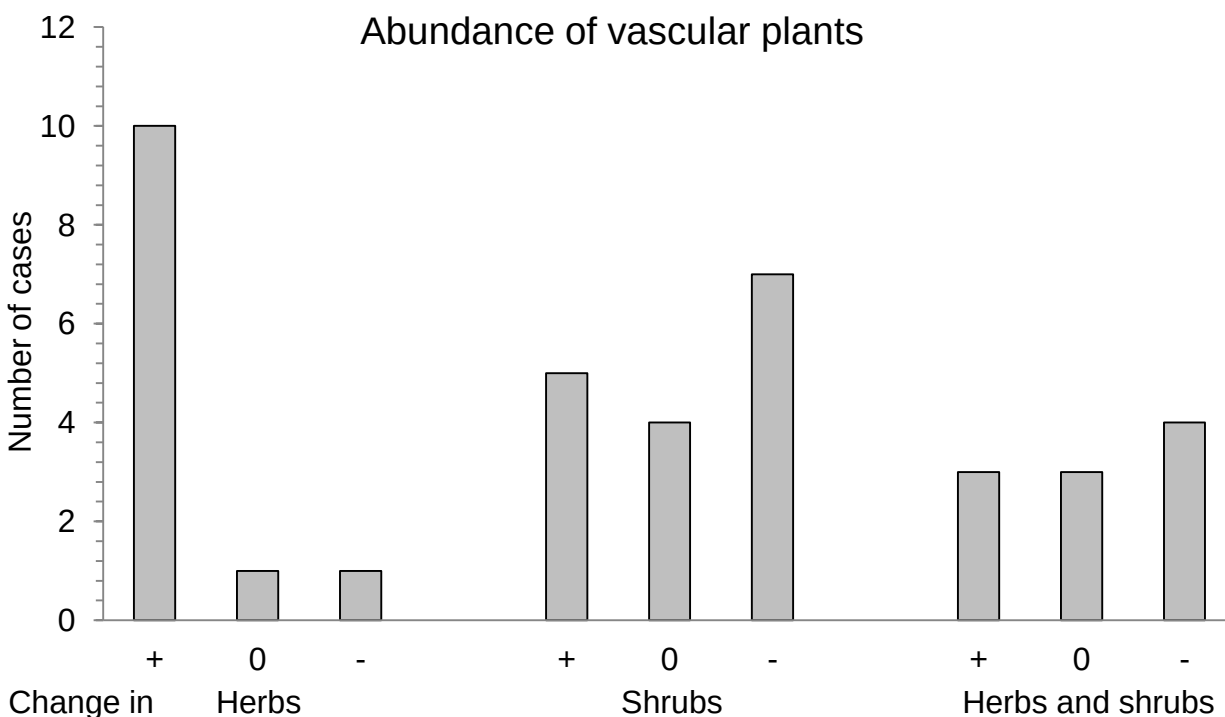
of nitrogen ranged from a minimum of 42 to a maximum of 2400 kg N/ha for a given study. Average rate of application of nitrogen per year was usually 150-250 kg/ha.

4.2.1.1 Vascular plants

As noted in Fig. 1, the majority (10 of 12) of measured responses of herb abundance to N fertilization showed an increase. For example, in the interior of BC, mean abundance of total herbs, grasses, and fireweed (*Epilobium angustifolium*) all increased dramatically with repeated fertilization, up to 3-4 times (Brockley 2007b) and 2.7 times (Lindgren and Sullivan 2013b) compared with unfertilized controls (Fig. 2a). Similar results were recorded elsewhere, at least where overstory canopy cover was sufficiently open (Riegel et al. 1991; Kellner and Redbo-Torstensson 1995; VanderSchaaf et al. 2000; and others, Appendix 1). In Sweden, grasses such as wavy hair-grass (*Deschampsia flexuosa*) and nitrophilous herbs such as fireweed and hairy wood rush (*Luzula pilosa*) dominated repeatedly fertilized stands (Kellner and Redbo-Torstensson 1995; Strengbom and Nordin 2008). Nams et al. (1993) and Turkington et al. (1998) also reported overall increases in grasses and some herbs (1.7-2.0 times) in response to annual fertilizer applications over nine years in Yukon boreal forest; however, arctic lupine (*Lupinus arcticus*) and northern anemone (*Anemone parviflora*) declined.

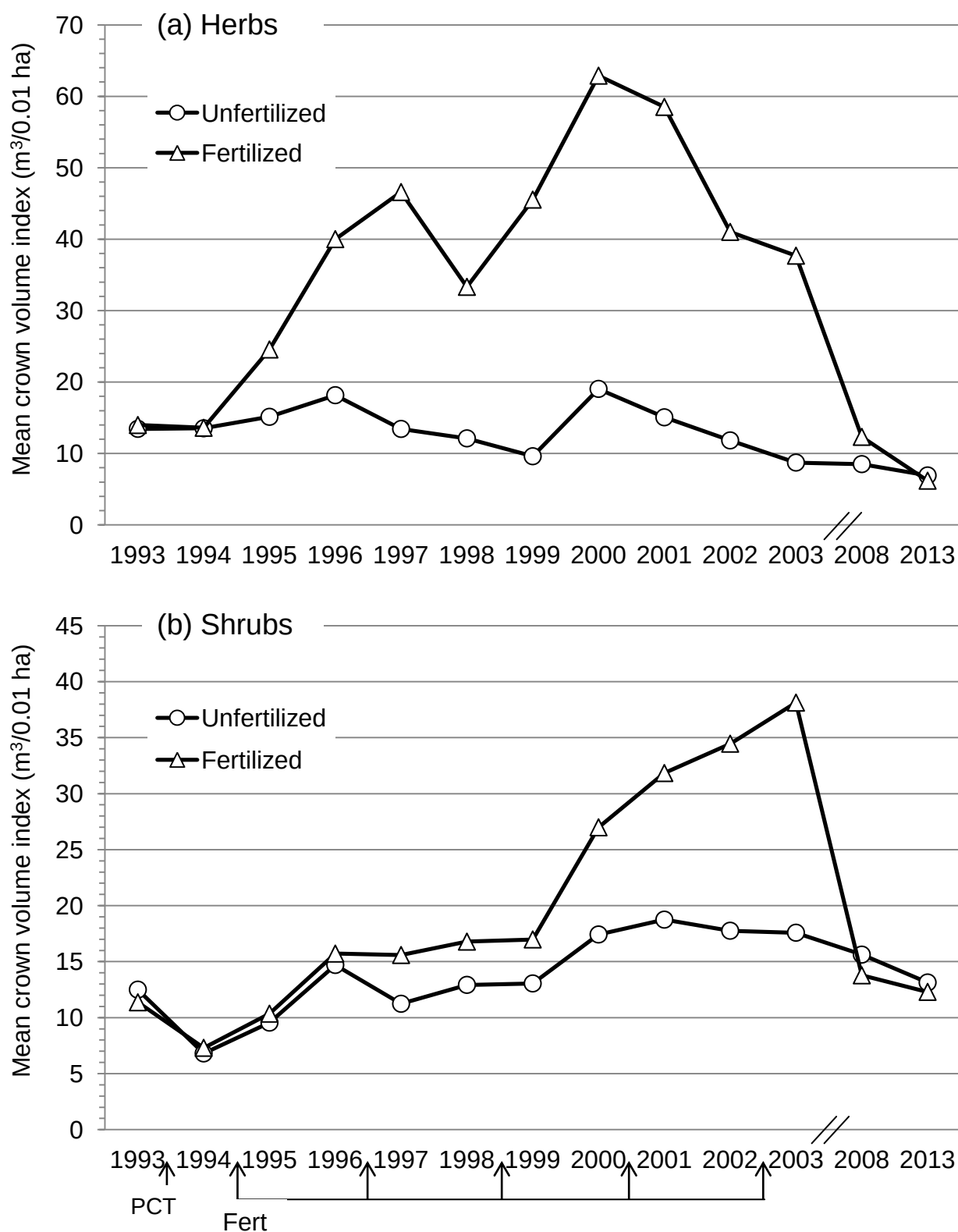
Combined herb and shrub layers, as well as shrub layers alone, indicated a mixed response to fertilization (Fig. 1). In the cases of increased abundance of shrubs, increased productivity of the herb layer may have contributed to the lack of shrub response. However, some shrubs in the fertilized stands, such as Sitka alder (*Alnus sinuata*), prickly rose (*Rosa acicularis*), and willow (*Salix* spp.), appeared to have

Figure 1. Changes in abundance of understory vascular plants.



escaped the herb layer suppression and eventually increased in abundance (1.6 times) in the long-term study in BC (Fig. 2b) (Lindgren and Sullivan 2013b). Fertilization over a 9-year period in boreal forest in the Yukon increased the growth rates of all shrubs by about 25-30% over unfertilized values, with gray willow (*Salix glauca*) and bog birch (*Betula glandulosa*) being dominant species (Krebs et al. 2001). Although positive responses were noted at 1-2 years after fertilization, there still tended to be a lag time of 5 to 6 years prior to a stable pattern of responses (Turkington et al. 1998). Although shrubs overall did increase in abundance in some studies (Figs. 1, 2b), dwarf shrubs such as twinflower (*Linnea borealis*) and kinnikinnick (*Arctostaphylos uva-ursi*) declined in these latter two Canadian studies. Similarly, the increased abundance of grasses likely contributed to a decline in the dwarf shrubs bilberry (*Vaccinium myrtillus*), lingonberry (*V. vitis-idaea*), and heather (*Calluna vulgaris*) in Sweden (Strengbom et al.

Figure 2. Mean abundance of herbs and shrubs 1993-2013 (Lindgren and Sullivan 2013b).



2001; Strengbom and Nordin 2008). An increasing canopy cover from rapidly growing crop trees in fertilized stands may also have contributed to this decline of dwarf shrubs (Hedwall et al. 2010; Lindgren and Sullivan 2013b).

4.2.1.2 Non-vascular plants

Abundance of bryophytes followed the pattern of dwarf shrubs with the majority of studies (14 of 16) reporting declines in these non-vascular plants (Appendix 2). In Sweden, lichens such as *Cladonia* spp. and the stair-step moss (*Hylocomium splendens*) and red-stem feather moss (*Pleurozium schreberi*) tended to disappear and may in some cases be replaced by litter-dwelling feather-mosses *Brachythecium* spp. and silk-mosses (*Plagiothecium* spp.) (Persson 1981; Dirkse and Martakis 1992; Strengbom and Nordin 2008; and others). Similar results of increases in amounts of nitrophilous herbs such as fireweed and shrubs such as red raspberry (*Rubus idaeus*), but declines in the mosses *H. splendens*, *P. schreberi*, and wavy-leaved moss (*Dicranum polysetum*), in response to nitrogen were reported in Norway (Rosberg 1997; Rosberg et al. 1998 as cited in Nilsen 2001). Similar declines in the three moss species noted above occurred in response to nitrogen fertilization in Finland (Malkonen et al. 1980, as cited in Saarsalmi and Malkonen 2001). In BC, terrestrial lichens and mosses declined in fertilized compared with unfertilized stands in the interior long-term study (Sullivan et al. 2009), and *H. splendens* declined in coastal fertilized stands focussed on control of salal (*Gaultheria shallon*) (Prescott et al 1993). Similarly, *P. schreberi* and *Cladonia* spp. lichens declined in fertilized jackpine (*Pinus banksiana*) stands in Quebec (Prescott et al. 1995).

4.2.2 Species richness-diversity of understory vascular plants

Species richness and diversity of understory herbs and shrubs declined or were unaffected in fertilized stands (Appendix 1, Figs. 3a+b). The decrease in richness and diversity was in accordance with several other studies of forest fertilisation (Thomas et al. 1999; Turkington et al. 2002; Strengbom and Nordin 2008; Hedwall et al. 2010; and others), whereas an opposite response was reported by Kellner and Marshagen (1991) and possibly for VanderSchaaf et al. (2000). These latter two studies, however, were conducted in forests that were initially relatively species-poor and unproductive. Hedwall et al. (2013a) found no difference in species richness and increased species diversity in fertilized stands in Sweden. In the long-term repeated fertilization studies in BC, mean species richness of herb and shrub layers were unaffected by fertilization. However, species diversity of the understory herb and shrub layers was significantly decreased by fertilization (Brockley 2007b; Lindgren and Sullivan 2013b) (Figs. 4a+b). The suggested mechanism for this decrease in diversity is competitive exclusion where a few likely nitrophilous species were successful at taking advantage of the added nutrients from fertilization, and potentially light in thinned stands, and hence thrived at the expense of other species. In a comparison of young managed (thinned and fertilized) stands of lodgepole pine with mature and old-growth stands, Sullivan et al. (2009) found that species richness and diversity of herbs and shrubs were similar in fertilized and unfertilized young stands, and old-growth stands. Richness and diversity of these understory layers were lowest in the mature stands.

Figure 3. Species richness and diversity of vascular plants.

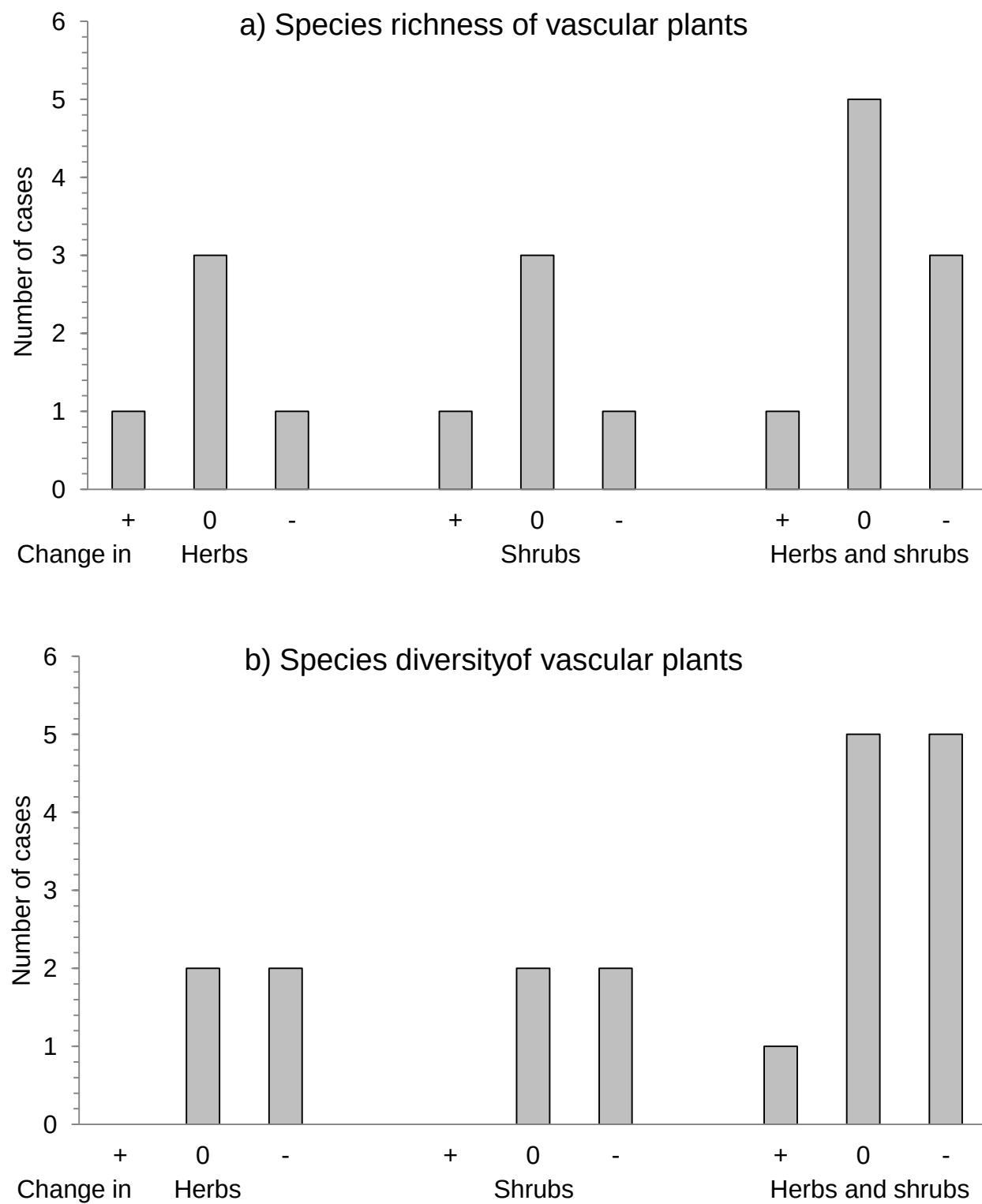
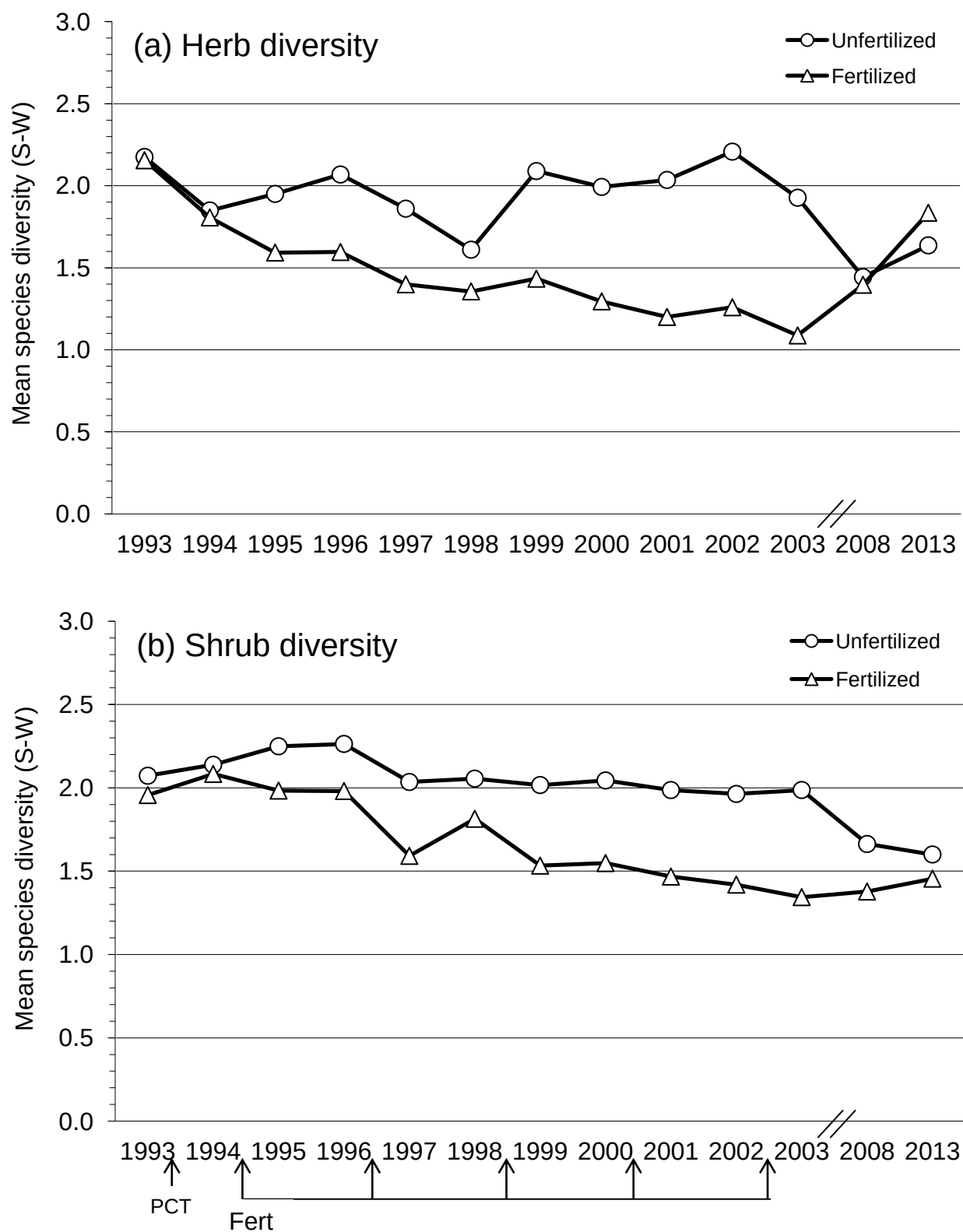


Figure 4. Species diversity of herbs and shrubs 1993-2013 (Lindgren and Sullivan 2013b).

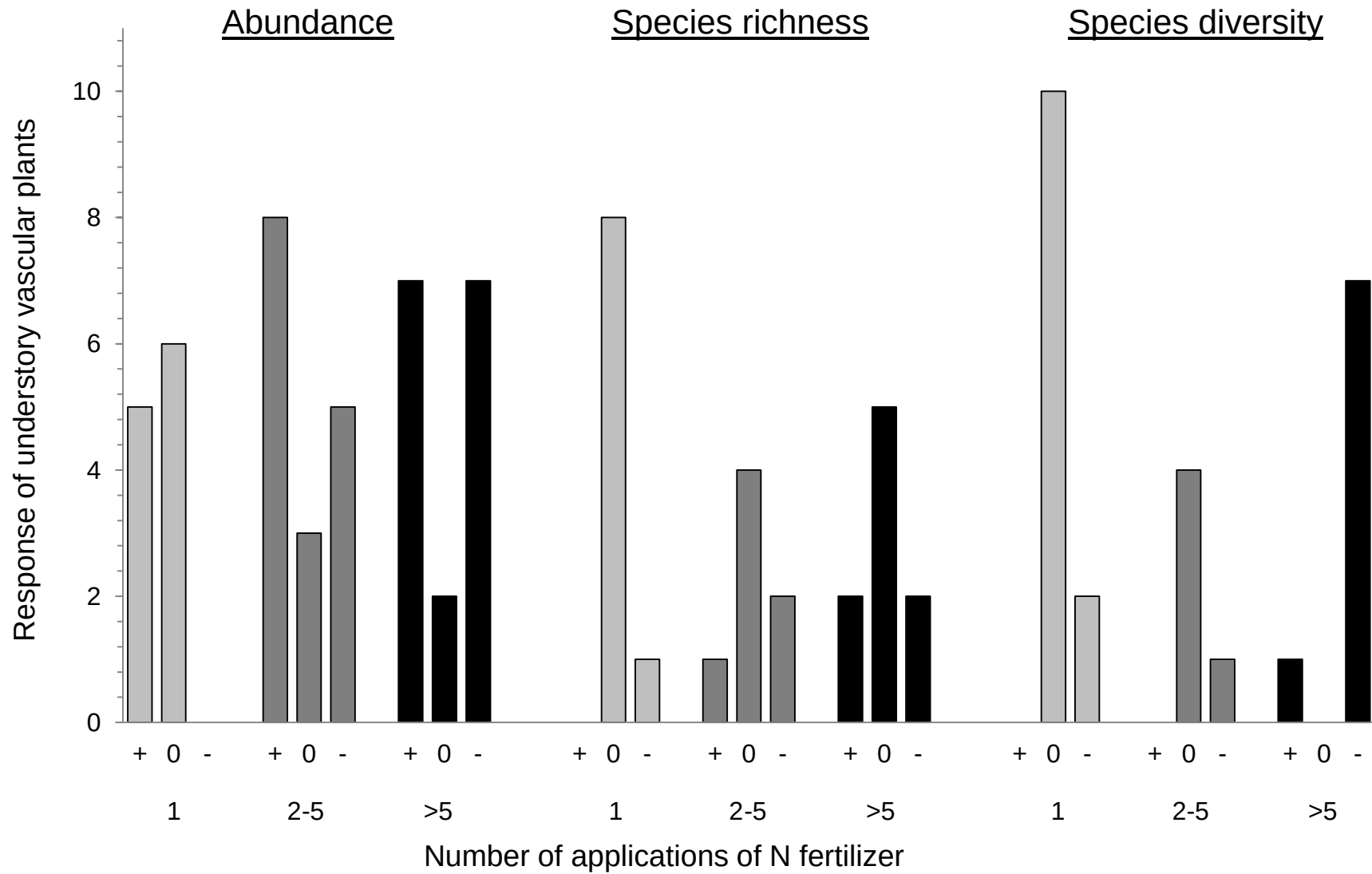


In summary, forest fertilization leads to species replacement in understory vegetation and a flora indicative of more fertile sites. On such sites, some herb and grass species may increase in abundance while dwarf shrubs tend to decrease, as discussed in section 4.2.1. Thus, the relatively high number of vascular plant comparisons for species richness and diversity that were no change (0) suggested that there is still understory vegetation in fertilized stands, albeit with some degree of altered species composition. Reduced species diversity (evenness) may be directly related to a few dominant species on a site, thereby reducing the biomass of neighbouring species. The potential influence of these compositional changes in understory vegetation need to be considered in light of changes in functional diversity and other trophic levels within the forest ecosystem (Hedwall et al. 2011, 2013a).

4.2.3 Number of N applications and understory vascular plants

The influence of number of nitrogen applications on overall responses of vascular plants was investigated for abundance, species richness, and species diversity. Number of applications were organized into classes of 1, 2-5, and > 5 and covered variable periods of time (see Appendix 1). Studies of a single application of nitrogen, which may occur in BC and other parts of the Pacific Northwest, although not exclusively, showed an increase (+) or no change (0) response in abundance of vascular plants. This pattern was similar for responses in species richness and diversity whereby 8 and 10 records of no change (0) were recorded, respectively. There were no increase responses in these diversity measurements with 3 decrease (-) responses overall for the single application (Fig. 5).

Figure 5. Responses of understory vascular plants to a range of applications of nitrogen.



The responses for 2-5 applications indicated that 8 reports showed an increase, 3 no change, and 5 a decrease for abundance of vascular plants. Species richness and diversity were similar at 1 (+), 4 (0), and 2 (-) and 0 (+), 4 (0), 1(-), respectively, for this range of applications. For those studies investigating the effects of > 5 applications of nitrogen, comparable reports for 7 increase and 7 decrease responses in abundance, with 2 no change were recorded (Fig. 5). Species richness was at 2 (+), 5 (0), and 2 (-) and species diversity at 1 (+), 0 (0), and 7 (-) for these high levels of nitrogen fertilization over time.

4.2.4 Duration of fertilization effects on plant biodiversity

Forest floor vegetation is an important part of forest biodiversity and plays a key-role in many ecosystem processes (Nilsson and Wardle 2005; Gilliam 2007). The effects of increased nutrient availability on forest ecosystems have been studied extensively and many studies have specifically dealt with plant diversity (Gilliam 2006; Bobbink et al. 2010). As noted in section 4.2.1, N-addition experiments in boreal forests of Scandinavia often show that common boreal dwarf-shrubs and feather-mosses decrease in abundance as an effect of fertilization, while grasses and nitrophilous herbs increase. Similar patterns were reported for responses of understory vegetation in boreal (Turkington et al. 1998, 2002) and temperate forests (Brockley 2007b; Lindgren and Sullivan 2013b) in the Yukon and BC, respectively. In general, as noted in section 4.2.2, plant diversity declined in repeatedly fertilized forests. A key question is: how long do these responses last, particularly after the final nitrogen application?

Olsson and Kellner (2006) measured vegetation in three Swedish forests 15–18 years after multiple N-fertilizations and 5–12 years after clear felling. They found

persistent differences in total vegetative cover compared to unfertilized controls at only one site, which was primarily due to changes in moss and lichen abundance, and concluded that the long-term effects of N-fertilization on vegetation were moderate because overall community-types were not altered. Strengbom and Nordin (2008) reported that residual effects of commercial forest fertilization on the ground vegetation was present more than 20 years after the last fertilization event, and that the effects extended into the next forest generation. The differences in vegetation composition may be attributed to altered competitive interactions among plant species. The ground vegetation in fertilized stands had a higher total cover and lower species evenness, presumably from the increased dominance of relatively few N-favoured species, and this interaction resulted in lower plant biodiversity than in unfertilized stands.

As noted, repeated fertilization leads to species replacement and a flora indicative of more fertile sites. However, these effects are likely temporary after less intensive fertilization (i.e., 1 or 2 applications) and usually only small remnant effects on vascular plants are to be found 10 years after fertilization (Kellner 1993; Nohrstedt 1998). These works are from the boreal forests of Scandinavia which tend to be species poor in understory vegetation. Temperate forests have a greater species richness of plants and we examined the longevity of effects of repeated fertilization on abundance and diversity of herbs and shrubs in a long-term study in the interior of BC. At 6 and 11 years after the last of five repeated fertilizer applications, mean abundance (Fig. 2) and mean species diversity (Fig. 4b) of herbs and shrubs in fertilized stands had returned to levels recorded in unfertilized stands. We did not observe the persistence of a fertilization effect in this study as was reported for post-clearcut stands, that had been previously

fertilized, in the boreal forest of Scandinavia (Olsson and Kellner 2006; Strengbom and Nordin 2008). Thus, there may be a fertilization-clearcut interaction whereby removal of the overstory trees may confound responses of herbs and shrubs growing in relatively “open” conditions compared with under a tree canopy (Strengbom and Nordin 2012). Similarly, the background nitrogen deposition may also affect the response of understory vegetation to forest fertilization, and potentially help explain why some plant responses to experimental nitrogen addition have been relatively small or absent (Hedwall et al. 2013b; Binkley and Hogberg 2016).

4.2.5 Forage and habitat production for mammals

Sullivan and Rochelle (1992) reviewed earlier reports detailing increased quantities of forage for various species of deer (*Odocoileus* spp.) from forest fertilization. Much of that work was conducted in pine plantations in the southeastern US prior to 1990, with a few studies in the Pacific Northwest. Total forage available for deer was generally higher (1.5 to 2.7 times) in thinned and fertilized stands. In general, most of these studies reported improvement in some parameters of nutritive quality of ungulate forage after fertilization (Sullivan and Rochelle 1992).

A total of 22 new publications (since 1990) reporting on comparisons of relative abundance, forage, and habitat production from forest fertilization covered a wide array of mammal species (Appendix 2). Eighteen studies reported on native mammals, three studies on domestic animals (cattle and sheep), and one study on cattle interactions with mule deer (*O. hemionus*). These studies were from Canada (BC and the Yukon) (16), Scandinavia (3), Europe (1), and the USA (1). Forest ecological zones and associated overstory tree species were boreal in Scandinavia, and boreal and

temperate in North America and Europe. In terms of number of applications, five studies had 1 or 2 and the others ranged from 5 to 7 applications of nitrogen. Sixteen studies had aerial operational applications of fertilizer and 5 studies had experimental small plot-based manual applications. Duration of studies ranged from 1 to 15 years and application rates of nitrogen ranged from a minimum of 150 to a maximum of 1250 kg N/ha for a given study. Average rate of application of nitrogen per year was usually 150-250 kg/ha.

4.2.5.1 *Relative abundance of mammal species*

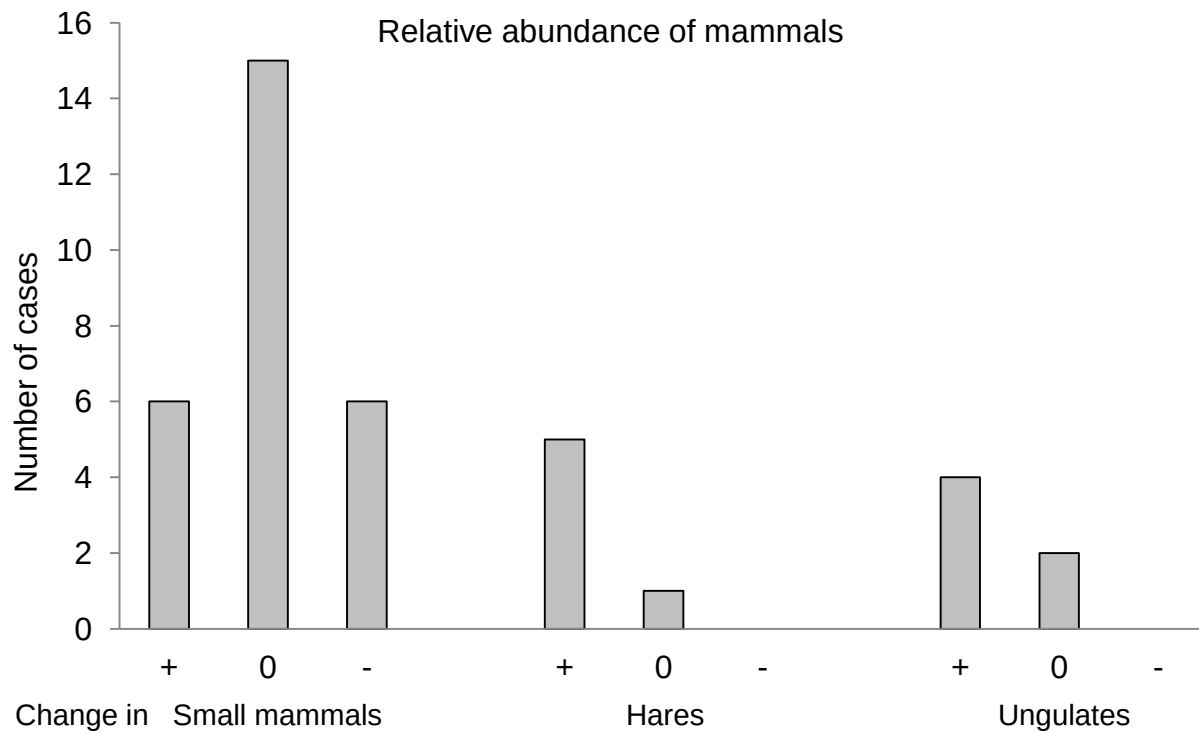
Where measured, relative abundance of a given mammal species was represented by track counts in snow, fecal pellets, and pellet-groups for large and medium-sized mammals; and by live-trapping for small mammals. In terms of the responses of relative abundance of individual native species to fertilization, there were 39 possible comparisons (Appendix 2). Of these individual species responses, 15 were an increase, 6 were a decrease, and 18 were no change. Of the group of species responses, 2 increased and 2 were no change. Quantity of forage mirrored the reported results for abundance of herbs and shrubs for most of these same studies in Appendix 1. In all but two cases, forage quantity appeared to increase or not change (Appendix 2). The decrease in abundance of the northern red-backed vole (*Myodes rutilus*) in response to fertilization in the Yukon was likely owing to the decline in dwarf shrubs and their berries (Boonstra and Krebs 2006), as noted in section 4.2.1. Another decrease was reindeer lichens that declined while the dwarf shrubs heather and lingonberry increased in abundance in northern Sweden (Eriksson and Raunistola 1993).

The lowered abundance reports for the red squirrel (*Tamiasciurus hudsonicus*) and Arctic ground squirrel (*Spermophilus parryi*) in the Yukon were possibly related to declines in mushrooms and legume food sources, respectively, from the long-term fertilization program (Boonstra et al. 2001a). Declines in these food sources were likely owing to changes in soil nutrients (mushrooms) and dramatic increases in abundance of grasses and fireweed. The common pattern of a shift in vegetation from dwarf shrubs and mosses-lichens to grasses and dominant herbs provided excellent habitat for voles of the genus *Microtus* (Boonstra et al. 2001b; Sullivan et al. 2012; Sullivan and Sullivan 2014) in Canada and also Scandinavia (Ball et al. 2000; Huitu et al. 2012) (Appendix 2). The dramatic change in habitat and high populations of the meadow vole (*M. pennsylvanicus*) may have contributed to lower numbers of the southern red-backed vole (*Myodes gapperi*), deer mouse, and northwestern chipmunk (*Neotamias amoenus*) in fertilized than unfertilized stands in the interior of BC (Sullivan and Sullivan 2012) during the 10-year fertilization period. This difference in numbers of red-backed voles between fertilized and unfertilized stands tended to disappear at years 15 (Sullivan et al. 2013) and 20 (Sullivan and Sullivan 2017), 5 and 10 years, respectively, after the final treatment was conducted in 2002. Overall for small mammals, there were 6 positive, 15 neutral, and 6 negative responses to fertilization (Fig. 6).

Responses of mid-sized mammalian herbivores included the mountain hare (*Lepus timidus*) in Scandinavia and the snowshoe hare (*L. americanus*) in BC and the Yukon. In 5 of 6 cases, relative abundance of hares increased in response to herbaceous or shrub vegetation in fertilized stands; with one case being no change for both shrub and hare response (Fig. 6; Appendix 2). Similarly for relative abundance of ungulates,

moose (*Alces alces*) and mule deer (*Odocoileus hemionus*) had 4 increases and 2 no changes in responses to fertilization (Fig. 6).

Figure 6. Responses in relative abundance of mammal species to forest fertilization.



4.2.5.2 Fertilization and forage quality

Where measured, browse quality for moose, hares, and other wildlife species, as indexed by nitrogen concentration, was significantly increased by forest fertilization in both downy birch (*B. pubescens*) and Scots pine (*Pinus sylvestris*) in Sweden (Edenius 1993; Ball et al. 2000) (Appendix 2). Nitrogen concentration and crude protein were increased in fertilized Scots pine stands in Norway (Solbraa and Brunvatne 1994, as cited in Nilsen 2001). These increases in forage quality appeared to relate directly to moose damage to pine crop trees (see section 4.2.6). In other Scandinavian studies, fertilization increased plant nitrogen concentrations in leaves of *D. flexuosa* and *V. myrtillus* in Sweden (Strengbom and Nordin 2008; Hedwall et al. 2010). In an earlier study of moose forage in Quebec, Grenier et al. (1977) reported a significant increase in crude protein in twigs of nitrogen-fertilized paper birch (*B. papyrifera*) trees. Lindgren and Sullivan (2014a) reported that repeated fertilization increased crude protein content of pinegrass (*Calamagrostis rubescens*) at five years after the most recent application in BC. However, Papanastasis et al. (1995) and Shaw et al. (2010) found no change in forage quality from fertilization (Appendix 2).

4.2.5.3 Forage production for livestock

Forest fertilization consistently improved forage production for livestock by the increased abundance of herbs and grasses for sheep (*Ovis aries*) (Papanastasis et al. 1995) and cattle (*Bos taurus*) (Lindgren and Sullivan 2012, 2014b) (Appendix 2). As noted above, forage quality also increased in response to fertilization and this result was relevant to both cattle and wildlife forage in fertilized forest stands. Relative habitat use by cattle was significantly enhanced by heavy thinning (e.g., 500 stems/ha) and fertilizer

treatments. The overall fertilizer effect was also significant with fertilized stands receiving 2.1 times more cattle use than unfertilized stands (Lindgren and Sullivan 2014b). With respect to mule deer-cattle interactions in forests managed with thinning and fertilization, grazing by cattle may be compatible with mule deer, at least in those forest sites managed intensively for timber production. Fertilization may result in sufficient forage production in the understory vegetation of these forest ecosystems to compensate for cattle grazing that reduces the live forage biomass (Lindgren and Sullivan 2014b).

4.2.6 Mammals and tree damage

Increases in the abundance and quality of plants as wildlife food seems to improve after forest fertilization. This is a favourable result from a wildlife management perspective, but not necessarily if tree growth and survival are adversely affected by mammals feeding on trees. Sullivan and Rochelle (1992) gave a general overview, up to 1990, of forage selection by mammals and damage to a range of fertilized seedlings, trees, and plant parts. We compiled the results of relevant experimental studies and reviews that concentrated on the incidence and management of mammal damage in young fertilized stands from sapling to pole-size timber. Twelve references were included in this survey: moose (2), black bear (*Ursus americanus*) (3), and red squirrels (7) (Appendix 3). Incidence of moose damage to Scots pine stands occurred in Sweden and Norway and was similar to earlier reports summarized by Sullivan and Rochelle (1992). Of particular relevance to BC were the red squirrel and black bear reports. The red squirrel is by far the most important mammal in terms of feeding damage to young

stands. Black bears and porcupines (*Erethizon dorsatum*) also have the potential to feed on fertilized trees in sapling and pole-sized stands.

4.2.6.1 Red squirrel damage

Red squirrel damage to lodgepole pine stands in the interior of BC was first observed in the 1980s as PCT and fertilization programs were first launched, and is the most serious mammal pest problem in young stands. Red squirrels feed on the vascular tissues of young (sapling to pole-size; > 6.0 cm diameter) trees during May to early July when other natural foods are unavailable (Fig. 7a). This period is when sugar concentration in sap is presumably high and the bark is easy to remove (Kenward 1983). Damage may completely girdle the tree resulting in mortality, or partial girdling (sublethal) damage can suppress diameter and height growth (Sullivan et al. 1993). Red squirrels preferentially damage vigorous stems, and the lost growth of these trees may be substantial (Brockley and Sullivan 1988). Incidence of damage to lodgepole pine trees in PCT stands 15-25 years of age ranged from 30% to 96% across the central and southern interior of the province (Sullivan et al. 1994). Snowshoe hares also feed on fertilized lodgepole pine, but only stems < 6.0 cm diameter, and hence they are unlikely to be a problem in sapling and pole-size stands (Fig. 7e).

As reported earlier by Sullivan and Sullivan (1982), nitrogen fertilization appeared to enhance feeding damage to pine trees by red squirrels. Brockley and Sullivan (1988) reported significantly more severe squirrel damage (i.e., > 50% of stem circumference girdled) occurred in fertilized than unfertilized stands, and damage intensity tended to be directly related to fertilizer application rate. In addition, Brockley (1989, 1996) found

Figure 7. (a) Red squirrel damage to lodgepole pine. Note bark strips at base of tree. Trees > 6.0 cm dbh, (b) Black bear damage to lodgepole pine. Note large strips of bark scraped from tree and tooth marks on sapwood, (c) Porcupine damage to western hemlock, (d) close-up of porcupine damage. Note tooth marks.

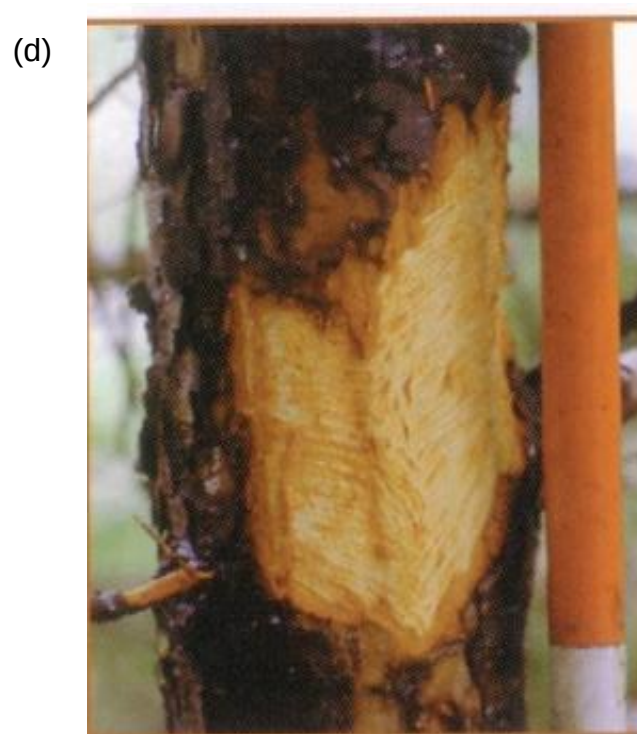


Figure 7(e). Snowshoe hare damage to lodgepole pine. Note ragged appearance of sapwood from hare feeding on vascular tissues and bark. Trees < 6.0 cm dbh.



that, three years after fertilization, the favourable effects on a stand volume basis were partly negated by red squirrel damage, and that 25% of lodgepole pine research installations sustained some damage from this rodent. In at least some cases, it was not clear how much damage had occurred in these stands prior to fertilization.

Thus, another crucial question arose from these studies: are all fertilized stands of lodgepole pine susceptible to severe feeding damage by the red squirrel? Another survey investigated damage in 23 stands in interior BC that had been operationally fertilized. Of these, 4 had severe levels (range of 43% to 74% of trees attacked) of damage (Sullivan 1992). These severely damaged stands were on good sites for tree growth, particularly with respect for moisture. Operational fertilization, therefore, apparently does not increase squirrel damage in target stands that are not already susceptible to attack because of other factors such as tree vigour, extensive areas of young stands, high levels of shrub cover, or relatively high squirrel populations (Sullivan et al. 1994).

4.2.6.2 Black bear damage

Black bear damage has been highly localized in BC, and is particularly common in the Golden timber supply area. Black bears are opportunistic feeders with a diet that includes conifer sapwood in the spring bud-burst period (May to early July) before preferred vegetation and berries are available. To gain access to the sugar-laden conifer sapwood, bears start at the base of the tree and use their claws to peel the bark in upward strips (Fig. 7b). Incisor teeth remove the vascular tissue leaving vertical marks. Complete girdling of trees in this fashion is lethal and partial damage may

reduce volume increment in stands. Levels of damage show some variability from year to year, but an area with damage tends to sustain increasing amounts in subsequent years. Black bears are known to damage up to 50-70 trees/day. Where bears are a problem, economic loss to forestry is significant (Schmidt and Gourley 1992).

A strong preference for fast growing, vigorous stems makes 15-25 year-old trees, particularly those in fertilized and/or thinned stands, highly susceptible to intense feeding by bears (Nelson 1989; Kimball et al. 1998). These factors may override tree species preference for damage. However, studies have indicated bear preferences for: lodgepole pine, western larch (*Larix occidentalis*), Douglas-fir, western red cedar (*Thuja plicata*), and western hemlock (*Tsuga heterophylla*) (Schmidt and Gourley 1992).

4.2.6.3 Porcupine damage

During winter months, porcupines use vascular tissues and foliage of pole-size (10-30 cm dbh) coniferous and hardwood trees as their principal food. Barking injury by this mammal leaves broad (0.3 cm), prominent horizontal and diagonal incisor marks on the exposed sapwood (Fig. 7c+d). Damage is particularly common in the upper section of tree stems and may result in loss of radial growth or mortality (Sullivan et al. 1986). Tree species damaged by porcupine in BC include western hemlock and Sitka spruce (*Picea sitchensis*) in north-coastal forests and lodgepole pine, Douglas-fir, and ponderosa pine (*P. ponderosa*) in interior forests (see review by Sullivan and Cheng 1989). We could find no reports on porcupine damage in fertilized stands, however, their preference to feed on vigorous dominant and co-dominant trees should be a cautionary note.

4.2.7 Management of mammal damage in fertilization programs

The first task in managing proactively to avoid mammal damage in fertilized stands is a pre-fertilization survey to determine if the stands currently have significant amounts (e.g., $\geq 15\%$ of trees with damage) of red squirrel, black bear, or porcupine damage. Incidence of damage will depend on tree species, age of stand, and degree of PCT (stand density). If lodgepole pine is the target tree species for fertilization, then the most likely mammal of concern is the red squirrel. Although black bears and porcupines may also feed on pine, such damage has been minor in BC.

To provide an assessment of the risk of squirrel damage when a pre-PCT or pre-fertilization survey is conducted, a decision-making profile is outlined in Fig. 8. Based on the 10 factors describing conditions that make young stands susceptible to squirrel damage, three levels of risk are given (Sullivan et al. 1994). Presumably, lodgepole pine stands with a high risk rating should be avoided in terms of fertilization programs. The investment should be allocated to other stands which have a low risk of future squirrel damage. Pine stands with a moderate risk of attack may still be fertilized but this risk may be minimized by reducing shrub cover, stand density, or diversionary feeding.

For black bears, it may be possible to ameliorate this damage problem in susceptible stands via altered silvicultural practices (Schmidt and Gourley 1992) such as: 1) create uneven-aged stands with a mix of tree species, possibly less preferred species where feasible; 2) delay thinning until trees are past the susceptible age range; 3) allow for higher stocking levels; 4) delay fertilization; 5) prune physiologically active lower branches; 6) protect and/or maintain patches of natural bear food; 7) seed landings and skid roads with clover and graminoids (but not in areas with potential vole

Figure 8. Assessment of the risk of red squirrel damage to fertilized stands.

DECISION-MAKING PROFILE**RISK ASSESSMENT CHECKLIST****WHEN**

- ☐ Significant cone crop in nearby mature forest this season or last? (Damage outbreak expected 1-2 years after cone crop)
- ☐ Peak years (± 2 years from expected peak) of snowshoe hare cycle (reduced predation on squirrels)
- ☐ Average stand diameter > 6.0 cm DBH
- ☐ Age classes 1 & 2 (10-40 years)

CHECKLIST SCORE

(maximum of 10)

1 – 2

3 – 5

6 – 10

FERTILIZATION**TO AVOID SUSCEPTIBLE STANDS****WHERE**

- ☐ Extensive stands (> 100 ha)
- ☐ Incidence of attack > 15% in unfertilized stand
- ☐ High slash load after PCT
- ☐ High levels of shrubs
- ☐ Fertilization planned
- ☐ Montane & Sub-boreal spruce BEC zones

DEGREE OF RISK

Low

Moderate

High

populations); 8) retain coarse woody debris to encourage invertebrate food for bears; 9) genetically select trees with higher terpene levels.

Besides natural forage enhancement, studies have been conducted at a management level in Washington and Oregon using an artificial diversionary food for bears (Ziegler 2004, 2006). Nutritional pellets are provided to the bears at feeding stations in high damage areas for the 2.5 months in the spring until natural foods become available. This technique does not appear to alter bear physiology, reproduction, home range behaviour, or survival, but does decrease damage levels to the point of economic viability.

4.2.8 Birds

Studies on the relationships between birds and fertilizers have tended to focus on the role of birds as predators of invertebrate herbivores in forest ecosystems (Edenius et al. 2011). The effects of fertilizer applications on the abundance, composition, and diversity of birds have received very little attention. Five references on responses of birds to forest fertilization included 2 from Sweden, 2 from the Yukon, and 1 from BC (Appendix 4). Where relative abundance of grouse species was measured, none showed any response to the fertilizer treatments (Ball et al. 2000; Martin et al. 2001). Ash and Bendell (1979) reported increased levels of nitrogen in fertilized food plants favoured by blue grouse (*Dendragapus obscurus*). However, Folkard and Smith (1995) found repeated fertilizer applications to have no effect on bird species richness in spruce forest with mixed canopy closure, but found numbers of the seven most abundant species to increase by 46% over three years. Similarly, Edenius et al. (2011) reported that repeatedly fertilized stands had 38% more species and 21% more

individuals than unfertilized stands. It was not clear whether the response in the bird community was related to changes in food resources (e.g., terrestrial invertebrates) (Edenius et al. 2012) or increased structural complexity in the forest canopy.

4.2.9 Terrestrial invertebrates (arthropods)

Much of the research into the effects of forest fertilization on terrestrial invertebrates (arthropods) has involved attempts to enhance the resistance of trees against needle and shoot damage by phytophagous pest insects (folivores). The influence of the nutrient status of trees on their resistance has been investigated by assessing the prevalence of damage and its causes in experimental plots (population level analyses) and by growing pest insects on trees or on components of trees in a laboratory (individual level analyses). Results at the population and individual levels appear contradictory because the effects on the population level may be strong enough to obscure the effects on the individual level. For example, nitrogen fertilization has been observed to make the needles and leaves more attractive to insects by elevating the concentrations of the amino acids and lowering the concentrations of defence compounds. In spite of this, the effects on the population level have usually remained relatively insignificant. This may be explained by the fact that, in addition to needle pests, predators and parasites benefit from fertilization (Kyto et al. 1996, 2000). The increase in biomass of understorey vegetation and the increased numbers of herbivorous insects add to the prevalence of predators and parasites, which in turn control the growth of the herbivore populations. This pattern can be seen in the results in Appendix 5 with 18 studies that examined a diversity of arthropods, primarily those pest species that feed on coniferous trees. Results of the influence of nitrogen

fertilization on populations of conifer pest species indicated 11 that increased (+), 7 with no change (0), and 4 species decreased (-) in abundance or other growth metric. Thus, there seemed to be little effect of nitrogen fertilization on enhancing resistance of forest trees to target pest insects.

This summary was primarily about needle and shoot feeding insect pests. There is, however, a very large literature base on insect-induced stem damage, particularly bark beetles in the genus *Dendroctonus*, and the efforts by researchers and managers to build resistance in target trees by fertilization and other silvicultural practices. That body of information is beyond the scope of this review, but may still be a worthwhile avenue to pursue to alleviate future outbreaks of MPB in BC.

In terms of non-conifer pest arthropod species, all of which had some connection as prey species for insectivorous birds, there were three publications in Appendix 5. Smith et al. (2001) sampling dipterans, lepidopterans, ground beetles, spiders, and sawfly larvae reported that arthropod biomass was not enhanced by fertilization of white spruce forest in the Yukon in the first two years of treatment. Seasonal changes in arthropod abundance were much larger than the effects of fertilization. Strengbom et al. (2005) found higher larval densities of the lepidopteran *Operophtera brumata* on shoots of *V. myrtillus* in fertilized than unfertilized forests in Sweden, particularly if avian predation was excluded. Edenius et al. (2012) reported that abundance of aphids (Hemiptera) and mites (Anactinotrichida and Actinotrichida) were higher in fertilized than unfertilized stands, but springtails (Collembola) were the converse in a study in Sweden. These positive effects on arthropod abundance may relate to higher numbers of birds that feed on folivorous arthropods. Repeated fertilization of young spruce has the

potential to enhance the suitability of these stands as winter feeding habitat for coniferous foliage-gleaning insectivorous birds compared to unfertilized stands in the same development stage (Edenius et al. 2012).

4.2.10 Soil animals

Responses of soil animals (mesofauna) to nitrogen fertilization, as with most organisms, appears to be species- and dose-specific and ameliorated or accentuated by surrounding micro- and macro-habitat characteristics (i.e., soil layer, acidity, N and C levels in the soil, etc.). Some studies showed single applications of standard forestry rates of N fertilizer, in the short term, had no significant effect on soil fauna (Abrahamsen and Thomas 1979; Nohrstedt and Westling 1995, as cited in Nohrstedt 2001; Berch et al. 2006) except under dry conditions (Sohlenius and Wasilewska 1984). However, Lohm et al. (1977) found a significant decrease in abundance of Enchytraeidae, Collembola, and Cryptostigmata abundance. Huhta et al. (1986) found that similar application rates of urea were enough to induce changes resulting in bacterial-feeding nematodes increasing temporarily, enchytraeid worms declining sharply, and some Coleoptera families infiltrating the treated area. Berch et al. (2009) found increases in forest floor Acari, Prostigmata and Oribatida, but increases of only Oribatida in mineral soil. After the initial two to four year period, abundance of enchytraeid fauna increased up to three times the control with temporary species dominance shifts regardless of nitrogen doses (100-1600 kg/ha) (Abrahamsen and Thompson 1979). Annual doses, for 13 years, of 75-100 kg N/ha/year also resulted in large shifts in soil microarthropod communities with no change in species richness or

diversity (Lindberg and Persson 2004). Some studies found higher doses of nitrogen reduced many microarthropod species and biomass (Huhta et al. 1986), specifically, mycophagous mites (Berch et al. 2006) and enchytraeid worms (Marshall 1974; Huhta et al 1986; Abrahamsen and Thompson 1979). However, Marshall (1974) found increased density of nematodes and no change in collembolans or mites at 224 and 448 kg/ha, respectively. Recovery from urea treatment varied by group or species and was still occurring two years after treatment (Huhta et al. 1986).

4.2.11 Non-timber forest products

Non-timber forest products (NTFPs) consist mainly of plants and fungi that may be used for a variety of cultural, subsistence, recreational, and commercial purposes (Vance et al. 2001). NTFPs have been, and continue to be, harvested throughout North America for traditional uses by local indigenous groups (Marles et al. 2000; Duchesne and Wetzel 2002). Understory herbs and shrubs, in particular, have been used for millennia by Canadian First Nations for a variety of uses to support livelihoods, including medicinals, edibles, cultural purposes, and trade (Duchesne and Wetzel 2002). Current livelihood values of these species has led to speculation that the harvest of NTFPs may be a sustainable use of natural resources that could aid in the diversification of forest management (Peterson and Maserud 2002). However, there is concern that forest fertilization may have undesirable effects on NTFPs. Thus, an evaluation of repeated fertilization on potential NTFPs in understory herb and shrub species in lodgepole pine stands was conducted in the interior of BC (Clason et al. 2009).

Fifty-four herb and shrub species were identified as potential NTFPs, with the responses of individual species, as well as mean total herb, shrub, berry-producing and

overall total NTFPs being assessed. Mean total abundance (crown volume index) of NTFPs, as well as mean total herb NTFPs, were significantly greater in fertilized than in unfertilized stands. PCT treatments (range of densities 250 to 2000 stems/ha) alone did not significantly affect NTFP abundance. However, fertilization treatments produced positive responses by individual species: yarrow (*Achillea millefolium*), fireweed, dandelion (*Taraxacum officinale*), and raspberry. However, the dwarf shrubs kinnikinnick, grouseberry (*V. scoparium*), and Prince's pine (*Chimaphila umbellata*) declined in fertilized stands. Other berry-producing shrubs appeared to do better in heavily thinned ($\leq 1,000$ stems/ha) stands with fertilization because of greater light in the open canopies, at least at this stage of succession (Kerns et al. 2004; Wender et al. 2004). This study did not evaluate the livelihood values of these crops, the actual berry production, flowering, and quality of fertilized shrub species, nor did we investigate other NTFPs such as fungi. Also, this was a repeated fertilization project based on optimum nutrition of lodgepole pine (Lindgren and Sullivan 2013a+b), and hence responses of potential NTFP herbs and shrubs may be different in standard forest fertilization practices.

Observations from earlier N-fertilization studies in Norway reported positive effects on *V. myrtillus* and *V. vitis-idaea* for both vegetative growth and berry production (Brantseg 1966, as cited in Nilsen 2001). In Finland, there was no consistent effect on biomass of herbs from nitroge fertilization, but the two *Vaccinium* shrubs declined on fertile sites, but not necessarily on poor sites (Makipaa 1994). Nitrogen fertilization had variable and contradictory effects on *Vaccinium* berry crops (review by Saarsalmi and Malkonen 2001). The decline in berry crops after fertilization on fertile sites may be

related to the enhanced growth of grasses and forbs on those specific sites. However, fertilization apparently had no harmful effects on the nutrient concentrations of the berries, as indicated by several authors in Saarsalmi and Malkonen (2001).

In Sweden, in addition to traditional forest products, berries provide alternative revenue within boreal forests (Kardell, 1980; Mattsson and Li, 1993), and the influence of fertilization on berry production should therefore be acknowledged when the effects of commercial forest fertilization is evaluated. Forest fertilization reduced the amount of berries produced by *V. myrtillus* by > 70%, but these results were from a clearcut site that had been last fertilized 20 years earlier (Strengbom and Nordin 2008). These authors found only a weak tendency towards lower number of berries produced per annual shoot in fertilized stands. The lower density of berries in these stands was largely caused by a lower number of current annual shoots and a lower overall abundance of *V. myrtillus*.

5.0 Conclusions

5.1 Direct effects of fertilization on wildlife

- 1) Amphibians and domestic mammals appear to be the most sensitive to urea used in fertilization programs. The avoidance behaviour and/or mortality of amphibians in laboratory studies was species-dependent. We did not find any published field studies of the influence of forest fertilization compounds on amphibians.
- 2) Ruminant animals, including wild ungulates such as deer, moose, elk, and caribou (reindeer), rapidly convert urea to ammonia and are susceptible to toxicity following ingestion of large amounts of urea. Fertilizer spills at storage or transfer facilities are

probably the greatest potential wildlife hazard, and careful management should avoid any problems.

- 3) Feeding on urea pellets by small mammals or ground-active birds (e.g., grouse) appears to be minimal as granules are unpalatable.

5.2 Indirect effects of fertilization on wildlife

5.2.1 Understory plants

- 1) The majority of responses of understory herbs to nitrogen fertilization showed an increase in abundance. In the interior of BC, mean abundance of total herbs, grasses, and fireweed all increased dramatically with repeated fertilization, up to 3-4 times compared with unfertilized stands. Some shrubs in repeatedly fertilized stands eventually increased in abundance in the long-term studies in BC and the Yukon. Dwarf shrubs such as twinflower, kinnikinnick, and various *Vaccinium* species declined, likely in response to competition from dominant herbs and increasing canopy cover from rapidly growing crop trees in fertilized stands. Abundance of bryophytes and terrestrial lichens followed the pattern of dwarf shrubs with the majority of studies reporting declines in these non-vascular plants.
- 2) Species richness and diversity of understory herbs and shrubs declined or were unaffected in fertilized stands. Competitive exclusion from a few dominant species was the likely explanation.
- 3) Response in abundance of vascular plants to a single application of nitrogen showed either an increase or no change. This pattern was similar for responses in species richness and diversity whereby 8 and 10 records of no change were recorded,

respectively. Repeated applications (2-5 and > 5) showed a trend to either no change or declines in responses of plant abundance and species richness-diversity.

5.2.2 Mammals

- 1) The shift in vegetation from dwarf shrubs and mosses-lichens to grasses and dominant herbs provided excellent habitat for *Microtus* voles in Canada and also Scandinavia. Overall for small mammal species, there were 6 increases, 15 no changes, and 6 decreases in responses to fertilization. Relative abundance of deer, moose, and hares, and forage quality as indexed by nitrogen concentration, was usually increased by fertilization.
- 2) Fertilization consistently improved forage production for livestock by the increased abundance of herbs and grasses for sheep and cattle. In the BC study, fertilized stands received 2.1 times more cattle use than unfertilized stands, with no apparent negative effects on mule deer occupying the same range.
- 3) The red squirrel (most important), black bear, and porcupine may feed on sapling to pole-size trees in fertilized stands. A pre-fertilization survey should be conducted to determine if the stands currently have significant amounts (e.g., $\geq 15\%$ of trees) of damage. A decision-making profile provides an assessment of the risk of squirrel damage based on 10 factors describing conditions that make young stands susceptible.

5.2.3 *Birds, insects, and soil animals*

- 1) For non-conifer pest arthropods, fertilization may provide winter feeding habitat for coniferous foliage-gleaning insectivorous birds in some cases. Five species of forest grouse showed no response to fertilizer treatments.
- 2) Responses of soil animals (mesofauna) to nitrogen fertilization appears to be species- and dose-specific and ameliorated or accentuated by surrounding micro- and macro-habitat characteristics.

5.2.4 *Non-timber forest products*

- 1) Mean total abundance and total herb NTFPs were significantly greater in repeatedly fertilized than in unfertilized stands in BC. In Scandinavia, nitrogen fertilization had variable and contradictory effects on *Vaccinium* berry crops with respect to site fertility.

5.3 Relevance to operational fertilization in BC

- 1) In terms of vegetation changes, a key question is: how long do these responses last, particularly after the final nitrogen application? In Scandinavia, repeated fertilization leads to species replacement and a flora indicative of more fertile sites. However, these effects are likely temporary after less intensive fertilization (i.e., 1 or 2 applications) and usually only small remnant effects on vascular plants are to be found 10 years after fertilization. Resilience of vegetation is likely slower in boreal than temperate forests, as indicated by the long-term repeated fertilization study in the interior of BC. At 6 and 11 years after the last of five repeated fertilizer

applications, mean abundance and mean species diversity of herbs and shrubs in fertilized stands had returned to levels recorded in unfertilized stands.

- 2) There may be management situations (e.g., range enhancement for cattle, winter range for ungulates, green-up and free-to-grow status) that require consistent tree cover and/or forage production during specific periods of forest succession.

6.0 Information and Research Needs

- 1) Monitoring of both the short- and long-term influence of conventional fertilization (e.g., one application every 6 years or so) on understory herbs, shrubs, and bryophytes and terrestrial lichens in BC would be a worthwhile endeavour. A sampling regime should be initiated to determine potential changes in understory vegetation in fertilized stands. This should be done annually for at least five years after fertilization at replicated sites. The research should be conducted at a scientific level so that results will be publishable in a suitable peer-reviewed journal. This is a reasonable funding investment (i.e., relatively low cost) if one can piggy-back on operational-scale treatments (adaptive management).
- 2) Conventional thinning treatments (e.g., 1600-2000 stems/ha) alone have had limited effect on enhancing understory plants for forage for wildlife and cattle. Addition of fertilization and heavy thinning (≤ 1000 stems/ha) has dramatically improved forage in the understory of managed stands. Needless to say, this approach needs to carefully assess the trade-off of understory habitat and merchantable tree volume.

- 3) Analysis of data, and synthesis into a manuscript for publication, for moss and terrestrial lichen datasets from the 20-year repeated fertilization project in lodgepole pine stands in south-central BC. Another low-cost investment.
- 4) In fertilization sites that have berry-producing shrubs, sampling of shrub cover or crown volume index, and berry production, before and after treatment, and in controls, would be worthwhile from a NTFPs and wildlife forage perspective. The impact of fertilization on berry production remains a contradictory issue, primarily because of a lack of rigorous sampling and experimentation. Quality and nutrition of berries could also be examined. Likely a moderate cost investment, but could be part of vegetation sampling (1) in treatment sites.
- 5) In addition to (4), the influence of fertilization on NTFP fungal and mushroom development in replicated control and treatment stands should be investigated. A relatively low-cost investment.
- 6) Field studies of amphibians, birds, and terrestrial invertebrates could be initiated to help fill the lack of information on responses to operational fertilizer applications by these groups. In all three cases, these studies would be a moderate cost investment, but kept to realistic levels by piggy-backing on operational treatments.

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8.0 Appendices

Appendix 1. Influence of forest fertilization on abundance, species richness, and diversity of understory plants.

Author(s)	Country	Habitat	Fertilizer	Appl. rate kgN/ha	# appl.	n	Years of, or after, fertilization	Abundance	Richness	Diversity	Abundance of Bryophytes
								Herbs Shrubs	Herbs Shrubs	Herbs Shrubs	
Ball et al. 2000	Sweden	<i>Pinus & Betula pubescens</i>	NH ₄ NO ₃	200	1	25	2	S+1			
Bauhus et al. 2001	Australia	<i>Eucalyptus sieberi</i>	NH ₄ SO ₄	100	1	3	6	HS0	HS0	HS0	
Brockley 2007b	Canada BC	<i>Pinus contorta & Picea sps.</i>	ureaRFON	200-900	1+6	3	6	HS+1	H0S0	H-1S-1	B-1
Carneiro et al. 2008	Portugal	<i>Eucalyptus globulus</i>	granular	42	1	4	8	HS0	HS0	HS0	
Dirkse & Martakis 1992	Sweden	<i>Pinus sylvestris</i>	BothRFON	120-180	18	4+6	17-19				B+1-1
Eriksson & Raunistola 1993	Sweden	<i>Pinus sylvestris</i>	BothRF	150-250	2	8	11	S+1			B-1
Hedwall et al. 2010	Sweden	<i>Picea abies</i>	NH ₄ NO ₃ RF	425-625	3, 4, 7	15	6	H-1S-1			B-1
Hedwall et al. 2011	Sweden	<i>Picea abies</i>	NH ₄ NO ₃ RF	425-625	3, 4, 7	15	6		HS-1	HS-1	B0
Hedwall et al. 2013a	Sweden	<i>Picea abies</i>	BothRF	1200-1600	20-23	2-4	20-23	HS-1	HS0	HS+1	
Kaye et al. 2008	USA PNW	<i>Pseudotsuga menziesii</i>	NH ₄ NO ₃	336-1345	1	5-7x5	24-28	HS0		HS0	
Kellner 1993	Sweden	<i>Pinus sylvestris + Picea abies</i>	BothRF	360-2400	3-5	4	17-21	H+1	HS0		B-1

Kellner & Mårshagen 1991	Sweden	<i>Pinus sylvestris</i>	NH ₄ NO ₃ RF	1510	8	15	7		H+1+S1			
Kellner & Redbo-Torstensson 1995	Sweden	<i>Picea abies</i> & <i>Pinus sylvestris</i>	NH ₄ NO ₃ RF	260	4	5	1-5	H+1S0				
Krebs et al. 2001	Canada, Yukon	<i>Picea glauca</i>	NH ₄ NO ₃ RF	1200	7	2	9	S+1				
Lindgren & Sullivan 2013b	Canada BC	<i>Pinus contorta</i>	ureaRFON	750	1+5	3	10	H+1S0	H0S0	H-1S-1		
Makipaa 1994	Finland	<i>Picea abies</i> & <i>Pinus sylvestris</i>	NH ₄ NO ₃ RF	596-926	5-7	6	26-30	H0S-1				B-1
Nams et al. 1993	Canada Yukon	<i>Picea glauca</i>	NH ₄ NO ₃ RF	188-1250	2	3	2	H+1S+1				
Nohrstedt 1998	Sweden	<i>Pinus sylvestris</i>	NH ₄ NO ₃ RF	600	2, 3, 4	2	8-12	S0				B-1
Oswald et al. 2009	USA Texas	<i>Pinus taeda</i>	N	224	1	?	2		HS-1	HS-1		
Persson 1981	Sweden	<i>Pinus sylvestris</i>	BothRF	640	7	?	8	HS+1				B-1
Prescott et al. 1993	Canada BC	<i>Tsuga heterophylla</i> & <i>Pseudotsuga menziesii</i>	ureaRF	300-2250	3	3	5	HS-1				B-1
Prescott et al. 1995	Canada Quebec	<i>Pinus banksiana</i>	urea NH ₄ NO ₃ RF	336-1344	6	?	9	S-1				B-1
Riegel et al. 1991	USA Oregon	<i>Pinus ponderosa</i>	NH ₄ NO ₃	50	1	3	1	HS+1				
Strengbom et al. 2001	Sweden	<i>Pinus sylvestris</i>	NH ₄ NO ₃ RF	990-2160	28	3	28	H+1S-1		HS-1	B+1B-1	
Strengbom & Nordin 2008	Sweden	<i>Picea abies</i> & <i>Pinus sylvestris</i>	NH ₄ NO ₃ RF	300	2	14,15	22-30	H+1S-1	HS+1	HS-1	B-1	
Sullivan et al. 2009	Canada BC	<i>Pinus contorta</i>	ureaRFON	750	5	3	10	H+1S0	H0S0	H0S0	B-1	

Thomas et al. 1999	USA Wash.	<i>Pseudotsuga menziesii</i>	ureaRF	1120-1512	3-5	6	12-15	HS-1	H-1S-1	HS0	B0
Turkington et al. 1998	Canada Yukon	<i>Picea glauca</i>	NH ₄ NO ₃ RF	1200	7	2	9	S-1			B-1
Turkington et al. 2002	Canada Yukon	<i>Picea glauca</i>	NH ₄ NO ₃ RF	1200	1+7	2	9	H+1	HS-1	HS-1	
Tyler et al. 1992	Sweden	<i>Fagus sylvatica</i>	NH ₄ NO ₃ RF	1200	5	?	5	HS-1			
VanderSchaaf et al. 2000	USA Wash., Idaho, Ore.	<i>Pseudotsuga menziesii</i> &/or <i>Pinus ponderosa</i>	Multi-nutr	220	1	5	1-2	H+1		H0S0	
Veen et al. 2015	Sweden	<i>Betula pubescens</i> & <i>tundra</i>	NH ₄ NO ₃ RF	100	3	5	3	H1S-1	HS0	HS0	
Walter et al. 2016	USA Appalachia	Appalachian forest	(NH ₄) ₂ SO ₄ RF	35	23	15	23	S+1			

Notes: RF = Repeated Fertilization; ON = Optimum Nutrition; Both = urea + NH₄NO₃.

Appendix 2. Influence of forest fertilization on abundance, forage, and habitat production for mammals.

Author(s)	Country	Habitat	Fertilizer	Appl. rate kgN/ha	# appl.	n	Years of, or after, fertilization	Species	Relative abundance	Forage quantity	Forage quality
									Mammals	Herbs Shrubs	Herbs Shrubs
Ball et al. 2000	Sweden	<i>Picea abies</i> & <i>Pinus sylvestris</i>	CaNH ₄ NO ₃	200	1	25	2	Moose	+1	+1 shrubs+ trees	+1
								Mountain hare	+1		
								Other mammals	+1		
Boonstra et al. 2001a	Canada Yukon	<i>Picea glauca</i>	NH ₄ NO ₃ RF	1200	7	2	9	Red squirrel	-1	+1 herbs	
								Ground squirrel	-1	+1 herbs	
Boonstra & Krebs 2006	Canada Yukon	<i>Picea glauca</i>	NH ₄ NO ₃ RF	1200	7	2	9	Red- backed vole	-1	-1 shrubs	
Boonstra et al. 2001b	Canada Yukon	<i>Picea glauca</i>	NH ₄ NO ₃ RF	1200	7	2	9	<i>Microtus</i> spp.	+1	+1 herbs	

Edenius 1993	Sweden	<i>Pinus sylvestris</i>	NH ₄ NO ₃ RF	48	1		1	Moose		+1 trees	+1
Eriksson & Raunistola 1993	Sweden	<i>Pinus sylvestris</i>	BothRF	150-250	2	8	11	Reindeer		+1 +1	
								Reindeer		-1 lichens	
Hodges et al. 2001	Canada Yukon	<i>Picea glauca</i>	NH ₄ NO ₃ RF	1200	7	2	9	Snowshoe hare	+1	+1 shrubs	
Lindgren & Sullivan 2012	Canada BC	<i>Pinus contorta</i>	ureaRFON	750	5	2	10	Cattle		+1 herbs	+1 herbs
Lindgren & Sullivan 2014a	Canada BC	<i>Pinus contorta</i>	ureaRFON	750	5	2	13	Cattle		+1 herbs	+1
Lindgren & Sullivan 2014b	Canada BC	<i>Pinus contorta</i>	ureaRFON	750	5	3	10	Cattle	+1	+1 0	
								Mule deer	+1		
Nams et al. 1996	Canada Yukon	<i>Picea glauca</i>	NH ₄ NO ₃ RF	188-1250	2	3	2	Snowshoe hare	+1	+1 grasses	
Papanastasis et al. 1995	Greece	<i>Pinus pinaster</i>	NPK	110	1	2	3	Domestic sheep		+1 grasses	0
Shaw et al. 2010	USA Tenn.	Mixed hardwoods	NH ₄ NO ₃	50	1	4	1	White-tailed deer		0	0

Sullivan et al. 2006a	Canada BC	<i>Pinus contorta</i>	ureaRFON	750	5	3	10	Snowshoe hare	+1	+1	0
Sullivan et al. 2006b	Canada BC	<i>Pinus contorta</i>	ureaRFON	750	5	3	10	Mule deer	+1	+1	0
								Moose	+1	+1	0
Sullivan et al. 2009	Canada BC	<i>Pinus contorta</i>	ureaRFON	750	5	3	10	Small mammals	0	+1	0
								Meadow vole	0		
								Long- tailed vole	0		
								Heather vole	0		
								Red- backed vole	0		
								Deer mouse	0		
								Chipmunk	0		
								Montane shrew	0		
								Masked shrew	0		

								Jumping mouse	0		
								Weasel	0		
Sullivan et al. 2010	Canada BC	<i>Pinus contorta</i>	ureaRFON	750	5	3	10	Snowshoe hare	0	0	0
								Mule deer	0		
								Moose	0		
Sullivan et al. 2012	Canada BC	<i>Pinus contorta</i>	ureaRFON	750	5	3	10	Small mammals	+1	+1	herbs
								Meadow vole	+1		
								Long-tailed vole	0		
								Heather vole	0		
								Red-backed vole	-1		
								Deer mouse	-1		
								Chipmunk	-1		
								Montane	+1		

								shrew			
								Masked shrew	0		
								Jumping mouse	0		
								Weasel	+1		
Sullivan et al. 2012	Canada BC	<i>Pinus contorta</i>	ureaRFON	750	5	3	10	Snowshoe hare	+1	+1	0
Sullivan et al. 2013	Canada BC	<i>Pinus contorta</i>	ureaRFON	750	5	3	10-15	Small mammals	0	+1	0
								Red-backed vole	0		
Sullivan & Sullivan 2014	Canada BC	<i>Pinus contorta</i>	ureaRFON	750	5	3	10	Meadow vole	+1	+1	herbs
Sullivan & Sullivan 2017	Canada BC	<i>Pinus contorta</i>	ureaRFON	750	5	3	20	Red-backed vole	+1	+1	shrubs

Notes: RF = Repeated Fertilization; ON = Optimum Nutrition; Both = urea + NH₄NO₃.

Appendix 3. Influence of forest fertilization on mammal feeding damage to crop trees.

Author(s)	Country	Habitat	Fertilizer	Appl. rate kgN/ha	# appl.	Study or review	n	Years of, or after, fertilization	Species	Relative density	
										Mammals	Damage
Ball et al. 2000	Sweden	<i>Picea abies</i> & <i>Pinus sylvestris</i>	CaNH ₄ NO ₃	200	1	Study	25	2	Moose	+1	+1
Brockley & Sullivan 1988	BC Canada	<i>Pinus contorta</i>	urea	100- 200	1	Study	3	1	Red squirrel		+1
Brockley 1989	BC Canada	<i>Pinus contorta</i>	urea	various		Review			Red squirrel		+1
Brockley 1996	BC Canada	<i>Pinus contorta</i>	urea	various		Review			Red squirrel		+1
Kimball et al. 1998	USA Wash. Ore.	<i>Pseudotsuga</i> <i>menziesii</i>	urea	224	1	Study	9	1-4	Black bear		+1
Nelson 1989	USA Ore.	<i>Pseudotsuga</i> <i>menziesii</i>	urea	448+22 4	2	Study	4	6 years later	Black bear		+1
Nilsen 2001	Norway	<i>Pinus sylvestris</i>	NH ₄ NO ₃			Review			Moose		+1
Schmidt & Gourley 1992	USA PNW	Several species				Review			Black bear		+1
Sullivan & Sullivan 1982	Canada BC	<i>Pinus contorta</i>	NH ₄ NO ₃	50-150	1	Study		1	Red squirrel		+1
Sullivan 1992	Canada BC	<i>Pinus contorta</i>				Review			Snowshoe hare Red squirrel		+1 +1
Sullivan & Klenner 1993	Canada BC	<i>Pinus contorta</i>	urea		1	Study	3	1	Red squirrel		+1
Sullivan et al. 1994	Canada BC	<i>Pinus contorta</i>				Review			Red squirrel		+1

Appendix 4. Influence of forest fertilization on birds.

Author(s)	Country	Habitat	Fertilizer	Appl. rate kgN/ha	# appl.	n	Years of, or after, fert.	Species	Relative	Forage	Forage	Richness		
									density	quantity	quality	Nutrition & diversity		
										Herbs	Herbs	Herbs		
									Birds	Shrubs	Shrubs	Shrubs	Birds	
Ash & Bendell 1979	Canada BC	<i>Pseudotsuga menziesii</i> <i>Tsuga heterophylla</i> <i>Thuja plicata</i>	NH ₄ NO ₃ + urea	112, 224, 336	1	5	1	Blue grouse			+1			
Ball et al. 2000	Sweden	<i>Picea abies</i> & <i>Pinus sylvestris</i>	CaNH ₄ NO ₃	200	1	25	2	Capercaillie	0	+1 shrubs	+1	Pine+ & birch+		
								Black grouse	0					
								Hazelhen	0					
Edenius et al. 2011	Sweden	<i>Picea abies</i>	RF	400-500	4	4,12	7	19 species	+1				R+1	
Folkard & Smith 1995	Canada, Yukon	<i>Picea glauca</i>	NH ₄ NO ₃ RF	1200	7	2	9	Passerine birds	+1				R0	
Martin et al. 2001	Canada, Yukon	<i>Picea glauca</i>	NH ₄ NO ₃ RF	1200	7	2	9	Spruce grouse	0					
								Ruffed grouse	0					

Note: RF = Repeated Fertilization.

Appendix 5. Influence of forest fertilization on terrestrial invertebrates (arthropods)

Author(s)	Country	Habitat	Fertilizer	Application rate kgN/ha	# appl.	n	Years after fert.	Common name	Response
Bakke 1969	Norway	<i>Picea abies</i>	urea	200	1	15	1.5	spruce seed moth	+1
Bjorkman et al. 1991	Sweden	<i>Pinus sylvestris</i>	NH ₄ NO ₃	50	1	16	1	sawfly	0
Edenius et al. 2012	Sweden	<i>Picea abies</i>	N	100–125	4	4+12		true bugs	+1
Heijari et al. 2008	Finland	<i>Pinus sylvestris</i>	(NH ₄) ₂ SO ₄ ; urea; NH ₄ NO ₃	82, 92 & 150-180	3-7	6	7-20	mites	+1
								mites	+1
								springtails	-1
								wood borer	+1 0 -1
Heliovaara et al. 1983	Finland	<i>Pinus sylvestris</i>	NH ₄ NO ₃ with lime	150	1	50	3	pine bark bug	+1
Heliovaara & Loyttyniemi 1989	Finland	<i>Pinus sylvestris</i>	(NH ₄) ₂ SO ₄ & urea	200- 400	3 - 4	2	1, 5, 10, 15	Curculinoid (1)	+1
								Curculinoid (2)	+1
Loyttyniemi & Heliovaara 1991	Finland	<i>Pinus sylvestris</i>	(NH ₄) ₂ SO ₄ & urea	84 & 92	4	8	4 yrs	spruce spider mite	+1 0
Mason et al. 1992	USA Ore.	<i>Abies grandis</i>	urea	350	1	4	4-5	spruce budworm	+1 0
McClure 1991	USA Conn.	<i>Tsuga canadensis</i>	Homogenite 41N	0.25 kg/tree	1	10	2-9 months	hemlock wooly adelgid	+1
McCullough & Kulman 1991	USA Wis.	<i>Pinus banksiana</i>	NH ₄ NO ₃	140 – 400	2	20	1	jack pine budworm	0
Mitchell & Paul 1974		<i>Pseudotsuga menziesii</i>		56 & 224	?	?	?	aphid	+1 0 -1

Moore & Layman 1978	USA N.C.	<i>Pinus taeda</i>	10N-10P-10K	1,121	1	5	20, 40 & 80 days	southern pine beetle	0
								black turpentine beetle	0
Popp et al. 1986		<i>Picea glauca</i>	NH ₄ NO ₃	224 & 448	1	30	2 months	spruce sawfly	+1 -1
Schmidt & Fellin 1983	USA Mont.	<i>Larix occidentalis</i>	urea	336	1	12	2, 4 & 6	western spruce budworm	+1
Selander & Immonen 1992	Finland	<i>Pinus sylvestris</i>	30-133 mg/l		1	125	0	pine weevil	+1
Shaw et al. 1978	Canada, NB	<i>Abies balsamea</i>	urea, ammonium acetate, calcium nitrate	313.6		2	1-2 months	spruce budworm	+1
Smith et al. 2001	Canada, Yukon	<i>Picea glauca</i>	NH ₄ NO ₃ RF	1200	7	2	9	lepidopteran	+1 -1
								sawfly	+1 -1
								ground beetles	0
								spiders	0
								arthropod	0
Strengbom et al. 2005	Sweden	<i>Picea abies</i>	NH ₄ NO ₃	12.5 & 50	7	6	for 7 yrs	winter moth	+1 0

Notes: RF = Repeated Fertilization; ON = Optimum Nutrition.

Appendix 6. Influence of forest fertilization on soil animals (mesofauna).

Author(s)	Country	Habitat	Fertilizer	Application rate kgN/ha	# appl.	<i>n</i>	Time after fertilization	Response
Abrahamsen & Thompson 1979	Norway	<i>Pinus sylvestris</i> & <i>Picea abies</i>	urea	0, 100, 400 & 1600	1	3	followed for 11 yrs	+1 0 -1
Berch et al. 2006	Canada BC	<i>Pinus contorta</i>	urea RFON	50-100 & 100-200	10	3	10 yrs	+1 0 -1
Berch et al. 2009	Canada BC	<i>Pinus contorta</i>	urea RFON	50-100 & 100-200	10	3	10 yrs	+1
Huhta et al. 1986	Finland	<i>Pinus sylvestris</i> & <i>Picea abies</i>	urea & NH ₄ NO ₃	200-460	1	2	2 & 4 yrs	+1 0 -1
Lindberg & Persson 2004	Sweden	<i>Picea abies</i>	NH ₄ NO ₃	75-100	13	4	10 yrs	+1 -1
Lohm et al. 1977	Sweden	<i>Pinus sylvestris</i>	NH ₄ NO ₃ & urea RFON	40-180	3	3	5 months-3 yrs	-1
Marshall 1974	Canada BC	<i>Pseudotsuga menziesii</i>	urea	0, 224, 448	1	3	monthly for 1 yr	+1 0 -1
Sohlenius & Wasilewska 1984	Sweden	<i>Pinus sylvestris</i>	N	610-1170	8	5	6 yrs	-1

Notes: RF = Repeated Fertilization; ON = Optimum Nutrition.