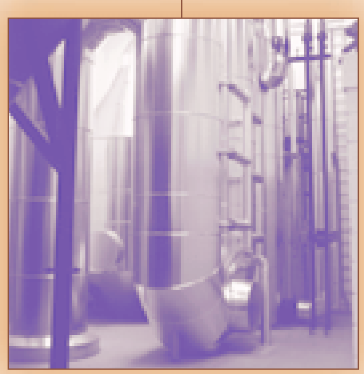
Production of Whole-Tree Chips for Energy—A Danish Perspective

Christian Gamborg



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Production of Whole-Tree Chips for Energy — A Danish Perspective

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Foreword

The Forest Management Activity of Task XII of the International Energy Agency Bioenergy Agreement (IEA Bioenergy) aims to improve the economies of biomass production from forests, increase understanding of the silvicultural processes involved, and develop cost-effective means to bring increased quantities of forest biomass to the marketplace. This goal has been pursued through a series of workshops, field study tours, and review studies in Canada and northern Europe.

The review studies of the Forest Management Activity are undertaken to develop definitive information on silvicultural or forest management systems that can potentially be used for the production of wood for energy (and for traditional forest products) in conventional forestry. The studies focus on specific regions and describe the stand conditions, silvicultural treatments, potential for forest-energy production, and economic considerations for each system. Information from one region or country can be used by other regions or countries to help develop strategies to increase their use of forest bioenergy.

This report presents the findings of a review study in Denmark of silvicultural systems that may increase the production of wood for energy from conventional forestry. Forest production in Denmark is based primarily on coniferous and to a lesser extent broadleaved species grown in plantations. The management of such plantations offers a number of opportunities for enhanced production of biomass for energy through choice of tree species, thinning regimes, control of plantation density, and the use of nurse trees. The Danish information can be applied in variable degrees to a number of other situations in the temperate forest regions of Europe and North America.

These findings were presented in summary form at the joint meeting of IEA Bioenergy Task XII Activities held in Jyväskylä, Finland, in September 1996. An abbreviated version of the study report was published in the proceedings of that workshop.[1] The complete study report contains considerably more information and data and merits this separate publication.

I offer my sincere appreciation to the author for his work in conducting the study and preparing and presenting the findings. Niels Heding, also of the Danish Forest and Landscape Research Institute, helped greatly in

[1] P. Hakkila, M. Heino, and E. Puranen (Editors). 1997. *Forest management for energy.* Proceedings of a joint meeting of [IEA] Activities 1.1, 1.2 and 4.2 of Task XII in Jyväskylä, Finland, September 9 and 10, 1996. Finnish Forest Research Institute Research Paper 640. 237 p.

Avant-propos

L’activité « aménagement forestier » au titre de la tâche XII de l’Accord sur la bioénergie de l’Agence internationale de l’énergie (AIE/Bioénergie) vise à accroître les économies liées à la production de biomasse forestière, à mieux comprendre les procédés de sylviculture s’y rapportant et à élaborer des moyens pour mettre sur le marché davantage de biomasse forestière, au meilleur rapport coût-efficacité possible. À cette fin, des études récapitulatives, des voyages d’étude et des ateliers ont été organisés au Canada et dans le nord de l’Europe.

Les études récapitulatives ont été entreprises en vue de produire une documentation complète sur les régimes sylvicoles ou mode de régénération convenant à la production de bois-énergie (et de produits forestiers traditionnels) dans le contexte de l’exploitation forestière classique. Axées sur certaines régions, les études décrivent, pour chaque mode de régénération, l’état des peuplements, les traitements sylvicoles, le potentiel de production de bois-énergie et les conditions économiques qui s’y appliquent. L’information obtenue pour une région ou un pays particulier pourrait servir à élaborer des stratégies de valorisation de la bioénergie forestière dans d’autres régions ou pays.

Cette publication présente les conclusions d’une étude effectuée au Danemark sur les régimes sylvicoles qui pourraient y accroître la production de bois-énergie dans le cadre d’une exploitation forestière classique. La production forestière au Danemark repose principalement sur des plantations de conifères, et, à un moindre degré, de feuillus. L’aménagement de telles plantations offre un certain nombre de possibilités pour accroître la production de biomasse énergétique par le choix des essences et des régimes d’éclaircie, le contrôle de la densité de plantation et l’utilisation d’arbres-abri. L’information danoise est applicable à un degré variable à un certain nombre d’autres situations dans les régions forestières tempérées de l’Europe et d’Amérique du Nord.

Les conclusions de l’étude danoise ont été présentées sous forme de résumé à la réunion conjointe sur les activités de la tâche XII d’AIE/Bioénergie à Jyväskylä, en Finlande, en septembre 1996. Une version abrégée du rapport de l’étude a été publiée dans le compte rendu de cet atelier.[1] La présente publication du rapport complet se justifie par l’abondance d’information, et de données qu’il contient.

[1] P. Hakkila, M. Heino et E. Puranen (éd.). 1997. *Forest management for energy*. Proceedings of a joint meeting of [IEA] Activities 1.1, 1.2 and 4.2 of Task XII in Jyväskylä, Finland, September 9 and 10, 1996, Finnish Forest Research Institute Research Paper 640, 237 p.

organizing and facilitating the study. The professional help of Victor Spassov and staff of VSES Communications, Ottawa, is gratefully acknowledged for their work in the copy-editing, proofreading, design, and layout of the publication. Catherine Carmody, Francine Langevin, Danielle Monette, and Denis Rochon of Scientific and Technical Publications, Science Branch, Canadian Forest Service, provided invaluable assistance with translation, cover design, and production.

J. Richardson
Activity Leader
Forest Management Activity

Je tiens à exprimer ma grande appréciation pour le travail de l'auteur qui a réalisé cette étude et en a préparé puis présenté les conclusions. Niels Heding, également rattaché à l'institut danois de recherche sur les forêts et les paysages, a beaucoup aidé à organiser et à faciliter l'étude. Il convient également de remercier Victor Spassov et le personnel de VSES Communications, à Ottawa, pour leur travail de révision, de correction d'épreuves, de conception graphique et de mise en page de la publication. Catherine Carmody, Francine Langevin, Danielle Monette et Denis Rochon, du service des publications scientifiques et techniques de la Direction des sciences du Service canadien des forêts m'ont aussi apporté une aide précieuse pour la traduction, la conception de la couverture et la production.

J. Richardson
Responsable d'activité
Activité « Aménagement forestier »

Abstract

The report examines different ways to increase the production of whole-tree chips for energy production. It assesses the effect of selected silvicultural factors like tree species, thinning program, and especially plant density and nurse trees, on the production of wood chips.

At present, a plant density of between 2500 and 4500 plants per hectare for Norway spruce is used in Danish forestry. Calculations based on Danish yield tables and results from field trials on plant density and thinning programs in Denmark show an increase in volume production when plant density is increased (Gamborg 1996). When plant density is increased to approximately 6500 plants per hectare, volume production, i.e. the production of chips, can increase by 30-50% depending on site quality. Plant densities of over 6500 plants per hectare show a trend toward diminishing returns in volume production. Using intolerant tree species, such as common alder or hybrid larch as nurse trees in spruce or beech stands, can increase whole-tree chip yield substantially if the nurse trees are chipped during early thinnings (*ibid.*).

We emphasize that production of whole-tree chips must not jeopardize the overall forest management objectives. It is important to consider the environmental impact of whole-tree chip production for energy purposes beforehand, especially at poorer sites, to ensure that it does not degrade the forest ecosystem. Whole-tree chip production has to be an integral part of a multiple-use forestry program.

Résumé

Ce rapport examine les différents moyens d’accroître la production de copeaux d’arbres entiers à des fins de production d’énergie. Il aborde également l’influence sur la production de copeaux de bois de certains facteurs sylvicoles, comme l’essence, le régime d’éclaircie et notamment la densité de plantation et les arbres-abris.

À l’heure actuelle, les forestiers danois ont recours à une densité de plantation de 2 500 à 4 500 plants d’épicéa commun (épinette de Norvège) par hectare. Des calculs fondés sur les tables de rendement du Danemark et les résultats d’essais sur le terrain concernant la densité de plantation et les régimes d’éclaircie révèlent qu’une augmentation de la densité de plantation entraîne un accroissement du volume produit (Gamborg, 1996). Si la densité de plantation passe à quelque 6 500 plants par hectare, ce volume, c’est-à-dire le volume de copeaux, pourrait augmenter de 30 à 50 %, selon la qualité de la station. Des densités supérieures à 6 500 plants par hectare ont tendance à entraîner une augmentation moindre du volume. L’utilisation d’essences de lumière, comme l’aulne glutineux ou le mélèze hybride, comme arbres-abris dans les plantations d’épinettes et de hêtres peut sensiblement accroître le rendement en copeaux d’arbres entiers lorsque les arbres-abris sont mis en copeaux lors des premiers passages en éclaircie (*ibid.*).

Le rapport souligne que la production de copeaux d’arbres entiers ne doit pas compromettre les grands objectifs d’aménagement forestier. Avant de se lancer dans une telle production, il importe de tenir compte des incidences sur l’environnement, notamment dans les stations de piètre qualité, afin de s’assurer que la production de copeaux d’arbres entiers à des fins énergétiques n’entraîne pas une dégradation de l’écosystème forestier. La production de copeaux d’arbres entiers doit s’inscrire dans le contexte d’une foresterie à objectifs intégrés.

Introduction

This report provides an analysis of different ways to increase the production of forest fuels in the form of whole-tree chips from the forest for energy purposes.

In practice, biomass for energy production is produced as whole-tree chips when the purchaser is a central energy producer, like a district heating plant, or a combined power and heating plant. Approximately one-half of the production of forest fuels is intended for these central purchasers of chips. However, most of the today's supply of forest fuels is used as firewood for heating of private homes.[1]

Silvicultural Options

The production of whole-tree chips can be manipulated by silvicultural means. Some of the silvicultural factors involved are shown in Table 1.

Table 1. Methods of Increasing Whole-tree Chip Production in Existing Forests, Including Afforestation.

Land Use	Silvicultural Factors
Existing Forests and Afforestration	Tree Species Plant Density Nurse Trees Thinning Program

These factors can be manipulated mainly to increase the production of biomass, and thus provide an increased volume of chips. Future demand for fuelwood in Denmark is not expected to change significantly (Lind 1994). In the future, whole-tree chips will be the wood energy of choice as chips become an alternative to central energy production based on coal, oil, or natural gas. The silvicultural options described in this report illustrate how to optimize chip yield from different silvicultural systems. These options apply to afforestration as well as replanting on existing forest land. It should be noted, however, that site quality is generally lower on forest land than on farm land.

The options shown in Table 2 are included in the analysis of the possibility of optimizing chip production through afforestation. For each option, current practice is described, then possible silvicultural optimization approaches are analyzed.

[1] Current consumption of fuelwood in Denmark totals 553 000 m^3: 333 000 m^3 as firewood and 220 000 m^3 as whole-tree chips (Lind 1994).

Table 2. Silvicultural Options for Optimizing Chip Production.

- Norway Spruce, East Denmark
- Norway Spruce, West Denmark
- Norway Spruce with Nurse Trees, East Denmark
- Norway Spruce with Nurse Trees, West Denmark
- Beech, Planted
- Beech, Planted, with Nurse Trees
- Beech, Natural Regeneration

The age at which a stand is closed and maximum biomass production reached, is 20 to 40, calculated on the basis of plant densities used in current forestry practice. The options in Table 2 are based on the assumption that by increasing the number of plants per hectare, stand closing is accelerated, a process that eventually leads to increased chip production. Greater plant density is imperative if the objective is to increase the production of fuelwood during the early thinnings; otherwise the quality of the remaining stand might be lowered substantially.

The main assumption is that the chip harvest can increase if fast-growing nurse trees are used. The idea is to harvest the nurse trees in the early thinnings as whole-tree chips, and thereby speed up fuelwood production.

An additional advantage of greater plant density (> 4500 plants per hectare) is that the diameter increment for the individual tree during the first very important 10-15 years from stand establishment is considerably below the diameter increment at low plant density. This reduces the share of juvenile wood in the stems while increasing both the strength and drying qualities of the wood significantly. High plant density thus has a positive impact not only on chip production but also on the quality of the permanent stand.

These options relate to the manipulation of two main factors: plant density and nurse trees. The task is to find the plant densities at which, with or without nurse trees, whole-tree chip production is optimized within the framework of sustainable, multiple-use forestry. The basis for these silvicultural options will examined in greater detail in the section on existing forests and afforestation below.

It must be stressed that Denmark practises multiple-use forestry. Some of the main 'products'of Danish forestry include high-quality timber, conservation of the natural environment, protection of the nation's cultural history, and provision of recreational opportunities.

The silvicultural options suggested as a way to increase whole-tree chip production in Danish forests are offered as a realistic option within the scope of current forestry practice. The production of fuelwood must not jeopardize overall forest management objectives like the production of high-quality timber and protection of the environment.

Early thinnings in conifer stands can only be carried out without cost to forest owners if they can sell the chips. Quite often, costs and revenues from these early thinnings barely balance, or even result in economic loss (Suadicani 1993). If no market for whole-tree chips exists, thinnings are often postponed until the trees in the stand reach a size at which thinning costs and revenues are better balanced. To ensure the production of high-quality timber, therefore, it is necessary to produce and sell whole-tree chips for energy. Hence the production of fuelwood has to be seen as an integral part of multiple-use forestry.[2]

Environmental Impacts

The environmental impacts of increased whole-tree chipping have to be taken into account. Every harvest of trees in a stand causes a loss of organic matter and essential nutrients from the forest ecosystem. Producing whole-tree chips accelerates this loss of nutrients. Calculations based on field trials made by the Danish Forest and Landscape Research Institute suggest that on poorer soils the remaining stand may show signs of deficiency, especially of calcium and potassium (Beier *et al.* 1995). On these types of soils, immediate whole-tree chipping and extraction from the stand after felling is not recommended (Ibid; Skovstyrelsen 1985). Chipping and immediate removal cause heavy losses of the nutrients stored in twigs and needles, which contain larger quantities of nutrients than the stem.

Instead the felling should be done between January and March, and the felled trees left lying in the stand for the summer (3-6 months) to dry and to allow the twigs and needles to wither and fall off before chipping. This method reduces needle and twig loss to approximately 10%.

Summer drying also reduces the moisture content in the chips from 50-55 % of total weight to approximately 40%, increasing the percentage of dry matter, and hence the net calorific value. Net calorific value is the energy content in the dry matter less the amount of energy required to evaporate the moisture contained in the fuel.

Another way to mitigate the problem of nutrient loss from the forest ecosystem as a result of (increased) whole-tree chip production is to fertilize and lime, or spread the ash from the burning of wood chips over the forest floor. Studies of the nutrient content of ash by the Danish Institute of Forest Technology[3] show that a substantial part of the nutrients removed by the harvest are found in the ash (Kofman 1987).

If the removal of nutrients from the forest ecosystem exceeds the supply of nutrients on an ongoing basis, a sustained yield cannot be maintained. It is thus important to assess the nutrient status of the different forest stands where production of whole-tree chips is contemplated. On richer soils, the withering of parent material and recycling of nutrients within the ecosystem may be sufficient to cover the loss of nutrients due to whole-tree chipping.

[2] Early thinning regimes under which whole-tree chips are produced as a result of the various suggested silvicultural options do not jeopardize future stand treatment.

[3] Now part of the Danish Forest and Landscape Research Institute.

Existing Forests and Afforestation

The principal tree species selected for the silvicultural options are Norway spruce (*Picea abies* [L.] Karst.) and beech (*Fagus sylvatica* L.).[4] Norway spruce and beech represent the vast majority of conifer and deciduous stands in Denmark. Furthermore, these species are expected to become the principal tree species in Danish forestry in the future. They will presumably be grown in mixed stands to a greater extent then than they are now.

The choice of tree species influences the optimum age for final felling and the chip yield of the individual stand on the basis of many rotations. Thus for a beech stand of medium quality the common age for final felling is 100-120 years, while a Norway spruce stand is clearcut at approximately 70 years.

In Table 2, the "Norway spruce" option can mean a stand of Norway spruce, Sitka spruce (*Picea sitchensis* [Bong.] Carr.), or even Norway spruce mixed with some other species, like Sitka spruce, Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco), silver fir (*Abies alba* Mill.), or Grandis (*Abies grandis* [Dougl.] Lindley). Similarly, the "beech" option can mean beech by itself or beech mixed with some other tree species like linden (*Tilia cordata* L.), cherry (*Prunus avium* L.), sycamore (*Acer pseudoplatanus* L.), Norway spruce, or Douglas-fir.

Today, stands established to harvest Christmas trees or greenery are typically intensive monocultures of Nordmann's fir (*Abies Nordmanniana* [Stev.] Spach) or noble fir (*Abies procera* Rehd.). They produce very limited amounts of wood for energy and are therefore not examined in this report.

A Norway spruce stand where a number of Christmas trees are felled without silviculturally compromising the future development of the stand is a different matter, however. Before the first thinning at a height of approximately 7 m, the number of plants is reduced from approximately 6500 to 3500-4500 plants per hectare. In terms of chip production, the Christmas tree option will in general be similar to the Norway spruce option below for an equivalent number of plants. If the plant density rises above 6500 plants per hectare, however, production of Christmas trees would be impossible.

The use of nurse trees is considered separately for Norway spruce as well as beech. Hybrid larch (*Larix x eurolepis* Henry), common alder (*Alnus glutinosa* [L.] Gaertn.), and poplar (*Populus spp*.) are presented as nurse tree options. Other nurse trees of relevance are Scots pine (*Pinus sylvestris* L.) and birch (*Betula verrucosa* Ehrh., *B. pubescens* Ehrh.), especially on sandy soils. Hybrid larch and common alder are perhaps the most frequently used nurse trees in Denmark today (Henriksen 1988). Furthermore, the wood production and quality of Scotch pine are thought to be quite similar to those of hybrid larch for the first 15 years. This also applies to birch and common alder (Statens forstlige Forsøgsvæsen 1990).

The common practice for nurse trees in both deciduous and coniferous stands is mixing by rows. This system facilitates management, reduces the price of establishment, and allows the most efficient use of a chipper, namely chipping by rows. As a result, only nurse trees mixed in rows have been used in the options described.

For Norway spruce, the silvicultural options describe both the plant density used in forestry today as well as higher plant densities. Volume production, and hence the potential fuelwood yield, will to a certain degree increase with increasing plant density over the period, until the stand is closed (Heding 1969; Handler and Jakobsen 1986). A corresponding correlation has not been demonstrated for beech (Henriksen 1988): as a result, the plant density for the beech option does not change.[5]

The thinning regimes are based on technical, biological, and economical considerations. Optimization of chip production has to be done within what is silviculturally possible in a given area and without decreasing the future sustainability of the area.

Choice of thinning intensity and thinning interval is determined by many diverging considerations including stem diameter development, age of final felling, storm stability, wood quality, risk of disease or insect attacks, and the stability of adjacent stands. The thinning programs used in the options described in this report are based on results from thinning and plant density experiments as well as experience gained from current Danish forestry practice.

The thinning grade is used as a measure of the actual standing volume as compared to potential standing volume, if a thinning had not been carried out. It is denoted by a capital letter: A-grade, B-grade, etc. The A-grade includes only dead trees, i.e., there is in fact no

[4] Oak (*Quercus robur* L., *Q. petraea* Liebl.) as pure stand and main category has not been included as an option because it constitutes a relatively small part of the Danish forest area (about 6% of the total).

[5] For the natural regeneration of beech option, however, different numbers of seedlings are examined.

thinning. Consequently the largest number of living tree standing volume can be found in stands that are only subjected to an A-grade thinning. B-grade thinning is light, whereas D-grade is a heavy thinning, removing half of the volume production in a stand subjected to A-grade thinning. By combining the letters, a change in thinning grade over time can be shown: for example, a D-B-grade thinning indicates that early thinnings were heavy, followed by lighter thinnings.

There are several ways for the individual forester to influence the production of biomass at a given site. In addition, there are environmental characteristics that limit potential chip production and that cannot be manipulated. These include, for example, local differences in the soil material, climatic impacts like precipitation, wind, and frost, as well as the length of the growing season. The total impact of these factors that cannot be manipulated is expressed as the site quality concept, defined as the potential production capacity of any given stand at a given site.

Because of the considerable differences in soil quality between East and West Denmark[6], the silvicultural options for a good-quality Eastern and a poor-quality Western site are presented separately. Biomass production, as well as the health and storm stability of a stand improve if the right tree species is chosen for a given site (site-adapted choice of tree species).

Norway Spruce, East Denmark

Current Practice

Currently, the plant density for Norway spruce stands varies between 2500 and 4500 plants per hectare. Generally, the choice of plant density is based on the consideration that fewer plants per hectare mean cheaper stand establishment, and fewer early thinnings. At the same time, there is a minimum plant density requirement if the objective for the stand is relatively high-quality timber production, and a reasonable use of its production potential. There are stands today with densities as low as 2500 plants per hectare in an effort to minimize establishment costs, as well as postpone and reduce the number of early thinnings that result in an economic loss, despite the well-known fact that the wood quality in such stands is barely acceptable and maximum wood production cannot be achieved.

In this century, the common plant density in Danish Norway spruce stands was approximately 6000 plants per hectare, corresponding to a planting at 1.3 m × 1.3 m. This plant density was based on considerations of the structural development of the stand and the production of high-quality timber. However, on the basis of a report on stand establishment by the State Forest Department in 1967, the plant density in Danish State forests, and a number of privately owned ones, was decreased to 2500 plants per hectare.

Two of the main reasons for this, as Henriksen (1988) points out, were to decrease stand establishment costs, and avoid the costs of early, usually unprofitable thinnings. The realization that stand establishment can be viewed as an investment, with interest, payback period etc., had given rise to a lot of discussion on how to lower costs, rather than how to raise profits. It soon became evident, however, that a plant density of 2500 plants per hectare was too low to utilize production potential fully, and produce high-quality timber. As a result, plant densities today are seldom less than 3500-4000 plants per hectare.

For Norway spruce, site quality II (Danish system), the first thinning is carried out at approximately age 20, when the average height of the stand is about 8 m. It is typically a thinning by rows, and the total thinning volume is chipped.

Yield tables have been generated for all major tree species in Denmark. The site quality index is obtained by relating the mean height and age of a given stand. The best, i.e. high-growth, site quality index is I (e.g., for beech: 32 m at age 100; Norway spruce: 27 m at age 60), whereas a poor site could be IV for beech, and VI-VII for Norway spruce.

Figure 1 shows the most common chipping procedure for thinning by rows. First the trees in the rows are felled manually. Then the trees are left during the summer to lower the water content of the wood from approximately 55% to 40% of total weight. After some months the trees can be chipped. The chips are emptied into a forwarder which transports them to a container by a paved road.

Figure 1. Common Chipping Procedure for Thinning by Rows, First Thinning (Hansen 1995).

The second thinning is carried out at approximately age 25, when tree height is about 10 m. It is a selective thinning, with a harvester, and the thinning volume is cut as pulpwood (70%) and by shortwood logging (30%). After that, thinning is carried out approximately every fifth year, and the thinning volume is cut mainly as longer logs. However it should be noted that the relation

[6] "East Denmark" is representative of the older (several hundred year-old) forest areas (Zealand and Funen) where the parent material for these richer soils is predominantly glacial till. "West Denmark" is representative of the more recent forest plantations on poorer soil (outwash plains), such as former Atlantic heath land.

between chips and other products is almost solely determined by the price level of the products versus the price of chips. With the chippers that are used today it is possible to chip even very large-diameter conifer logs.

Tops are usually left at the site after thinning or felling wherever the pulpwood or timber is cut. They represent an as yet unexploited volume. Chipping of top ends is done at several places and will likely become common practice in the future, if there are markets for the chips. Studies by the Danish Forest and Landscape Research Institute show that chipping of dried tops from clearcuts yield approximately 14 m^3 solid volume (38 m^3 loose volume) of chips per hectare (Kofman 1989).

Optimizing Chip Production

The silvicultural option used to optimize chip production from Norway spruce in East Denmark is an attempt to establish thinning programs for different plant densities. This option demonstrates the plant densities that yield the largest chip harvest and also the optimal time to start the thinnings.

The option uses plant densities that range from 1500 to 10 500 plants per hectare. Recent plant density experiments in Norway spruce stands (Handler and Jakobsen 1986) show a correlation between increasing plant density and increasing volume production. A precondition for the establishment of the option is a previous study of stem-number reduction and diameter development in unthinned Norway spruce stands (Heding 1969).

The underlying principle of this option is that differences in the original plant density and subsequent natural thinning produce different amounts of volume up to a certain stand height, where a harmonization of stem number, height, and diameter occurs. The harmonization takes place according to a traditional thinning program (C-grade), at a harmonization height fixed at 11.7 m.

After the harmonization, the stands are expected to be basically identical. The thinnings follow current practice: The first one is done manually by row, with later thinnings limited to where an existing trail is extended or where new trails are felled. All thinnings made before the stand reaches a height of 11.7 m are chipped. *All chip production results presented in the following section are from thinnings made in stands before they reach a height of 11.7 m.*

The timing of the first thinning and the thinning interval of later thinnings is a compromise between silvicultural and technical as well as economical considerations. Silvicultural and economical considerations involve a relatively early first thinning for medium and high density (> 4500 plants per hectare). This is done out of consideration for the further structural development of the stand.

If the first as well as later thinnings are postponed significantly, the stem diameter development of the individual tree will be impeded, and the result will be either smaller wood dimensions (and hence lower income) or a longer rotation with a subsequent interest charge and stability risk. Late thinnings will likewise contribute to a larger height-diameter relationship in the stand, which increases the risk of snow load and presumably reduces the storm stability of the stand (Henriksen 1988).

Moreover, there is an upper limit for the volume that can be extracted in a single thinning. Even during a heavy thinning, it is important to leave the remaining stand in a condition to allow full use of the production potential of the site, and ensure a relatively homogeneous diameter development for the sake of the wood quality.

Furthermore, in this option, there is a rule which states that for practical and economical reasons, thinnings are not to be carried out if the thinning volume is less than 30 m^3 solid volume per hectare.

Table 3. Total Chip Production for Norway Spruce in East Denmark at Different Plant Densities (all figures per hectare).

Plant Density	Total Chip Harvest*			Stems	Branches
No. of Seedlings	*m^3 solid vol.*	*m^3 loose vol.*	*tonnes d.m.*	*m^3 solid vol.*	*m^3 solid vol.*
1 500	24.0	64.9	9.4	21.6	2.4
2 000	49.5	133.8	19.3	44.6	4.9
3 500	74.1	200.3	28.9	66.3	7.8
4 500	103.6	280.0	40.4	92.2	11.4
5 500	122.7	331.6	47.9	108.3	14.4
6 500	137.2	370.8	53.5	120.5	16.7
7 500	151.6	409.7	59.1	132.7	18.9
8 500	159.6	431.4	62.2	138.7	20.9
9 500	160.6	434.1	62.6	139.5	21.1
10 500	166.4	449.7	64.9	144.3	22.1

* Total chip harvest = chip harvest (stem volume) + branch volume.

Chip production at different plant densities and their thinning programs can be seen in Table 3, which shows chip production, including branch volume[7] per hectare in m^3 solid volume, m^3 loose volume, and tonnes dry matter (d.m.) for Norway spruce in East Denmark.[7]

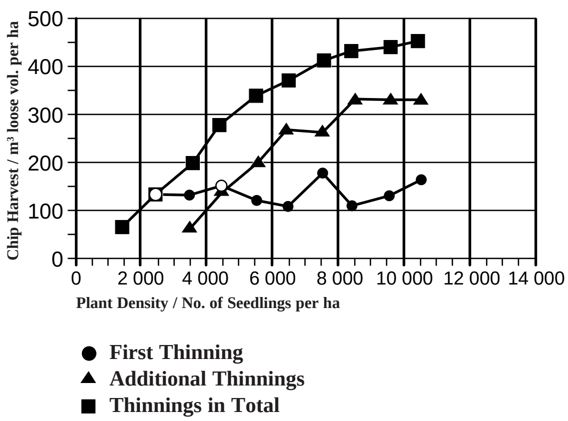
There is an increase in chip production in the interval between 1500 and 10 500 plants per hectare. The difference in chip harvest between 1500 and 10 500 plants per hectare is more than 142 m^3 solid volume (385 m^3 loose volume) per hectare when branch volume is included. The maximum chip production per hectare for Norway in East Denmark is achieved at 10 500 plants per hectare, corresponding to a plant density at approximately 1.0 × 1.0 metre.

A graphic illustration of chip production in m^3 loose volume per hectare for various thinnings at a height of 11.7 m for Norway spruce, East Denmark, at different plant densities, is shown in Figure 2.[8]

Please note that at plant densities of 1500 and 2500 plants per hectare only one thinning has been carried out. Obviously, this results in lower costs than at higher plant densities when several thinnings are necessary.

Despite of the fact that maximum chip production is reached at a plant density of 10 500 plants per hectare, it is useful to observe how the rate of increase for chip production is affected by plant density: at 6500 plants per hectare and up, the relative increase in chip production stagnates.

Figure 2. Chip Harvest of the First and Additional Thinnings for Norway Spruce in East Denmark at Different Plant Densities.



This means that using very high plant densities (7500-10 500 plants per hectare) produces a relatively small increase in chip production when compared to using moderate plant densities (6500 plants per hectare): the production gain is highest at the lower plant density.

Plant density experiments at Norway spruce stands in East Denmark (Handler and Jakobsen 1986) show that total volume production, and thus chip production, actually decreases at plant densities higher than 10 000 plants per hectare.

The conclusion is that at a plant density of 6500 plants per hectare (see Table 3), chip production of about 137 m^3 solid volume (371 m^3 loose volume) per hectare was achieved for Norway spruce in East Denmark. *This is a chip production of approximately 34 to 88 m^3 solid volume per hectare (91 to 237 m^3 loose volume per hectare) more than at the plant densities of 2500 to 4500 plants per hectare common today.*

Norway Spruce, West Denmark

Current Practice

The silvicultural practices for Norway spruce in West Denmark are in many ways similar to the practices in East Denmark. Plant densities in West Denmark range between 2500 and 4500 plants per hectare, and the same thinning systems are used: by rows or selective, manual or mechanical. Because of the generally poorer growing conditions in West Denmark, however, the first thinning is done later than in East Denmark.

For site quality V (G. West-Nielsen's production table) thinning is carried out for the first time after 40 years. For lower plant densities (2500 plants per hectare) thinning is done at intervals of 4-8 years, while higher plant densities (>4,500 plants per hectare) are thinned at intervals of 3-5 years.

This is a relatively heavy thinning done when the stand reaches a height of 15 m, after which there is practically no thinning until the clearcut (D-A or D-B-grade)[9]. This is necessary to secure the wind stability of the stand until clearcut or shelterwood felling. Typical climatic conditions at Norway spruce stands in West Denmark (frost, wind) are more severe than those in East Denmark. The poor climate often makes stand establishment especially difficult.

[7] The relationship between solid volume and loose volume, the solid content factor, is 0.37. The density of Norway spruce is 390 kg/m^3 solid volume. It is assumed, on the basis of practical experience, that 50% of all thinning tree branches are chipped, and that 10% of the needles are lost.

[8] Please note that the separate data are connected by a straight line. These lines do not represent a mathematical correlation. This applies to all figures that follow in this report.

[9] See the paragraph on Danish thinning terminology in the introduction to Existing forests and afforestation above.

Optimizing Chip Production

As with the Norway spruce study in East Denmark, the West Denmark study shows a correlation between plant density and optimimal chip production. Variations of thinning methods, such as chipping a larger part of the total volume to be thinned, or varying the time of the first thinning as well as the number of thinnings, are integrated into the silvicultural options. The outline of these options as well as some of the basic stand preconditions are described in the following paragraphs.

Empirical data illustrating the variation of volume production in terms of plant density in West Denmark (mainly forest on heath and dune land) is extremely limited. Total volume production per hectare at various plant densities is estimated on the basis of the plant density experiment at the Gludsted Plantation – the only existing measured and calculated plant density experiment on heath land, and a felling experiment at the same location.

The thinning program for the individual plant density was devised by means of a mathematically formulated model for Norway spruce in forestry on heath land (Skovsgaard 1995). The felling intensity was chosen in accordance with common silvicultural practice in West Denmark.

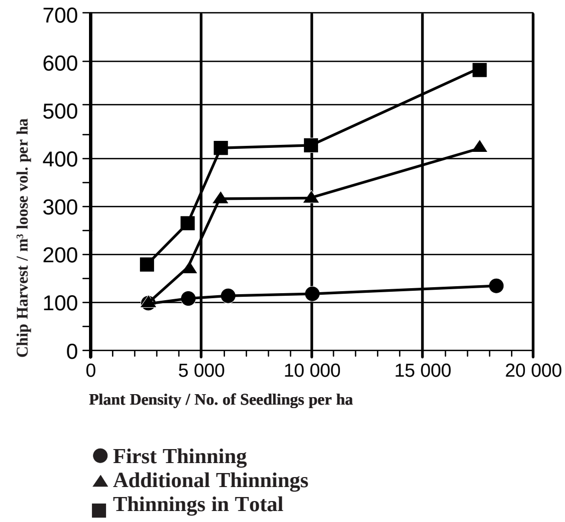
This option further has set a minimum thinning yield of 30 m^3 solid volume per hectare. It assumes that all thinnings carried out before the stand reaches a height of 11.7 m are chipped. The 11.7-m height is chosen to allow a comparison with volume production and chip yield in East Denmark. Naturally, there are a variety of options to chip either more or less of the total volume.

One to four thinnings are carried out, depending on the original plant density: a low plant density means fewer thinnings and vice versa. Thinning methods – including time of thinning, number of thinnings, and thinning by row or selective thinning – follow standard practice in West Denmark.

Total chip yield, including branch volume per hectare for Norway spruce in West Denmark at different plant densities is shown in Table 4.

Table 4 shows that the total chip harvest increases with plant density. The largest yield is 217 m^3 solid volume at a plant density of 17 778 seedlings per hectare.[10] Especially when compared with the results from East Denmark, it is surprising that wood production apparently increases in the density range of 10 000-17 778 plants per hectare. Chip harvest yields at various plant densities, from different thinnings, are shown in Figure 3.

Figure 3. Chip Harvest from the First and Later Thinnings for Norway Spruce in West Denmark at Different Plant Densities.



We note again that these calculations are based on limited data from the trial plots at the Gludsted Plantation. Furthermore, it is not likely that Norway spruce stands with such high plant densities could be established because of the high economic cost of planting.

It would thus be more realistic to consider chip production at plant densities of between 6400 and 10 000 plants per hectare. Unfortunately, there is no empirical data to illustrate stand yield within this interval:

[10] A density of 17 778 plants per hectare corresponds to a spacing of 0.75 m × 0.75 m.

Table 4. Total Chip Harvest for Norway Spruce in West Denmark at Different Plant Densities (all figures per hectare).

Plant Density	Total Chip Harvest*			Stems	Branches
No. of Seedlings	*m^3 solid vol.*	*m^3 loose vol.*	*tonnes d.m.*	*m^3 solid vol.*	*m^3 solid vol.*
2 500	67.9	183.5	26.5	59.4	8.5
4 500	98.6	266.5	38.5	84.8	13.8
6 400	155.0	418.9	60.5	131.3	23.7
10 000	157.2	424.9	61.3	132.7	24.5
17 778	217.2	587.0	84.7	199.4	35.6

* Total chip harvest = chip harvest (stem volume) + branch volume.

nevertheless, 6400 plants per hectare is probably the most realistic choice, as it is common practice to use densities of between 2500 and 4500 plants per hectare.

The West Denmark silvicultural option indicates that at a density of 6400 plants of Norway spruce per hectare, the chip yield (site quality V, G. West-Nielsen) at a height of 11.7 m totals about 155 m^3 solid volume (419 m^3 loose volume) per hectare. *This level of production is approximately 56 to 87 m^3 solid volume (152 to 235 m^3 loose volume) per hectare greater than the corresponding yield at plant densities of 2500 and 4500 plants per hectare respectively*.

A comparison of the West Denmark chip yield at a plant density of 6400 plants per hectare (approximately 179 m^3 solid volume per hectare) to the East Denmark yield at a plant density of 6500 plants per hectare (approximately 137 m^3 solid volume per hectare) shows that chip production is a bit higher in West Denmark. One significant difference, however, is that the duration of production in West Denmark is 20 years longer than in East Denmark.

This difference is important from an economic point of view. Interest on the initial stand establishment investment has to be paid for 20 years longer for the West Denmark stands. Even though whole-tree chip production might be greater there, it is not certain that the subsequent larger income from the thinnings would actually offset the higher interest payments, given the low prices paid for whole-tree chips.

The price of whole-tree chips depends on their energy content. Chip prices currently average approximately 35 Danish krone (DKr.) (~ US$ 6) per Gigajoule. This corresponds to approximately DKr. 370 (~ US$ 63) per tonne, at a water content of ~ 40% (percentage of total weight).

Production of whole-tree chips is generally not viewed as a profitable part of forestry. If the cost of the early thinnings can be covered, however, the thinnings can actually be carried out. As noted earlier in this report, the benefits of the early thinnings have to understood in terms of ensuring future stand development as well as in monetary terms.

Norway Spruce with Nurse Trees, East Denmark

Current Practice

Nurse trees are trees planted simultaneously with the principal tree species. In general, they are used for:

- protection of other, more sensitive tree species;
- production enhancement;
- improvement of biological diversity; and
- aesthetic considerations.

Nurse trees can protect the main tree species from damage caused by frost, game, and the competing herbaceous layer. Furthermore, by creating shelter and shadow, the nurse trees will often foster good tree form development. Protection is often the main motive behind the planting of nurse trees. Using nurse trees also creates a greater variety of woody species at a given area, potentially improving the biological diversity (flora and fauna) in the initial phase of the stand development. Some species used as nurse trees can also improve soil conditions.

Norway spruce is a relatively resistant and safe starter species; because of this, nurse trees are not currently used at the establishment of pure Norway spruce stands in East Denmark. In addition, an increased use of the shelterwood system will limit the need for nurse trees in an already established forest. But nurse trees might well become more relevant as Norway spruce is mixed with less safe-starting, frost-sensitive tree species like silver fir, Douglas-fir, and beech.

Optimizing Chip Production

The principal species in Danish forestry – Norway spruce and beech – are both so-called tolerant, or climax tree species. They can grow in the shade of other trees for many years before they finally reach the canopy and start dominating the development of the stand, but they are not very adept at using openings or light to considerably improve their growth. In the early years, the volume production of tolerant species is lower than the production of the most commonly used nurse trees in Denmark: larch, common alder, poplar, etc., which are the so-called intolerant or pioneer tree species.

The intolerant tree species often self-seed in areas that are not overgrown or in stand openings, and possess considerable ability to transform light energy into volume production. However, the growth of the intolerant trees stagnates relatively early, and if total production is calculated over the entire rotation period of the stand, the tolerant tree contribution will surpass that of the intolerant ones.

If the silvicultural objective is simply volume production, it is obviously best to use intolerant trees. This concept is used in short-rotation forestry where, for example, basket willow (*Salix viminalis* L.) is cultivated in short rotations of 20-25 years, with harvest cycles of 3-5 years (Ledin and Willebrand 1996; Kelkjær 1992). Typically, the lower-quality products of conventional forestry become the main products of short-rotation forestry (Heding 1989). If the biomass is to be used as fuelwood, short-rotation forestry represents one way to produce the wood chips for district heating plants.

In a multiple-use forestry, however, there is a wide range of objectives: renewable production of pulpwood and high-quality timber; preservation of biodiversity; conservation of nature, aesthetic considerations of the forest landscape; and the creation of good opportunities for recreation. Most of the forest area thus has to be covered with tolerant trees to satisfy these multiple objectives in the best possible way. The use of nurse trees is a solution, where the total production is increased considerably without reducing either the biodiversity or the opportunities for recreation.

Hybrid larch is the nurse tree suggested in the silvicultural option for optimizing chip production through the use of nurse trees,. Larch is the most commonly used nurse tree in conifer stands.

The thinning program in the hybrid larch-Norway spruce option is essentially the same as in the Norway spruce option. All larch trees are removed at the first thinning without considering the height at which the thinning is done. This results in the planting of a different number of larch trees, which, depending on the original plant density in the stand (1500-10 500) corresponds to the number of trees felled at the first thinning as described in the Norway spruce option.[11]

If the focus is on a mixed stand, where the larch is planted in rows with the Norway spruce instead of in rows of nurse trees only, the larch trees can be felled selectively in a later thinning, and in most cases increase the total production and with that the potential harvest of chips. This possibility is especially reasonable for medium and high plant densities where the second and third thinnings are done relatively early. At that time the larch growth has not yet slowed down and possibilities for high-volume products from the thinnings are limited.

[11] 480 larch trees per hectare were planted at a total plant density of 2500 Norway spruce plants per hectare. The corresponding numbers for 4500, 6500, 7500, and 10 500 Norway spruce plants per hectare were 960, 1500, 1990, and 2625 larch trees per hectare respectively.

Chip production at different plant densities with a corresponding thinning program are set out in Table 5, which shows the chip yield (including branch volume) per hectare in m^3 solid volume, m^3 loose volume, and tonnes dry matter for Norway spruce with larch as nurse trees in East Denmark.

Table 5 shows that chip production for Norway spruce with larch as nurse trees rises (almost) throughout the entire plant density range from 1500 to 10 500 plants per hectare. The production difference between these two values is approximately 185 m^3 solid volume (500 m^3 loose volume) per hectare.

The additional chip production due to the use of larch as nurse trees is plotted in Table 6, which shows chip production in m^3 loose volume per hectare at different plant densities for Norway spruce, and for Norway spruce with larch as nurse trees in East Denmark.

Table 6 shows that a good deal of additional production is achieved when larch are used as nurse trees in a Norway spruce stand. This additional production peaks at a plant density of 7500 plants per hectare. When larch are used as nurse trees in Norway spruce stands, additional production of approximately 55 m^3 solid volume (150 m^3 loose volume) is achieved at a plant density of 7500 plants per hectare. Table 6 is presented graphically in Figure 4.

Chip harvest yields from stands of Norway spruce and Norway spruce with nurse trees gradually increase with plant density, although they diminish at plant densities greater than 7500 plants per hectare. As noted above, larch probably generates higher chip yields at low plant densities than these calculations show, while the opposite is likely true for high plant densities.

Table 5. Total Chip Production for Norway Spruce with Larch as Nurse Trees in East Denmark at Different Plant Densities (all figures per hectare)

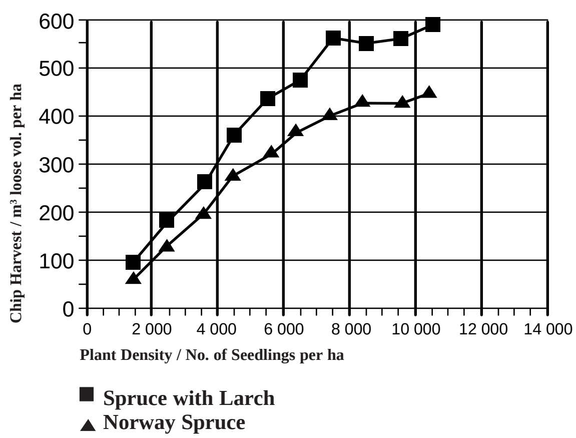
Plant Densities	**Total Chip Harvest***			**Stems**	**Branches**
No. of Seedlings	***m³ solid vol.***	***m³ loose vol.***	***tonnes d.m.***	***m³ solid vol.***	***m³ solid vol.***
1 500	33.8	91.4	13.2	30.5	3.3
2 500	70.0	189.2	27.3	63.1	6.9
3 500	97.3	263.0	37.9	86.9	7.9
4 500	134.7	364.1	52.5	119.6	10.1
5 500	162.8	440.0	63.5	142.9	12.0
6 500	177.6	480.0	69.3	155.3	12.2
7 500	206.7	558.6	80.6	180.0	16.6
8 500	203.7	550.5	79.4	175.2	14.3
9 500	205.9	556.5	80.3	177.0	14.7
10 500	218.3	590.0	85.1	187.3	16.8

* Total chip harvest = chip harvest (stem volume) + branch volume.

Table 6. Total Chip Production for Norway Spruce and Norway Spruce with Larch as Nurse Trees in East Denmark at Different Plant Densities (all figures per hectare).

Plant Density *No. of Seedlings*	Total Chip Harvest, Norway Spruce *m³ loose vol.*	Total Chip Harvest, Norway Spruce with Larch *m³ loose vol.*	Additional Production due to Larch Nurse Trees *m³ loose vol.*
1 500	64.9	91.4	26.5
2 500	133.8	189.2	55.4
3 500	200.3	263.0	62.7
4 500	280.0	364.1	84.1
5 500	331.6	440.0	108.4
6 500	370.8	480.0	109.2
7 500	409.7	558.6	148.9
8 500	431.4	550.5	119.2
9 500	434.1	556.5	122.4
10 500	449.7	590.0	140.3

Figure 4. Total Chip Production for Norway Spruce and Norway Spruce with Larch as Nurse Trees in East Denmark at Different Plant Densities.



On the basis of the results in Figure 4, it appears reasonable that plant densities of between 5500 and 7500 plants per hectare optimize chip harvest yields when larch are used as nurse trees in a Norway spruce stand. At a density of 6500 plants per hectare, the Norway spruce/larch ratio would be 5000 to 1500. This silvicultural option means that *Norway spruce with larch as nurse trees in the proportion noted above should yield chip production of 178 m³ solid volume (480 m³ loose volume) per hectare at a height of 11.7 m*.

This study demonstrates that *the additional chip yield achieved over and above the Norway spruce option totals about 40 m³ solid volume (109 m³ loose volume) per hectare at a height of 11.7 m, or a chip harvest about 40% higher than from a Norway spruce stand without nurse trees*. In terms of optimizing chip production, using the intolerant tree species larch as nurse trees in Norway spruce stands in East Denmark has been shown to result in a significantly higher chip harvest yield.

Norway Spruce with Nurse Trees, West Denmark

Current Practice

Norway spruce is such a good pioneer tree species, that despite the harsh growing conditions in West Denmark, nurse trees are not always used when Norway spruce stands are established. This does not necessarily mean that the protection provided by nurse trees is not effective. It is simply an economic decision to establish Norway spruce stands without nurse trees.

Greater interest in nurse trees may come in the future as the Norway spruce stands on heath land are converted into stands of other tree species which might be more sensitive to frost, but are generally more adapted to the natural conditions of the location. The conversion of spruce stands also may increase because spruce stands have shown signs of disintegration (increased susceptibility to windthrow, insects, salt and airborne pollution) before they reach optimum rotation age. In a recent report on the conversion of spruce stands on former Atlantic heath land, Neckelmann (1995) concludes that conversion would be difficult without shelterwood systems, but that stands would have a better chance for success if nurse trees were used.

Optimizing Chip Production

An option for Norway spruce with larch as nurse trees is offered, which corresponds to the option for East Denmark above. The thinning program for Norway spruce in West Denmark is used to determine the thinning volume for Norway spruce. There are no production tables for larch in West Denmark.

Instead, the ratio of volume production of the Norway spruce to the Norway spruce-larch option, combined with the plant densities from East Denmark stands, is used as an approximation. The rest of the principles and preconditions for the silvicultural options are the same as for Norway spruce with larch as nurse trees in East Denmark. Larch should not be used as nurse trees at very high plant densities; thus a plant density range of 2500-10 000 plants per hectare was chosen.

Chip production at various plant densities, with corresponding thinning programs, is set out in Table 7, which shows the chip yield, including branch volume per hectare in m^3 solid volume, m^3 loose volume, and tonne dry matter for Norway spruce with larch as nurse trees in West Denmark.

Chip production for Norway spruce with larch as a nurse trees in West Denmark increases across a plant density range of 2500-10 000 plants per hectare. The increase in production across that range totals 126 m^3 solid volume (341 m^3 loose volume) per hectare. The additional production of chips due to the use of larch as nurse trees is shown in Table 8.

Table 8 shows that the additional production of chips due to the use of larch nurse trees in Norway spruce stands increases with plant density. The table is presented as a graph in Figure 5, with chip production in m^3 loose volume. Figure 5 shows a gradual increase in additional yield when larch are used as nurse trees up to a plant density of 6400 plants per hectare. At this level, additional production comes to about 52 m^3 solid volume (140 m^3 loose volume) per hectare. At higher plant densities, the increase in additional chip production slows, so that if plant density is increased by about 50%, from 6400 to 10 000 plants per hectare, the additional chip yield comes to only 57 m^3 solid volume (154 m^3 loose volume), an increase of just 5% when compared to the additional production achieved at a plant density of 6400 plants per hectare. It is plausible that larch at lower plant

Figure 5. Chip Harvest for Norway Spruce and Norway Spruce with Larch as Nurse Trees in West Denmark at Different Plant Densities.

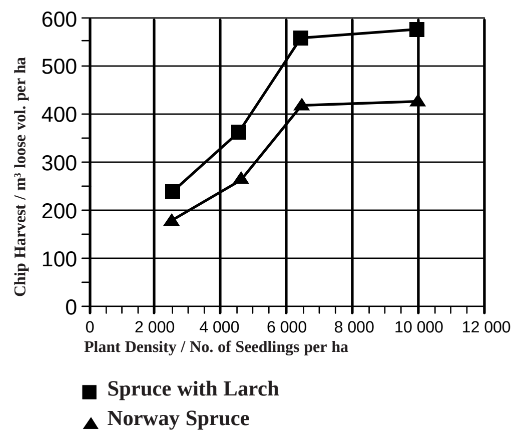


Table 7. Total Chip Production for Norway Spruce with Larch as Nurse Trees in West Denmark at Different Plant Densities (all figures per hectare).

Plant Density	Total Chip Harvest*			Stems	Branches
No. of Seedlings	*m^3 solid vol.*	*m^3 loose vol.*	*tonnes d.m.*	*m^3 solid vol.*	*m^3 solid vol.*
2 500	88.0	237.8	34.3	76.7	11.3
4 500	131.8	356.2	51.4	112.5	19.3
6 400	207.5	560.8	80.9	173.6	33.9
10 000	214.1	578.6	83.5	178.0	36.1

* Total chip harvest = chip harvest (stem volume) + branch volume.

Table 8. Total Chip Production for Norway Spruce and Norway Spruce with Larch as Nurse Trees in West Denmark at Different Plant Densities (all figures per hectare).

Plant Density	Total Chip Harvest Norway Spruce	Total Chip Harvest Norway Spruce with Larch	Additional Production due to Larch Nurse Trees
No. of Seedlings	*m^3 loose vol.*	*m^3 loose vol.*	*m^3 loose vol.*
2 500	183.5	237.8	54.3
4 500	266.5	356.2	89.7
6 400	418.9	560.8	141.9
10 000	424.9	578.6	153.8

densities would produce more than the amounts given in Table 8, and less at higher plant densities.

The conclusion is that it would be reasonable to use 6400 plants per hectare in Norway spruce stands with larch as nurse trees, in a proportion of 4200 Norway spruce to 2200 larch. This plant density is also recommended because the establishment costs exceed the excess profits gained from increased chip production at a plant density of 10 000 plants per hectare.

When all the larch trees are felled in the first thinning, *the Norway spruce with larch nurse trees option yields a total chip production of 210 m^3 solid volume (560 m^3 loose volume) per hectare at a height of 11.7 m. This amounts to about 63 m^3 solid volume (142 m^3 loose volume) per hectare,* or *a production increase of 35% when compared to Norway spruce stands without nurse trees*.

Beech, Planted

Current Practice

Two principal methods are used to establish a beech stand: natural regeneration, with the precondition that the area already be covered with beech forest, and planting. Planting is an option when: *i)* the future beech forest is on farm land; *ii)* the existing stand is not beech; *iii)* beech is grown on the site but a change is desired; *iv)* natural regeneration has not worked; *v)* natural regeneration is more expensive than planting; and *vi)* the parent beech stand is disintegrating.

Normally in Denmark, beech seedlings are planted with a spacing of about 1.5 m between rows and 0.6-1.0 m between the plants in the row. This corresponds to a plant density range of 6000-10 000 plants per hectare. The first thinning is done motor manually at an age of about 20 years, and a height of 6 m (site quality II, East Denmark).

Thinning is done every second or third year for the next 10-20 years. On poorer sites in West Denmark, the first thinning is carried out even later, and there are longer intervals between each thinning. It is quite common to leave the early thinnings to private individuals.

Optimizing Chip Production

It would be reasonable to assume that a yield pattern similar to that of Norway spruce, where chip production increases with plant density up to about 10 000 plants per hectare, would also apply to beech. But there has been no empirical evidence of this. This report therefore does not discuss optimal plant densities for beech chip production.

What can be done is to vary the thinning method, in this context understood as choice of product. Chipping in juvenile deciduous stands is not yet particularly common in Denmark, although there has been some at a few beech stands on fertile land, at a height of 10 m, when no private individuals were interested in felling (Klitgaard, pers. comm. 1995).

The production of chips does not represent production that is additional to the total volume produced; it merely expresses that a part of the thinning volume has been *chipped. If the total thinning volume in beech is chipped at a height of 10 m, a chip yield of about 100 m^3 solid volume (270 m^3 loose volume) per hectare for site quality II is achieved at age 30*. At a poorer-quality site (IV), the chip yield at a height of 10 m is about 110 m^3 solid volume (300 m^3 loose volume) per hectare at age 40.

Beech, Planted, with Nurse Trees

Current Practice

There is an advantage to using intolerant species as nurse trees for the principal tree species either to protect the stand or to increase production at the site. Larch is the most commonly used nurse tree in beech stands and is often planted in pure larch rows. Common alder, birch, and poplar are used as nurse trees as well. In East Denmark beech stands are often established without nurse trees, while in West Denmark they are used more often.

Hybrid aspen was once used as nurse tree, but is no longer because is is not commercially attractive and because it tends to develop strong root sprouts. Chipping would make poplar interesting as a nurse tree, but hybrid aspen should be avoided for the reason noted above.

There are several ways to mix rows of beech with rows of nurse trees. Typically, rows of beech and larch are planted alternately with a space of 1.25-1.5 m between the rows, 0.5-1.0 m between the beech trees and 1-2 m between the larch trees. The result is a plant density of 6 000 to 12 000 plants per hectare, with 4000-8000 beech and 2000- 4000 larch stems per hectare.

The thinning is carried out as described in the section on Norway spruce with nurse trees in East Denmark. The larch is felled and used for pulpwood when it is estimated to affect the growth of the principal species in a undesirable way, which in East Denmark would be at about age 15, and in West Denmark at about age 20.

Optimizing Chip Production

This option investigates the chip yield at age 15 in a pure beech stand and in a beech stand with various nurse tree species mixed in rows, in East Denmark. The first thinning is carried out at age 15.

It should be noted that the figures are derived from general thinning programs for pure beech stands or pure stands of each of the nurse tree species. It is assumed that the nurse trees in all three cases are felled, dried, and chipped at age 15.

In addition, the estimated calorific value of the chips for the four different silvicultural options presented is given to illustrate the point that not only the amount of chips produced, but also the tree species used for chip production, and their quality as fuelwood, are the important factors that determine the value of the chips. This is particularly relevant when hardwoods and softwoods like beech and alder, or poplar and larch, are compared.

Table 9 summarizes chip production at year 15 for four silvicultural options for beech with and without three nurse trees: common alder, poplar, and hybrid larch.

Beech with *larch or poplar nurse trees has a chip production three times larger than the pure beech stand.* Common alder produces a little less than poplar and larch. Pure beech stands produce, depending on the option selected, about 22 m^3 solid volume (60 m^3 loose volume) of chips per hectare at year 15, while beech with larch as nurse trees produce 68 m^3 solid volume (184 m^3 loose volume) of chips per hectare.

Beech has the highest calorific value (3.7 GJ per m^3) when compared to common alder, poplar, and larch (2.5 GJ per m^3), but because of the lower chip production at pure beech stands, beech has the lowest total calorific value *per hectar*e of the four different options. The calorific value of the beech with larch as nurse trees option (461 GJ per hectare) is more than double the value of the pure beech stand (217 GJ per hectare).

It can be concluded that if chip production in beech stands is to rise, there is *a considerable advantage to using nurse trees*. In addition, we can conclude that *hybrid larch is to be preferred as a nurse tree in beech stands to generate increased chip production,* a fact confirmed by considerable existing practical experience.

It has not been possible to create a corresponding chip production option for beech with nurse trees in West Denmark because there are no yield tables for larch, poplar, or common alder in West Denmark. The lack of such tables for Norway spruce with nurse trees in West Denmark was compensated for by adapting a ratio for Norway spruce and larch from East Denmark. It seems less satisfactory to do the same when it concerns beech with nurse trees, as they are not both conifer species and have very different requirements for site, production capacity, and rotation age.

However, since the nurse tree species used in West Denmark produce chip volumes considerably greater than beech, *it is therefore also reasonable to recommend that West Denmark use them as nurse trees in beech stands where a greater chip yield is required*. Larch would presumably be best suited as nurse trees for beech stands.

Beech, Natural Regeneration

Current Practice

It is quite common in Denmark to carry out a few relatively heavy precommercial thinnings[12] in natural regeneration of beech. In practice, this means two to three precommercial thinnings, depending on the plant density, before the trees in the stand have reached dimensions that make it necessary to carry out real thinnings. These thinnings are intended to:

- encourage diameter development for the individual tree, in part to avoid a large height-diameter ratio and the risk of snow pressure as a result, in part to achieve high-priced dimensions;
- ensure acceptable form development in the stand by removing trees with bad form or dominating trees; and
- control the proportion of different tree species in the stand. Often the growth of sycamore, for example, will exceed the growth of the natural regeneration of beech, or crowd parts of the site.

Typically, a brush cutter which cuts the plants by row (and sometimes in perpendicular patches) is used for the first precommercial thinning. This treatment can be

[12] Precommercial thinning is a thinning of young trees from which no, or very few, products are obtained.

Table 9. Chip Production and Calorific Values for Silvicultural Options Using Beech with and without Nurse Trees at Year 15 in East Denmark (all figures per hectare).

Silvicultural Option	Plant Density*	Chip Harvest			Calorific value	
	No. of Seedlings	*m^3 solid vol.*	*m^3 loose vol.*	*tonnes d.m.*	*GJ/m^3 loose vol.*	*GJ/ha*
Beech	6400/0	21.5	58.1	12.3	3.7	217
Beech with Alder	5000/1667	51.0	137.8	22.4	2.9	396
Beech with Poplar	5000/1667	64.5	174.3	23.5	2.4	417
Beech with Larch	5000/1430	68.0	183.8	26.5	2.5	461

* Beech/nurse trees.

combined with motor-manual, selective precommercial thinning to control the proportion of species in the stand in ways other than reducing the stem number. The second and third precommercial thinnings, if necessary, are normally carried out motor-manually (Skovteknisk Institut 1979). After the third thinning it is quite common to leave the early thinnings to private individuals. From this point on, the natural regeneration will follow the development of the planted beech stand (Madsen 1993).

It should be stressed that one of the silvicultural disadvantages of chipping as opposed to brush cutting is the size of the trails, which is directly related to size of the chipper. Typically, a brush cutter is 1 m wide, and leaves trails where light penetrates the stand, enhancing tree growth.

The chipper measures 2.5 m across and leaves gaps in the stand wide enough to affect the growth potential of the area. Chippers *less* than 2.5 m wide are not yet available. The problem is most acute at the first thinning; at later thinnings, the trees are taller and thus better at using the extra light.

Optimizing Chip Production

This section looks at the possibility of replacing brush cutting with chipping at the later precommercial thinnings. The volume felled at the precommercial thinnings is left on the forest floor. No nutrients leave the stand, but at the same time, the opportunity to use the produced biomass for energy purposes is lost.

In natural regeneration stands with low plant densities (20 000-30 000 plants per hectare) it is reasonable to wait until the trees have reached a height of 5 m before doing the first precommercial thinning. The opportunity is to chip the volume from this first precommercial thinning and increase the chip yield from a beech stand with natural regeneration, even though it had not been tried earlier (Madsen, pers. comm. 1995; Klitgaard, pers. comm. 1995).

In natural regeneration stands with high plant densities (60 000-100 000 plants per hectare) precommercial thinnings have to be done earlier (height: 3 m) to encourage good form and diameter development. In practice, trails will be created manually for the first precommercial thinning. At the same time a selective precommercial thinning will be carried out, and the stems placed next to the trail. After a few months of drying for the felled trees, the chipper will go through the stand and process them.

As noted in the section on the establishment of planted beech stands, it is possible to chip beech trees at a height of 10 m (for site quality II, age 30; for site quality IV, age 45). This could be done in natural regeneration stands, which at this point follow the development of the established stand. In this way, the total chip yield of the stand with natural regeneration is further increased.

Generally, the precommercial thinning will reach a level of between 20-50% of the original plant density at the site. In the four silvicultural options described, a heavy precommercial thinning of 50% of the original plant density is used. Thus the chip yields given in Tables 9 and 10 express the common practice maximum for two precommercial thinnings.

In addition, please note that this option can be applied to both East and West Denmark, as only height and stem number are included. The difference between East and West Denmark is that chip yield is achieved 15-20 years later in West Denmark than in East Denmark. Table 10 shows chip production from the first precommercial thinning in beech stands with natural regeneration for four different plant densities, from 20 000 to 100 000 plants per hectare.

There is no significant difference in chip production at plant densities of 20 000 or 30 000 plants per hectare. The harvest yield of the first precommercial thinning is approximately 29 m^3 solid volume (78 m^3 loose volume). At the high plant densities of 60 000 and 100 000 plants per hectare, the precommercial thinning volume is too low to use a chipper in the stand.

At the second precommercial thinning, three years after the first, a brush cutter removes 50% of the volume,

Table 10. Chip Harvest, First Precommercial Thinning, for Two Natural Regeneration Options in Beech Stands for Low and High Plant Densities (all figures per hectare).

Option	Plant Density	Chip Harvest			Total Stem Volume
	No. of Seedlings	*m^3 solid vol.*	*m^3 loose vol.*	*tonnes d.m.*	*m^3 solid vol.*
LOW	20 000	28.9	78.0	16.5	57.7
	30 000	28.6	77.4	16.3	57.3
HIGH	60 000	13.7	37.1	7.8	27.5
	100 000	10.6	28.7	6.0	21.2

which is then chipped. The trails are widened from 1.0 to 2.5 m, the thinning volume is felled manually into the trails, and chipped, after drying for a few months. Table 11 illustrates the chip harvest for four options in the second precommercial thinning.

The yield from the second precommercial thinning of natural regeneration in beech stands with the "low" plant density is approximately 32 m³ solid volume (92 m³ loose volume) per hectare. The precommercial thinning volume from the high plant density options is only about 15 m³ solid volume (44 m³ loose volume) per hectare, which is too low to use a chipper. It appears from Table 10 that, in the second precommercial thinning as with the first, the low plant densities yield the largest precommercial thinning volumes and thus the greatest chip production.

Figure 6 shows the total chip yield for the first and second precommercial thinnings in beech stands with natural regeneration for low and high plant densities.

The conclusion on chip production in beech stands with natural regeneration from the first and the second precommercial thinnings is that *high plant densities of 60 000 and 100 000 plants per hectare produce too small a chip yield to use a chipper in the stand*. On the other hand, for heavy precommercial thinnings with a 50% reduction of the stem number *and low plant densities of 20 000 to 30 000 plants per hectare, it may be worthwhile to send a chipper into the stand, as the chip yield is approximately 60 m³ solid volume (162 m³ loose volume) per hectare.*

Figure 6. Chip Harvest for First and Second Precommercial Thinnings of Beech, Natural Regeneration, at Different Plant Densities.

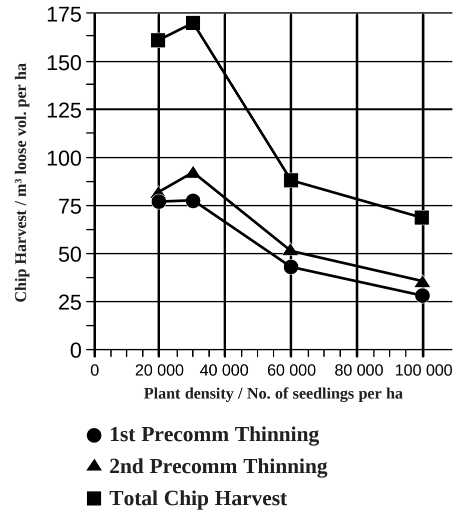


Table 11. Chip Harvest, Second Precommercial Thinning, for Two Natural Regeneration Options in Beech Stands for Low and High Plant Densities (all figures per hectare).

Option	Plant Density	Chip Harvest			Total Stem Volume
	No. of Seedlings	***m³ solid vol.***	***m³ loose vol.***	***tonnes d.m.***	***m³ solid vol.***
LOW	20 000	31.0	83.8	17.7	62.0
	30 000	33.9	91.7	19.3	67.9
HIGH	60 000	17.7	47.8	10.1	35.3
	100 000	14.1	38.2	8.1	28.3

Summary and Conclusions

In the following paragraphs, the main conclusions on how to increase biomass yield, i.e. whole-tree chip production under different silvicultural systems, are outlined for each silvicultural option presented in the previous sections.

Norway Spruce, East Denmark

At densities of 6500 plants or above per hectare the relative increase in chip production stagnates. As a result, a relatively small chip production gain is obtained through the use of very high plant densities (7500-10 500 plants per hectare) as opposed to a moderate plant density (6500 plants per hectare).

At this moderate level, chip production of about 137 m^3 solid volume (371 m^3 loose volume) per hectare is achieved for Norway spruce in East Denmark. *This yield is from 34 to 88 m^3 solid volume per hectare (91 to 237 m3 loose volume per hectare) higher than chip production at the currently used plant densities of 2500 to 4500 plants per hectare.*

Norway Spruce, West Denmark

In West Denmark, with this option, Norway spruce planted at a density of 6400 plants per hectare yield a chip production (site quality V, G. West-Nielsen) of approximately 155 m^3 solid volume (419 m^3 loose volume) per hectare at a height of 11.7 m. *That total is about 56 to 87 m^3 solid volume (152 to 235 m^3 loose volume) per hectare more than the yields of stands with plant densities of 2500 and 4500 plants per hectare respectively.*

Comparing the chip production of the stand in West Denmark with a density of 6400 plants per hectare (approximately 155 m^3 solid volume per hectare) to the production at the East Denmark stand with 6500 plants per hectare (approximately 137 m^3 solid volume per hectare), it is observed that the chip production is almost the same. The significant difference is that chips can be produced in West Denmark for 20 years longer than in East Denmark.

Norway Spruce with Nurse Trees, East Denmark

It seems reasonable to use a density of 6500 plants per hectare to increase chip production by planting larch nurse trees in a Norway spruce stand, in a proportion of 5000 Norway spruce trees to 1500 larch.

With this option, a stand of *Norway spruce with larch as nurse trees in the proportion given above should yield a chip harvest of 178 m^3 solid volume (480 m^3 loose volume) per hectare at a height of 11.7 m*.

This yield surpasses a comparable one from the Norway spruce without nurse trees option by about 40 m3 solid volume (109 m3 loose volume) per hectare at height of 11.7 m, an increase in chip production of about 40%. Obviously, in terms of optimizing chip production, this is a significant increase in production due to the use of the intolerant tree species larch as nurse trees in East Denmark Norway spruce stands.

Norway Spruce with Nurse Trees, West Denmark

The conclusion is that it would be reasonable to use a density of 6400 plants per hectare at Norway spruce stands with larch as nurse trees in a proportion of 4200 Norway spruce to 2200 larch. This plant density is also recommended because the establishment costs would likely exceed the additional profits from increased chip production at a plant density of 10 000 plants per hectare.

When all larch trees are felled in the first thinning, *the option of using Norway spruce with larch as nurse trees results in a total chip harvest of 210 m^3 solid volume (568 m^3 loose volume) per hectare* at a *height of 11.7 m, about 52 m^3 solid volume (142 m3 loose volume) greater per hectare than one from a comparable Norway spruce stand without nurse trees – an increase of 35%.*

For quick reference, Table 11 provides a summary of the chip yield at a height of 11.7 m and the calorific value per hectare of the four options for Norway spruce stands with and without larch as a nurse trees in East and West Denmark.

The yield is higher for West Denmark (poor site quality) than East Denmark (good site quality). Production time in West Denmark, however, is about 20 years longer than in East Denmark and the thinning program in the West is more intensive at the start than the one used in the options for the East.

To conclude: the preceding analysis of the relationship between plant density and volume production shows that, from a productivity point of view, a plant density of about 6500 plants is optimal for chip production, taking future stand development into account. Furthermore, using larch as nurse trees in a Norway spruce stand increases total chip yield by between 30 and 40% in East and West Denmark.

Beech, Planted

The production of chips does not represent additional production in relation to the total volume produced; it merely states that a part of the traditional thinning volume is *replaced* by chips. *If the total thinning volume of beech is chipped at a height of 10 m, a chip yield of about 100 m^3 solid volume (270 m^3 loose volume) per hectare for site quality II is achieved at age 30*. On a poorer-quality site (IV), the chip yield at a height of 10 m is about 110 m^3 solid volume (300 m^3 loose volume) per hectare at age 40.

Beech, Planted, with Nurse Trees

A beech stand with larch or poplar nurse trees has a chip production three times larger than a pure beech stand. Common alder production is somewhat below that of poplar and larch. Pure beech stands produce, with this option, about 22 m^3 solid volume (58 m^3 loose volume) of chips per hectare at year 15, while beech with larch as nurse trees produces 68 m^3 solid volume (184 m^3 loose volume) of chips per hectare.

It can be concluded that *a considerable gain in whole-tree chip production is possible through the use of nurse trees in beech stands*. In addition, *hybrid larch is the preferred nurse tree for optimal chip production from beech stands,* a conclusion confirmed by a considerable amount of practical experience.

Beech, Natural Regeneration

The conclusion on whole-tree chip production in beech stands with natural regeneration from the first and second precommercial thinnings is that *high plant densities of 60 000 and 100 000 plants per hectare produce too low a chip yield to merit sending a chipper into the stand*. On the other hand, for heavy precommercial thinnings with a 50% reduction in stem number *at low plant densities of 20 000 to 30 000 plants per hectare, sending a chipper into the stand may be advisable, as the chip yield is about 60 m^3 solid volume (162 m^3 loose volume) per hectare.*

Final Remarks

From the above analysis it is obvious that whole-tree chip yields from Norway spruce and beech stands can be much higher than those achieved under the current practice of manipulating the plant density and the thinning program. Higher plant densities of up to 6500 plants per hectare in Norway spruce stands, as opposed to the currently used densities of 2500 to 4500 plants per hectare, appear to optimize the chip harvest. Its viability depends, however, on the premise that there is a market for the chip harvest, and that whole-tree chip production income, at a minimum, will offset expenses.

The planting of nurse trees, intolerant species such as common alder and especially hybrid larch, can increase the chip yield substantially in both beech and Norway spruce stands, taking advantage of the fast juvenile growth of the intolerant tree species. The greatest chip yield in absolute terms is achieved in Norway spruce stands, particularly with larch as nurse trees: a chip harvest 30 to 40% higher than one from a spruce stand without larch as nurse trees can be expected.

Figure 7. Chip Harvest for Beech with and without Nurse Trees to Age 15 in East Denmark.

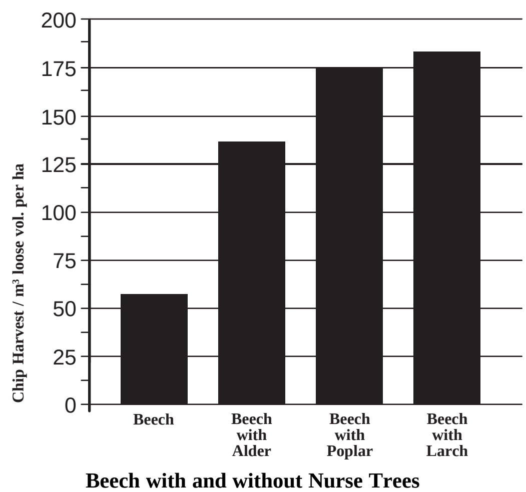


Table 12. Whole-tree Early-thinning Chip Yields and Calorific Values at Selected Plant Densities for Norway Spruce with and without Larch as Nurse Trees in East and West Denmark (all figures per hectare).

	Silvicultural Option	**Plant Density**	**Chip Harvest**			**Calorific Value**	
		No. of Seedlings	***m^3 solid vol.***	***m^3 loose vol.***	***tonnes d.m.***	***GJ/ m^3 loose vol.***	***GJ/ ha***
East Denmark	Norway Spruce	6500	137	371	54	2.5	931
	Norway Spruce with Larch	6500 (5000/1500)*	178	480	69	2.5	1051
West Denmark	Norway Spruce	6400	155	419	61	2.5	1205
	Norway Spruce with Larch	6400 (4200/2200)*	208	561	81	2.5	1408

* Norway spruce/larch.

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