Forest Ecology and Management 320 (2014) 118–128

Contents lists available at ScienceDirect

Forest Ecology and Management

journal homepage: www.elsevier.com/locate/foreco

Long-term responses of Scots pine and Norway spruce stands in Sweden to repeated fertilization and thinning

Johan Bergh[a,*], Urban Nilsson[a], H.Lee Allen[b], Ulf Johansson[c], Nils Fahlvik[a]

[a] Southern Swedish Forest Research Centre, Swedish University of Agricultural Sciences, P.O. Box 49, SE-230 53 Alnarp, Sweden
[b] Department of Forestry and Environmental Resources, North Carolina State University, Raleigh, NC 27695, USA
[c] Unit for Field-based Forest Research, Swedish University of Agricultural Sciences, P.O. Box 17, SE-310 38 Simlångsdalen, Sweden

ARTICLE INFO

Article history:
Received 18 December 2013
Received in revised form 12 February 2014
Accepted 14 February 2014
Available online 29 March 2014

Keywords:
Pinus sylvestris
Picea abies
Nitrogen
Phosphorous
Interactions
Guidelines

ABSTRACT

Recent investigations have shown that annual wood production in Sweden can be increased by 30 million m^3 per year in a long-term perspective (>50 years) by using new forest management methods such as new tree species or seedling materials. However, to meet the increased demands during the next 20 years, Sweden will have to rely on silvicultural methods available today. Growth in boreal and cold temperate forest is with only few exceptions limited by nutrients availability, primarily nitrogen, and one way to satisfy the increased demands in a short-term perspective is nitrogen fertilization. A set of thinning and fertilization experiments were started in the 1960's in Scots pine and Norway spruce stands over the whole of Sweden representing different soil, moisture and vegetation types. We used data from these experiments to examine the long-term effects of repeated fertilization in thinned stands on growth, stand development, and yield. The 34 Scots pine sites and 13 Norway spruce sites included in our analyses had at least four treatment plots (no thinning, repeated light thinnings, repeated light thinnings with repeated N fertilization, and repeated light thinnings with repeated N + P fertilization). In northern Sweden, 100 kg N ha^{-1} and 150 kg N ha^{-1} were applied at each fertilization event for Scots pine and Norway spruce stands, respectively. In southern Sweden, 150 kg ha^{-1} N was applied in Scots pine stands and 200 kg ha^{-1} N in Norway spruce stands. Phosphorus was applied at the rate of 100 kg ha^{-1}. Several sites also included non-thinned fertilized plots. Pine stands but not spruce stands were responsive (up to 25% more growth depending of the attribute assessed) to repeated fertilization. Surprisingly, the non-thinned pine stands showed strong continuing response to fertilization throughout the 30+ year observation period resulting in higher cumulative volume response than the thinned stands. In thinned stands incremental volume response to fertilization continued but slowly diminished with time indicating that fertilization and thinning effects were less than additive. However, thinning and fertilization effects were additive for diameter growth. Fertilization accelerated stand development with significant shifts in diameter distributions to larger and potentially more valuable trees. Conclusively, repeated nitrogen fertilization is a silvicultural practice that will result in significant and sustained increases in Scots pine production.

1. Introduction

There are numerous indications of future shortages of raw wood and fiber material from forests in Sweden (Nilsson et al., 2011). There will be an increase in the requirement for raw material by the forest industry and increased demand for sustainable sources of energy in the future, both in Sweden and other parts of Europe. At the same time, there is an expectation that the supply of forest raw materials will decline as a result of certification of forestry and the requirement by the community for multiple use and protection of forest land. Forestry in Sweden must meet these demands and consider all environmental aspects, and at the same time maintain a high level of felling and cost-effective production.

In order to meet the demand from the forest industry and society, silvicultural actions can be taken to increase the production and harvest. Recent investigations in Sweden have shown that new silvicultural methods (intensive fertilization, clonal forestry, exotic tree species) can increase the annual production by 30 million m^3 per year in a long-term perspective (>50 years) (Nilsson

* Corresponding author. Tel.: +46 40 415159; fax: +46 40 462325.
E-mail addresses: johan.bergh@slu.se (J. Bergh), urban.nilsson@slu.se (U. Nilsson), Lee_Allen@ncsu.edu (H. Allen), ulf.johansson@slu.se (U. Johansson), nils.fahlvik@slu.se (N. Fahlvik).

http://dx.doi.org/10.1016/j.foreco.2014.02.016
0378-1127/

et al., 2011). However, to meet the increased demands during the next 20 years we have to rely on silvicultural methods available today, which can increase the production and possibilities to harvest more in a shorter time perspective. One more controversial way of course is to harvest more than annual increment in Sweden.

Growth in boreal and cold temperate forests is with only few exceptions limited by nutrients, primarily nitrogen (N) (Tamm, 1991; Tamm et al., 1999) and one way to satisfy the increased demand in a short-term perspective is nitrogen fertilization. Fertilization has been conducted in Sweden since the 1960′s and reached a peak in the late 1970’s, when 189.000 hectares were fertilized every year (Lindkvist et al., 2011). Fertilization decreased drastically in the 1980’s and 1990’s and reached a low level in 2002, when only 14.000 hectares were fertilized. Since then there has been a strong increase with about 90.000 ha fertilized in 2010. The present recommendations for fertilization are to use ammonium nitrate fertilizers in mature stands, with N-supplied at 150 kg ha^{-1}. The ammonium nitrate fertilizers contain usually ca 4% calcium (Ca) and 2% magnesium (Mg) to compensate for the acidification an increased growth due to fertilization can cause. Besides N (+Ca and Mg), boron (B) is also commonly added to avoid deficiencies, which might occur with repeated nitrogen fertilization on nutrient poor sites (Sundberg, 2010). The effects of fertilization generally last for 8–10 years and the additional volume increment is normally between 13 and 20 m^3 ha^{-1}, depending on location, tree species and site characteristics (Pettersson, 1994; Jacobson and Pettersson, 2001). For Scots pine (*Pinus sylvestris* L.) and Norway spruce (*Picea abies* (L.) Karst.), the recommendation for northern Sweden is for 450 kg N ha^{-1} to be applied during a whole rotation period, while in Central Sweden it is 300 kg N ha^{-1}. This means that the fertilization can be repeated 2 or 3 times during a rotation period which typically is between 60 and 100 years depending on site fertility. The rationale for these limits in the amount of fertilizers is the risk for nutrient leaching. In southern Sweden fertilization is not recommended except for Norway spruce stands in south-eastern Sweden, where forest residues are removed at final harvest. There is a general belief that the fertilization effect decreases the 2nd and 3rd time that a stand is fertilized (Jacobson and Nohrstedt, 1993).

Thinning has been used in Sweden during the last 100 years and the main purposes are (i) to remove trees to improve the remaining stand development and economy, (ii) to avoid self-thinning, (iii) to obtain an early income during the rotation period and (iv) to keep up the level of harvest in order to supply the forest industry with raw material (Wallentin, 2007). Different thinning regimes will change the structure, tree dimensions and might influence the quality and the areal production of the stand. Today coniferous stands in Sweden are normally thinned 2–4 times during the rotation period, depending on soil fertility. Thinning guidelines, often based on dominant height and basal area, are commonly used. Thinning is also combined with fertilization to further promote the development of individual trees (Valinger, 1990).

Stem wood production in a forest stand is determined by the amount of light absorbed during the growing season and the efficiency with which this absorbed light is converted to stemwood (Cannell, 1989). If stand leaf area levels are low to moderate, due to low fertility and/or thinning, additions of limiting nutrients will typically result in substantial increases in leaf area and light absorption (Linder and Axelsson, 1982; Linder, 1987; Albaugh et al., 1998; Sampson and Allen, 1999). In addition, fertilization results in enhanced light use efficiency including greater photosynthesis rates (Roberntz and Stockfors, 1998) and proportionately increased allocation of fixed carbon to stem wood production (Linder and Axelsson, 1982; Albaugh et al., 1998; Bergh et al., 1999). In contrast to fertilization, thinning typically reduces stand leaf area to levels that are lower than what is needed for maximum light interception, thereby reducing stand growth on a per hectare basis. However, individual tree growth is typically enhanced due to greater light absorption by individual trees and also greater light use efficiency (Mäkinen and Isomäki, 2004; Blevins et al., 2005).

In Sweden, a new series of thinning and fertilization experiments were started in the 1960’s in Scots pine and Norway spruce stands (Nilsson et al., 2010). These experiments have a good climatic and geographical representation over the whole of Sweden for different soil, soil moisture and vegetation types. The experimental setup had 8 different thinning regimes and several thinning treatments were combined with fertilization.

The objectives of this paper were to (i) determine the long-term effects of repeated fertilization in repeatedly thinned Scots pine and Norway spruce stands, (ii) examine the effects of repeated thinning and repeated fertilization and their interactions in Scots pine and Norway spruce stands, (iii) provide guidelines for fertilization and thinning.

2. Materials and methods

The experiments were installed at the time of first thinning (dominant height 12–18 m) in uniform, even-aged, pure or almost pure, stands of Scots pine and Norway spruce. The experiments were installed over an 18-year period from 1966 to 1983. The Scots pine stands were located all over Sweden (lat. 56.4° to 66.7° N), whereas the Norway spruce stands were only located in the south and central parts of Sweden (lat. 56.1° to 61.7° N) (Fig. 1). In total 48 experiments in Scots pine and 24 experiments in Norway spruce were installed. In this study, 14 experiments in Scots pine and 11 experiments in Norway spruce were excluded because they did not include fertilization, an appropriate control for the fertilized treatment, or had not been through at least three cycles of thinning. The description of the experiments below relates to the 34 Scots pine sites and 13 Norway spruce sites included in this study. The experimental design of the larger study was recently summarized in Nilsson et al. (2010).

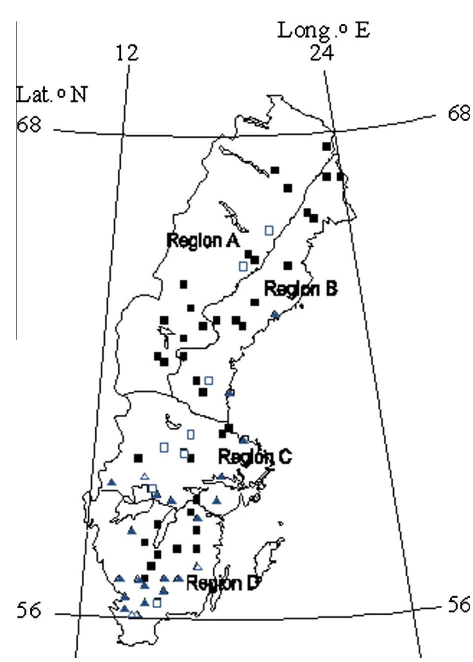

Fig. 1. Geographical location of blocks of the thinning and fertilization experiments in Scots pine (squares) and Norway spruce (triangles).