Can Repeated Fertilizer Applications to Young Norway Spruce Enhance Avian Diversity in Intensively Managed Forests?

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Abstract Repeated fertilization of forests to increase biomass production is an environmentally controversial proposal, the effects of which we assessed on breeding birds in stands of young Norway spruce (*Picea abies*), in an intensively managed forest area in southern Sweden. Our results show that fertilized stands had 38% more species and 21% more individuals than unfertilized stands. Compared with stands under traditional management, the further intensification of forestry by repeated applications of fertilizers thus seemed to enhance species richness and abundance of forest birds. We cannot conclude at this stage whether the response in the bird community was caused by changes in food resources or increased structural complexity in the forest canopy due to the skid roads used for the application of the fertilizers. Future studies should focus on structural and compositional effects of fertilization processes during the entire rotation period and at assessing its effects in a landscape context.

Keywords Intensive forestry · Fertilization · Birds · Biodiversity · Norway spruce

INTRODUCTION

The demands for wood fiber and biofuels are expected to increase significantly in the near future (Raunikar et al. 2010). An important means to satisfy these demands is to increase biomass production in existing forests (e.g. Nabuurs et al. 2007). However, the intensification of biomass production is usually associated with a loss of biodiversity, thus any undertaking to intensify forestry should be carefully considered within the framework of a sustainable

approach before new silvicultural measures are implemented over large scales (Hartmann et al. 2010).

As productivity in northern forests is limited primarily by nitrogen (Tamm 1991), applying supplementary nitrogenous fertilizers can potentially increase the production of wood fiber biomass far above that achievable under traditional silvicultural management (e.g. Kenk and Fisher 1988). Repeated applications of fertilizers to young stands of Norway spruce (*Picea abies*), a dominant tree species in northern European forests, has been shown to enhance growth markedly, with the increased production of stem wood being estimated at 80–300% above that achieved by traditional forest management (Bergh et al. 2005, 2008).

With repeated applications, fertilizers are first applied when young Norway spruce are about 2 m tall, and again every second year until the stand closes 10–12 years later. Thereafter, fertilizer is applied on two or three occasions every 10th year, till final felling at about 40–60 years of age (Bergh 2000). It has been estimated that over the coming 10 years, 300000 ha of forest land in Sweden could be allocated for repeated fertilizer applications to young forest, and that 10% of the forest land is suitable for this kind of forestry (Skogsstyrelsen 2008). This scheme of fertilizer application adds approximately 700–1000 kg ha⁻¹ of nitrogen to forest over its rotation period in southern Sweden, and as much as 900–1200 kg ha⁻¹ in northern Sweden, which amounts to a substantial extra input of nitrogen to the forest ecosystem compared to traditional, single-event fertilizations. As trees grow faster in fertilized stands and the rotation period is shortened, the succession from young to old forest is shortened and the time a forest spends in mature and old stages is reduced compared to traditional forest management. Consequently, organisms associated with

trees while in these specific growth stages, e.g. old forest specialists, and species adapted to the early stages of forest succession, may be adversely affected by these changes in forest dynamics. Most studies of the environmental impacts of fertilizers have hitherto focused on nutrient leakage and insect damage, while studies of fertilizer effects on specific biota are scarce (but see Sullivan et al. 2009).

Hedwall et al. (2010) found that fertilizers directly affect the ground vegetation by altering the nutrient balance, and indirectly by altering the light regime. Thus, both compositional and structural changes in the forest canopy take place. Several studies have reported that additional nitrogen can significantly change the community composition and biomass of belowground fungi in forests (Peter et al. 2001; Wallenstein et al. 2006; Allison et al. 2007). In another study, Lindberg and Persson (2004) found the soil micro-arthropod community composition in Norway spruce stands to be markedly affected by the intensive application of nitrogen fertilizers, although species richness remained stable.

Studies on the relationships between birds and fertilizers have almost exclusively dealt with the role of birds as predators of invertebrate herbivores, i.e. the function of birds as regulators of food web dynamics in forest ecosystems (e.g. Marquis and Whelan 1994; Strong et al. 2000; Garibaldi et al. 2010). The effects of repeated fertilizer applications on the abundance, composition and diversity of birds have received very little attention. One rare example is a study in northern Canada by Folkard and Smith (1995) who 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. In the present study, we investigate the effect of repeated fertilizer applications to young Norway spruce on the breeding bird community attributes by comparing fertilized young spruce stands with unfertilized stands in an intensively managed hemi-boreal forest area. Besides examining overall species richness and abundance, we focus on insectivorous birds: a species group that we expected to be closely linked to the effects of fertilizer applications through food web dynamics.

MATERIALS AND METHODS

Study Area

The present study was conducted in Toftaholm, which is located in the hemi-boreal zone in southern Sweden (57°00' N/14°09' E) (Ahti et al. 1968). The terrain is basically flat (145–170 m a. s. l.), and is dominated by Norway spruce forest intermixed with patches of deciduous forest and lakes. The mean annual temperature, based on 1961–1990 data, is 6.5°C, (15°C in July; −1.5°C in January). The mean annual precipitation is about 800 mm, with the maximum falling in July–August and November–December (Raab and Vedin 1995). The number of days with precipitation is about 200 per year, i.e. the climate is relatively humid. The bedrock is composed of granite with pockets of (ultrabasic) diorite and amphibolite (Fredén 1994). The mean site productivity, expressed in the H100-index system (tree height at 100 years of age), varies between 30 and 34 m, which is high for the region. Toftaholm was severely affected by the storm Gudrun in January 2005, which felled >50% of the standing tree volume. Consequently, there are large areas of regenerating forest in the area.

Sweden's largest ongoing full-scale trial with repeated fertilizer applications to young Norway spruce forest is currently held in Toftaholm. Since 2003, approximately 35 ha of young Norway spruce have been fertilized every second year, i.e. had received up to four fertilizer applications at the time of the present study. On each occasion, 100–125 kg ha^{−1} N was machinery distributed from the ground along skid roads transecting the fertilized stands at c. 50 m regular distance. We compared fertilized and unfertilized spruce stands in the same developmental stage distributed over a c. 15 km² large area at Toftaholm. Four fertilized stands and 12 unfertilized stands were selected for the study, i.e. 16 stands in total. We used all available fertilized stands and included many more unfertilized stands to cover as large gradient as possible in stand characteristics among young managed spruce stands in the area. Stand age varied between 6–27 years (Table 1). In essence, the investigated stands represent a 21-year

Table 1 Characteristics of fertilized and unfertilized Norway spruce stands surveyed

Category	No. of stands	Area, ha	Age, years	Height, m	Volume spruce, m ³ ha ^{−1}	Volume birch, m ³ ha ^{−1}	Variation in stem density, CV%	Canopy closure, %
Fertilized	4	7.3 (4.6–13.4; 2.0)	12 (11–13; 0.6)	9.6 (9.3–9.9; 0.2)	58 (45–90; 11)	2.5 (0–5; 1.4)	45 (24–72; 12)	41 (11–13; 0.6)
Unfertilized	12	7.1 (3–18.6; 1.3)	14.5 (6–27; 1.9)	10 (5.6–12.9; 0.6)	89 (5–280; 24)	5.8 (0–20; 2.3)	37 (21–69; 4)	41 (6–27; 1.9)

Means (range; and standard error)

chronosequence of young, intensively managed Norway spruce forest. The stands had been subjected to mechanical cleaning of deciduous trees (birch, *Betula* spp.) before the study. We avoided stands that had been recently cleaned so as to minimize the impact of this disturbance source. Because of the severe Gudrun storm in 2005, most of the selected stands were surrounded by a matrix dominated by young forest.

Stand Surveys and Data Analysis

Bird surveys were made as 5-min point counts, repeated six times between April 8 and May 26 2010. Thirty survey points were located in the 16 stands, with between one and four points per stand depending on the size of the stand such that each survey point represented approximately 3–4 ha of forest. In larger stands, survey points were located randomly within 50 m from stand borders, whereas in smaller stands (<4 ha) the survey point was located at the center of the stand. Multiple survey points in stands were at least 100 m apart. Each observation of birds encountered visually or acoustically was recorded as distance (m) and direction (degrees) from the survey point. Over-flying birds were excluded from the analysis. Bird surveys were made during early morning hours (04–09) on days with little or no wind, and no rain. Visits at survey points were randomized with respect for day, visit order, and observer. Two observers (LE and GM) accounted for all surveys.

Age, volume of spruce, and birch were extracted from the stand record data. Besides spruce and birch there were very few other tree species in the stands. At each survey point we estimated the number of tree stems >1.3 m in height along four 2.5 m wide transects running 10 m N–S and W–E from the survey point. A measure of structural heterogeneity in the forest canopy was derived by taking the coefficient of variation in stem numbers across the four 25 m² transects. Height, determined with a Suunto inclinometer, was taken as the average of the three tallest trees closest to the survey point. Percentage canopy closure was determined from a wide-angle photograph taken with a digital camera pointed straight up at the sky from 0.5 m above ground at the survey point. Point survey data were analyzed as averages taken over stands, i.e. stands were treated as the experimental unit. Toms et al. (2006) have shown that true abundance tends to be best correlated with maximum abundance data. Taking into consideration the fact that there is a strong phenological gradient in activity patterns of birds at these latitudes, we used the maximum number of individuals per survey point over the six visits as a measure of species abundance.

We analyzed the bird data in terms of species richness and abundance at the community and guild level. Foliage-

gleaning and ground-feeding insectivore guilds were designated according to the classification by Alerstam (1982) (Table 2). As our aim in the present study was to analyze effects at the stand level, we only used bird data relating to observations made within 50 m of the survey points.

Generalized linear modeling (GLM) was employed to analyze the data. The different bird-attribute variables were included as dependent variables, and a set of explanatory variables were derived from the forest data (Table 1). Fertilization was added as a binary (1,0) effect variable. Pearson correlation analysis revealed that stand height and age were correlated ($r = 0.47$) and to reduce the problem with co-linearity we included only height in the GLM-analyses, reasoning that height is more functional descriptor of bird habitat than age. For the same reason, we selected height before canopy closure as also these variables were correlated ($r = 0.77$). The final set of explanatory variables in the GLM-models included area, tree height, volume spruce and birch, variation in stem density, and the binary fertilization variable. The volume and stem density variables were log-transformed before analysis in order to homogenize the variance.

RESULTS

Number of bird observations within 50 m from survey points amounted to 514 of 19 species. Willow Warbler (*Phylloscopus trochilus*) was most numerous, followed by Chaffinch (*Fringilla coelebs*), Robin (*Erithacus rubecula*), and Dunnock (*Prunella modularis*) (Table 2). Coniferous foliage gleaners (Goldcrest *Regulus regulus* and Coal Tit *Periparus ater*) constituted 2–5% of all birds, i.e. their share of the whole bird community was very small. In contrast, the share of deciduous foliage gleaners (Willow Warbler, Blackcap *Sylvia atricapilla*, Lesser Whitethroat *Sylvia curruca*, and Garden Warbler *Sylvia borin*) and ground-feeding insectivores was much higher at 33–38% and 32–36%, respectively.

The GLM-analyses revealed a significant ($P < 0.05$) effect of fertilization on species richness and total bird abundance (Table 3). On average, fertilized stands had 38% more species and 21% more birds than unfertilized stands (Fig. 1). There was no significant effect of the forest variables for any of the bird guild variables ($P > 0.05$). However, among individual species Chaffinch, Lesser Whitethroat, Goldcrest, and Garden Warbler were more numerous in fertilized stands (Table 2). All of these species except for Chaffinch have been classified by Alerstam (1982) as insectivorous foliage gleaners.

Table 2 Mean abundance and (SE) of bird species in descending order of abundance, and designation into foraging guilds

Species	Fertilized stands ($N = 4$)	Unfertilized stands ($N = 12$)	Guild designation ^a
Willow Warbler <i>Phylloscopus trochilus</i>	4.1 (0.4)	4.2 (0.2)	FG
Chaffinch <i>Fringilla coelebs</i>	2.9 (0.2)	1.9 (0.2)	
Robin <i>Erithacus rubecula</i>	2.3 (0.3)	2.2 (0.2)	GfI
Dunnock <i>Prunella modularis</i>	1.5 (0.3)	1.3 (0.2)	GfI
Blackbird <i>Turdus merula</i>	1.1 (0.1)	1.0 (0.2)	GfI
Blackcap <i>Sylvia atricapilla</i>	1.1 (0.1)	1.0 (0.2)	FG
Song Thrush <i>Turdus philomelos</i>	1.0 (1.0)	1.1 (0.2)	GfI
Goldcrest <i>Regulus regulus</i>	0.9 (0.1)	0.4 (0.1)	FG
Lesser Whitethroat <i>Sylvia curruca</i>	0.7 (0.1)	0.4 (0.1)	FG
Garden Warbler <i>Sylvia borin</i>	0.7 (0.2)	0.3 (0.1)	FG
Great Tit <i>Parus major</i>	0.6 (0.3)	0.5 (0.2)	
Jay <i>Garrulus glandarius</i>	0.5 (0.3)	0.6 (0.1)	
Woodpigeon <i>Columba palumbus</i>	0.4 (0.1)	0.3 (0.1)	
Yellowhammer <i>Emberiza citrinella</i>	0.4 (0.4)	0.4 (0.2)	
Tree pipit <i>Anthus trivialis</i>	0.3 (0.2)	0.2 (0.1)	GfI
Siskin <i>Carduelis spinus</i>	0.2 (0.1)	0.3 (0.2)	
Black Woodpecker <i>Dryocopus martius</i>	0 (0)	0.03 (0.03)	
Green Woodpecker <i>Picus viridis</i>	0 (0)	0.03 (0.03)	
Coal Tit <i>Periparus ater</i>	0 (0)	0.03 (0.03)	FG

^a Foliage-gleaning insectivores (FG), Ground-feeding insectivores (GfI)

Table 3 Results of GLM-analysis of the effects of forest variables on (a) bird species richness, and (b) total bird abundance

Effect	Coefficient	SE	Std. coefficient	<i>t</i> -Value	<i>P</i> -value
a					
Constant	6.506	7.663	0.000	0.849	0.418
Area	0.247	0.170	0.359	1.454	0.180
Height	−0.691	0.517	−0.414	−1.336	0.214
Volume spruce	0.608	1.104	0.179	0.551	0.595
Volume birch	−0.257	0.248	−0.208	−1.037	0.327
Variation in stem density	2.073	1.654	0.279	1.253	0.242
Fertilization	3.611	1.292	0.546	2.796	0.021
b					
Constant	13.998	6.413	0.000	2.183	0.057
Area	−0.031	0.142	−0.060	−0.215	0.834
Height	0.069	0.433	0.055	0.159	0.877
Volume spruce	−0.556	0.924	−0.219	−0.602	0.562
Volume birch	0.162	0.207	0.175	0.781	0.455
Variation in stem density	1.243	1.384	0.224	0.898	0.392
Fertilization	3.244	1.081	0.656	3.002	0.015

Adjusted R^2 value 0.465 and 0.328 in model (a) and (b), respectively

DISCUSSION

We surveyed stands that were intensively managed by means of soil preparation, plant cultivation, and recurrent cleanings and thinnings, followed by clear-felling harvest. Most of the investigated stands were in their second or

third rotation. Hence in this landscape, the increased fertilizer applications further intensified an already intense level of forest management carried out form long time. In effect, our study has evaluated fertilizer treatments against alternative silvicultural methods within the same management system, as recommended by Rochelle (1981).

Fig. 1 Species richness and total bird abundance in fertilized ($N = 4$) and unfertilized ($N = 12$) stands. Mean values and ± 1 SE

In the present study, stands subjected to repeated fertilizer applications had higher species richness and total bird abundance than unfertilized stands. Furthermore, three species classified as insectivorous foliage gleaners, Lesser Whitethroat, Goldcrest and Garden Warbler, were more numerous in fertilized than in unfertilized stands. These results indicate that fertilized stands may support larger populations of invertebrate food resources for some foliage-gleaning species. However, there was also a clear abundance difference in favor of fertilized stands for Chaffinch, a species classified as granivorous by Alerstam (1982) based on the year-around diet which indeed is dominated by seeds. However, other authors, Dolnik (1982) for instance, found in Kaliningrad region (western Russia) that animal material compose 90% of species' diet in breeding season while only 3% during rest of year. Moreover, diet of nestlings consists almost wholly invertebrates and largely leaf-dwelling insects (see Cramp et al. 1994). Therefore, it may be more correct to classify the Chaffinch as an insectivorous species in the breeding season.

It should be kept in mind that we only surveyed young stages of forest development. In operational use, repeated fertilizer applications markedly shorten the rotation period normal under traditional forest management, which implies that individuals and species associated with old forest characteristics will have less time over which to accumulate in fertilized stands. When applied over large scales, the cumulative effects of repeated fertilizer applications might result in loss of habitat for those species primarily found in older forests. However, such species already experience difficulty in intensively managed landscapes, as surveyed in the present study, where young, second-growth forests abound. The vast majority of birds encountered in the surveyed stands were habitat generalists; more specialized and species of conservation importance are rare in these

intensively managed forests. The successful management of such species requires securing the presence of stands that include high quality elements of old-growth legacies such as suitable quantities of dead wood and deciduous trees, as well as there being functional habitat networks for population persistence at the landscape scale (Angelstam et al. 2004). Notwithstanding the fact that intensively managed, even-aged spruce forests are clearly unable to provide suitable habitat for such species, whether or not they undergo repeated fertilizer treatments, by including some such stands in a landscape dominated by other forest types, our results suggest that the overall diversity of forest avifauna at this scale may be increased (e.g. Gjerde and Sætersdal 1997).

Compared with Folkard and Smith (1995), we found a somewhat lower response of birds to the fertilization of stands in the present study. One explanation might be that Folkard and Smith conducted their Canadian study in a less productive environment where nitrogen supplementation might be expected to have a much stronger effect than in the much more productive Toftaholm area (Tamm 1991). During the breeding season, foliage-gleaning birds may be less limited by food resources in resource-rich environments than in nutrient poor systems where bottom-up effects prevail (Folkard and Smith 1995; Niemi et al. 1998).

CONCLUSION

Our results suggest that, within the time frame of the study, the repeated application of fertilizers to young Norway spruce may increase species richness and the overall abundance of birds at the stand scale. The potential interaction between fertilization and the increased heterogeneity in the forest canopy caused by the skid road system used for the fertilization application deserves further attention. Other studies in managed forests have demonstrated a positive relationship between low-traffic forest roads and bird species richness (Šálek et al. 2010). At the present state, we cannot conclude to what extent the higher abundance of some foliage-gleaning insectivore bird species in fertilized stands is related to direct effects of nutrient enrichment on folivorous invertebrate numbers, or indirect effects of increasing structural heterogeneity with skid roads. Increasing spatial heterogeneity in the canopies of managed forest has been suggested as way of accelerating the rate of convergence to old-growth forest characteristics (Carey and Wilson 2001). This may be a feasible option in a productive forest area such as Toftaholm, as other studies have found a close relationship between bird species richness and forest structural complexity in energy-rich (productive) landscapes (Verschuyl et al. 2008). Forest

managers may thus consider using secondary roads and altered tree stem density as tools to manipulate habitat suitability for forest birds within intensified forestry.

In summary, our results suggest that the repeated application of fertilizers to young growth stages in even-aged, second-growth spruce forest may enhance conditions for generalist birds. However, such approaches to management should be adopted with caution before their effects on other groups of organisms have also been evaluated (Kneeshaw et al. 2000). Future studies should focus on structural and compositional effects of fertilization processes during the entire rotation period (Sullivan et al. 2010). Finally, the large-scale effects of shortened rotations on the quality of forest at felling age should be studied and assessed before further management recommendations can be provided.

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REFERENCES

- Ahti, T., L. Hämet-Ahti, and J. Jalas. 1968. Vegetation zones and their sections in northwestern Europe. *Annales Botanici Fennici* 5: 169–211.
- Alerstam, T. 1982. *Fågelflyttning*, 295. Uppsala: Signum (in Swedish).
- Allison, S.D., C.A. Hanson, and K.K. Treseder. 2007. Nitrogen fertilization reduces diversity and alters community structure of active fungi in boreal ecosystems. *Soil Biology and Biochemistry* 39: 1878–1887.
- Angelstam, P., J.-M. Roberge, A. Löhmus, M. Bergmanis, G. Brazaitis, M. Dönn-Breuss, L. Edenius, Z. Kosinski, et al. 2004. Habitat modelling as a tool for landscape-scale conservation—a review of parameters for focal forest birds. *Ecological Bulletins* 51: 427–453.
- Bergh, J., ed. 2000. *Fiberskog—a report from a research programme on intense forestry*. Report no 6, Department for Production Ecology, Faculty of Forestry, SLU, 66. ISSN 1401-5625.
- Bergh, J., S. Linder, and J. Bergström. 2005. Potential production of Norway spruce in Sweden. *Forest Ecology and Management* 204: 1–10.
- Bergh, J., U. Nilsson, H. Grip, P.-O. Hedwall, and T. Lundmark. 2008. Effects of frequency of fertilization on production, foliar chemistry and nutrient leaching in young Norway spruce stands in Sweden. *Silva Fennica* 42: 721–733.
- Carey, A.B., and S.M. Wilson. 2001. Induced spatial heterogeneity in forest canopies: Response of small mammals. *Journal of Wildlife Management* 65: 1014–1027.
- Cramp, S., C.M. Perrins, and D. Brooks. 1994. *Handbook of the birds of Europe the Middle East and North Africa. The birds of western palearctic*, vol. 6. Oxford, New York: Crows to Finches Oxford University Press.
- Dolnik, V.R. 1982. Population ecology of the Chaffinch (*Fringilla coelebs*). In *Proceedings of the zoological Institute*, Vol. 90. Leningrad: Nauka. (in Russian with English summary).
- Folkard, F.G., and J.N.M. Smith. 1995. Evidence for bottom-up effects in the boreal forest: Do passerine birds respond to large-scale experimental fertilization? *Canadian Journal of Zoology* 73: 2231–2237.
- Fredén, C. (ed.). 1994. *Geology*. Stockholm: National Atlas of Sweden.
- Garibaldi, L.A., T. Kitzberger, C. Noemí Mazía, and E.J. Chanton. 2010. Nutrient supply and bird predation additively control insect herbivory and tree growth in two contrasting forest habitats. *Oikos* 119: 337–349.
- Gjerde, I., and M. Sætersdal. 1997. Effects on avian diversity of introducing spruce *Picea* spp. plantations in the native pine *Pinus sylvestris* forests of western Norway. *Biological Conservation* 79: 241–250.
- Hartmann, H., G. Daoust, B. Bigué, and C. Messier. 2010. Negative or positive effects of plantation and intensive forestry on biodiversity: A matter of scale and perspective. *Forestry Chronicle* 86: 354–364.
- Hedwall, P.-O., A. Nordin, J. Brunet, and J. Bergh. 2010. Compositional changes of forest-floor vegetation in young stands of Norway spruce as an effect of repeated fertilization. *Forest Ecology and Management* 259: 2418–2425.
- Kenk, G., and H. Fischer. 1988. Evidence from nitrogen fertilisation in the forests of Germany. *Environmental Pollution* 54: 199–218.
- Kneeshaw, D.D., A. Leduc, P. Drapeau, S. Gauthier, D. Pare, R. Carignan, R. Doucet, and C. Messier. 2000. Development of integrated ecological standards of sustainable forest management at an operational scale. *Forestry Chronicle* 76: 481–493.
- Lindberg, N., and T. Persson. 2004. Effects of long-term nutrient fertilisation and irrigation on the microarthropod community in a boreal Norway spruce stand. *Forest Ecology and Management* 188: 125–135.
- Marquis, R.J., and C.J. Whelan. 1994. Insectivorous birds increase growth of white oak through consumption of leaf-chewing insects. *Ecology* 75: 2007–2014.
- Nabuurs, G.J., A. Pussinen, J. van Brusselen, and M.J. Schelhaas. 2007. Future harvesting pressure on European forests. *European Journal of Forest Research* 126: 391–400.
- Niemi, G.J., J. Hanowski, P. Helle, R. Howe, M. Mönkkönen, L. Venier, and D.A. Welsh. 1998. Ecological sustainability of birds in boreal systems. *Conservation Ecology* (online) 2(2): art. 17. <http://www.consecol.org/vol2/iss2/art17>.
- Peter, M., F. Ayer, and S. Egli. 2001. Nitrogen addition in a Norway spruce stand altered macromycete sporocarp production and below-ground ectomycorrhizal species composition. *New Phytologist* 149: 311–325.
- Raab, B., and H. Vedin (eds.). 1995. *Climate, lakes and rivers*. Stockholm: National Atlas of Sweden.
- Raunikaar, R., J. Buongiorno, J.A. Turner, and S. Zhu. 2010. Global outlook for wood and forests with the bioenergy demand implied by scenarios of the Intergovernmental Panel on Climate Change. *Forest Policy and Economics* 12: 48–56.
- Rochelle, J.A. 1981. The effects of forest fertilization on wildlife. In *Proceedings of 1979 forest fertilization conference*, ed. S. P. Gessel et al., 164–167. Institute of Forest Resources, Contribution No. 40. Seattle: University of Washington.
- Šálek, M., J. Svobodová, and P. Zasadil. 2010. Edge effects of low-traffic forest roads on bird communities in secondary production forests in central Europe. *Landscape Ecology* 25: 1113–1124.
- Skogsstyrelsen. 2008. *Skogliga konsekvensanalyser—SKA-VB 08*. Swedish Forest Agency Rapport 25/2008, 157. (in Swedish).
- Strong, A.M., T.W. Sherry, and R.T. Holmes. 2000. Bird predation on herbivorous insects: Indirect effects on sugar maple saplings. *Oecologia* 125: 370–379.
- Sullivan, T.P., D.S. Sullivan, P.M.F. Lindgren, and D.B. Ransome. 2009. Stand structure and diversity of plants and small mammals in natural and intensively managed forests. *Forest Ecology and Management* 258S: 127–141.

- Sullivan, T.P., D.S. Sullivan, P.M.F. Lindgren, and D.B. Ransome. 2010. Long-term responses of mammalian herbivores to stand thinning and fertilization in young lodgepole pine forest. *Canadian Journal of Forest Research* 40: 2302–2312.
- Tamm, C.-O. 1991. *Nitrogen in terrestrial ecosystems*. Berlin: Springer Verlag.
- Toms, J.D., F.K.A. Schmiegelow, S.J. Hannon, and M.-A. Villard. 2006. Are point counts of boreal songbirds reliable proxies for more intensive abundance estimators? *Auk* 123: 438–454.
- Verschuyt, J.P., A.J. Hansen, D.B. McWethy, R. Sallabanks, and R.L. Hutto. 2008. Is the effect of forest structure on bird diversity modified by forest productivity? *Ecological Applications* 18: 1155–1170.
- Wallenstein, M.D., S. McNulty, I.J. Fernandez, J. Boggs, and W.H. Schlesinger. 2006. Nitrogen fertilization decreases forest soil fungal and bacterial biomass in three long-term experiments. *Forest Ecology and Management* 222: 459–468.

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