# CALCULATION OF BIOMASS AND NUTRIENT REMOVAL FOR DIFFERENT HARVESTING INTENSITIES*

INGE STUPAK MØLLER

Danish Forest and Landscape Research Institute, Department of Forest Ecology,
Hørsholm Kongevej 11, 2970 Hørsholm, Denmark.

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## ABSTRACT

Whole-tree harvesting of precommercial trees from first thinnings for wood chip production has been practised in Denmark for more than 10 years. Encouraged by Governmental energy and forest policies, markets and production are both increasing. Most wood chips are produced in coniferous stands on relatively poor soils. There has been concern that this practice may lead to nutrient depletion of the soil and decreased production potential in the long-term. More biomass is removed with this practice, with higher mean nutrient concentrations, than when only stems are harvested in whole or in part. It is common practice to cut the trees during the winter and leave them to dry in the stands during the summer so that nutrient-rich tree parts such as needles and twigs are returned to the forest soil. A preliminary study was carried out at one site to measure differences in amounts of biomass and nutrients removed, when whole trees were harvested fresh or dried, or when only stems were removed. Drying trees reduced the amount of nutrients removed by 20–45% compared to fresh harvest, and biomass removed was reduced by 15%. Harvesting stems alone reduced the amount of nutrients removed by 70–90% compared to fresh harvest, while biomass removed was reduced by 35%. Compared to stem harvest, 55% and 30% more biomass was removed in harvesting of fresh and dried whole trees respectively. Compared to stem harvest, the amounts of nitrogen, phosphorus, potassium, calcium, and magnesium removed increased 6.5, 8.0, 3.5, 3.5, and 3.5 times respectively for fresh harvesting. For harvesting of dried trees removals increased 4.5, 4.5, 2.5, 3.0, and 2.5 times for nitrogen, phosphorus, potassium, calcium, and magnesium respectively. When harvesting of fresh and dried whole trees was simulated for the first two thinnings and stem harvest for the later thinnings and the clear-cut, calculations showed that over one rotation period there were still clear differences between whole-tree harvesting scenarios and stem harvest only. Inherently, differences decreased when stem harvesting was simulated in clear-cut and later thinnings for all three scenarios.

**Keywords**: whole-tree harvesting; nutrient removal; nutrient budgets; wood chips; biomass equations; modelling; *Picea abies*.

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## INTRODUCTION

In Denmark the removal of biomass from forests has been intensified since the early 1980s when the National Forest Agency initiated a wood chip project. Forestry needed better economics in first thinnings of Norway spruce (*Picea abies* (L.) Karst.) and Sitka spruce (*Picea sitchensis* (Bong.) Carr.) and in conversion of pine plantations (e.g., *Pinus contorta* Dougl.) on marginal soils to more productive species (Billeschou 1983). The aim of the project was to create a market for wood chips for heating and other purposes. Such a market has now been established, and it is still Governmental policy to strengthen a steady market basis for delivering wood chips as a renewable energy source (Anonymous 1999c). Since 1980, marginal wood resources have been a part of the Danish energy supply policy (Brenøe 1980; Fodgaard 1990; Anonymous 1996a). There are several reasons to believe that the use of wood chips from whole-tree harvesting will increase in the future and reach a higher level than at present. In particular, the decision to double the forested area in Denmark from 11 to 22% during one tree rotation (80–100 years) will lead to increased Danish wood resources for bioenergy (Anonymous 1996b). Today 9% of the total energy consumption is supplied by renewable energy sources, 0.4% being energy produced from wood chips (Anonymous 1999b). For forestry this is of economic importance, as at least 15% of fellings in conifers were chipped in 1998 (Anonymous 1999a).

In forestry and in forest science there is an on-going debate as to whether or not whole-tree harvesting is sustainable in the long-term (e.g., Boyle *et al.* 1973; Maliondo 1988; Hakkila 1989; Hornbeck 1991; Olsson 1996; Proe *et al.* 1997; Egnell *et al.* 1998). In whole-tree harvesting, more biomass of the nutrient-rich tree parts is removed than when only stems or parts of stems are harvested. Whether this will significantly affect long-term productivity and nutrient status of a site will depend on the size of nutrient pools in the soil and forest floor, the release rate from these pools, the amount of atmospheric nutrient deposition, the amount of nutrient leaching induced by, e.g., clear-cutting, deposition of acidifying components, and natural acidification processes, and finally, the weathering capacity of the site (Hornbeck 1991).

In the Danish forestry sector the debate about the ecological consequences of increased biomass and nutrient removal from the forests started in the early 1980s when the National Forest Agency's wood chip project was initiated. In 1985, the Danish Forest Agency published a report on the matter (Anonymous 1985) and laid down guidelines within the State Forests (Billeschou & Klitgaard 1985). In general it was recommended that coniferous trees from precommercial thinnings be left to dry in the stands for at least 2 months in the spring or summer to allow nutrient-rich components (needles and twigs) to fall off and thus remain in the forest floor in the stand. The guidelines are very similar to recommendations from other countries (e.g., Anonymous 1998; Hornbeck 1991).

Existing coniferous forests (about 0.25 million ha) are the main source of wood chips for bioenergy in Denmark. These are to a large extent located on relatively nutrient-poor sites. Trees from the first thinnings (until breast height diameter is roughly 20 cm) are utilised as whole-trees. The guidelines mentioned above are followed also in private forests. Therefore, the practice of leaving trees from precommercial thinnings to dry in the stands is a mitigation measure usually pursued by Danish forestry. So far, how much this practice reduces nutrient removals has not been investigated.

This paper uses a preliminary case study from a Norway spruce stand on a single site for a preliminary analysis of the quantitative differences in removed biomass and nutrients between the different harvesting intensities practised in Denmark. Removals of biomass and nutrients were assessed for single trees from a thinning operation in a Norway spruce stand, and scaled to the whole stand and to the rotation period by simple calculation models. Furthermore, the paper briefly discusses the size of the nutrient removal by harvest compared to other ecosystem nutrient inputs and outputs.

## MATERIALS AND METHODS

### Site Description

The study was carried out in Hareskoven, located in Copenhagen's State Forest on Zealand, Denmark (UTM Zone 32 m 713800 E, 6186330 N). The distance from the North Sea is 270 km and the distance to the nearest water (Øresund) is 10 km. The height above sea level is 50 m. The annual mean precipitation is 660 mm, and the annual mean temperature 8°C. Mean January temperature is 0°C and mean July temperature 16°C. Deposition of nitrogen is roughly 20 kg/ha annually (Bak 1996). The soil parent material is glacial deposits from Weichsel. Maximum mean annual increment is about 24 $m^3$/yr in gross total volume, which corresponds to a site index lower than 1 according to Møller (1933). The stand is of high productivity for Danish conditions.

The stand was Norway spruce, 23 years old from seed in 1998. In the part of the stand investigated, mean height of the trees was around 12.5 m and mean breast-height diameter approximately 15 cm. The stand was planted in 1979 in rows following an old beech stand. The spacing was 3 × 1.5 m (approximately 2200 stems/ha) (H.C.Petersen, Copenhagen State Forest, pers. comm.). The slash from the beech harvest was removed before planting. The stand was being managed for timber production, with wood chips as a byproduct from the first thinning, and maybe partly the second thinning.

The first thinning took place in April 1998. Whole rows were cut for trails, and between trails the stand was thinned selectively. All thinned trees were dragged to the trails and left to dry. In November 1998 the dried trees were chipped. In the midcrown some thinned trees still carried many green needles on the upper side and brown/black, partly decomposed needles on the lower side. In the upper and lower crown most needles had fallen off. Based on simple measurements it was judged that about $^3/_4$ of the needle biomass had fallen off before chipping.

### Sampling

Five fresh trees and 10 trees dried in the stand were chosen to assess biomass and nutrient removal for different harvesting intensities: (1) removal of fresh whole-trees (Fresh WTH) and (2) removal of pre-dried whole-trees (Dried WTH). A third harvesting intensity, (3) harvesting of stems only, was assessed as described below. The sample trees were chosen to represent the range of diameters and heights in this part of the stand. Distances between sampled trees were selected to secure independent samples. The non-random sampling was judged to be of minor importance for the results. Dbh and tree height were measured for all trees. Each tree was chipped separately and the total amount of chips was weighed in order to determine the total biomass of the tree. Two samples (2–3 kg fresh weight per sample) of wood chips were collected per tree for determination of moisture content and nutrient concentrations. Samples were taken in a manner which attempted to reproduce the distribution of coarse and fine material in the original pile of chips. Moisture content and nutrient concentrations of nitrogen, phosphorus, potassium, calcium, and magnesium were measured. The difference between the two samples is a representation of the nutrient concentration sampling error, found to be about 10% for dried trees and about 20% for fresh trees. At breast height, stem discs were sampled from one fresh and one dried tree with mean dimensions. Wood and bark were separated to create two wood samples and two bark samples. Nutrient concentrations were measured. The stem of a fresh tree (F) was weighed. This measure was used partly to estimate wood and bark densities.

## Chemical Analyses

Chip samples were a mixture of wood, bark, needles, twigs, and small amounts of sand and soil. Samples were dried at approximately 55°C for a minimum of 2 days (until constant weight), and then ground in a Retsch SM2000 mill with a 10-mm riddle. A subsample of about 500 g was removed and ground with a 1.5-mm sieve. Thereafter a subsample of about 70 mg was digested in concentrated nitric acid in a PTFE bomb in a microwave oven (CEM), and the concentrations of phosphorus, potassium, calcium, and magnesium were measured by ICP-AES (Perkin Elmer, Optima 3000 XL). Nitrogen was determined from a subsample of about 200 mg using a LECO CNS-2000 Analyzer (Dumas method).

## Statistics and Calculations for a Single Thinning Operation

The effect of drying trees in the stand on the nutrient concentrations of the chips was tested using univariate analyses of variance (F-test). Tests were performed for nutrient concentration means of the two samples from the same tree with fresh/dried as the independent variable. The effect of drying trees in the stand on single tree biomass was tested using multiple regression and analysis of variance with all main effects of dbh, tree height, and fresh/dried and their interactions (F-test). Analyses were performed using the SAS package, PROC GLM (SAS Institute Inc. 1989). Significance was set at $p<0.05$.

Equations for single tree biomass and nutrient content were constructed for fresh trees, dried trees, and stems. Stand level results for a single thinning operation were estimated using mean stand diameter at breast height and mean stand height as equation inputs followed by simple multiplication by number of stems per hectare. Calculations for whole rotation periods were performed using a growth model as described below. Equation parameters were estimated using the SAS package, PROC NLIN (SAS Institute Inc. 1989).

Biomass and nutrient content of fresh and dried trees were modelled using the equation:

$$X = k_x \cdot dbh^2 \cdot h \qquad [1]$$

where X is the total dry biomass or total nutrient content of the tree (nitrogen, phosphorus, potassium, calcium, or magnesium), $k_X$ is a constant, dbh is diameter at breast height (1.3 m), and h is tree height. A diameter-height relationship was established on the basis of the measured trees to smooth the model [1]:

$$h = \alpha \cdot \ln(dbh) \qquad [2]$$

where $\alpha$ is a constant.

Dry biomass of stems was calculated using volume functions (Madsen & Heusérr 1993). These functions model bark and stem wood volume together, and so a separation of wood and bark volume was needed. Holmsgaard & Jakobsen (1970) found the following relationship for Norway spruce:

$$p_v = 2.11 \cdot p_d \qquad [3]$$

where $p_v$ is total bark volume as a percentage of total stem volume (bark and wood), and $p_d$ is bark thickness at dbh as a percentage of total dbh. Holmsgaard & Jakobsen (1970) also generalised measurements to create the relationship between bark thickness and dbh with regard to different site indices. Bark and wood volume could thus be estimated separately with only dbh as input.

Mean green wood density, $d_{stem}$, was estimated by dividing the measured dry biomass of tree F by the calculated volume of F. Green bark density, $d_{bark}$, was set as 80% of green wood density, $d_{wood}$, and estimated by solving the following equations:

$$v_{stem} \cdot d_{stem} = v_{wood} \cdot d_{wood} + v_{bark} \cdot d_{bark} \qquad [4]$$

$$d_{bark} = 0.8 \cdot d_{wood} \qquad [5]$$

where $v_{stem}$, $v_{wood}$, and $v_{bark}$ are the calculated volumes of total stem, stem wood, and stem bark respectively for tree F. Nutrient contents of stem wood and stem bark were multiplied by calculated biomass to create total nutrient contents of stems. Stem wood and stem bark nutrient concentrations in calculations are means of the nutrient content in stem disc samples mentioned above. Biomass and nutrient content of measured stems were calculated. For bigger dimensions, mean trees from yield tables were used (Skovsgaard 1995). Biomass and nutrient content were then modelled using [1] as for whole-trees. This model means that the relative difference between the three scenarios ((1) Fresh WHT, (2) Dried WTH, and (3) Stems) is independent of the diameter and height distribution of the stand. The calculated difference, e.g., the difference between Scenarios 1 and 3, $P_{1-3}$, is therefore valid at both single tree and stand level (but not at rotation level):

$$p_{1-3} = \frac{(k_1 \cdot \sum_{i=1}^{N} dbh_i^2 h_i - k_3 \sum_{i=1}^{N} dbh_i^2 h_i)}{k_3 \sum_{i=1}^{N} dbh_i^2 h_i} \qquad [6]$$

$$p_{1-3} = \frac{k_1 - k_3}{k_3} \qquad [7]$$

where $k_1$ and $k_3$ are the constants for biomass or nutrient content for Scenarios 1 and 3 respectively, $dbh_i$ and $h_i$ are the diameter and height of tree "i", and N is the number of stems.

## Calculations at Rotation Level

At rotation level the three scenarios were: (1) harvesting of fresh whole-trees in thinnings with mean dbh less than 20 cm (Fresh WTH), (2) harvesting of dried whole-trees in thinnings with mean dbh less than 20 cm (Dried WTH), and (3) stem only harvest (Stems). For mean dbh more than 20 cm, only stems were "harvested" in all three scenarios. The amounts of biomass and nutrients removed from a stand within one rotation period were calculated by use of a variable density growth model based on a normal yield table (Skovsgaard 1995).

Inputs were initial stem number $N_{start}$, relative tree distance after thinning $S_{AT}$, relative tree distance before thinning $S_{BT}$, rotation age $A_{rotation}$, and site index SI. In calculations these variables were $N_{start} = 2500$ (lowest possible), $S_{AT} = 0.18$, $S_{BT} = 0.15$ (thinning regime: medium), $A_{rotation} = 90$, and site index = 12 (maximum mean annual increment of 12 $m^3$/ha, corresponding to site index 3.5 according to Møller (1933)). This was the highest site index, that could be chosen in the model, and it corresponds to a site of medium productivity for Danish conditions. This discrepancy between actual site productivity for the study site and site productivity for calculated stand data means that the age of model trees of certain dimensions will be higher than that of trees of equal dimensions from the study site. This could mean that biomass was under-estimated for a site of lower productivity, as wood densities are higher. On the other hand, spacing and thinning regimes could be a more important error, due to their influence on crown biomass. The model provided information about stem reduction, mean dbh, and height of thinned trees. The absolute amounts of biomass and nutrients removed were calculated by input of mean dbh and mean height into single tree equations and multiplying by number of stems removed per hectare.

## Deposition Calculations

Deposition of base cations was modelled using data from the EXMAN project published by Kreutzer *et al.* (1998). They listed the mean annual flux rates of bulk precipitation and throughfall (THF) for five sites in Northern Europe. Bulk precipitation does not include dry deposition. Throughfall measurements include dry deposition, but they also include canopy leaching. A large part of base cation input, especially potassium in throughfall, may originate from canopy leaching. As input to the ecosystem, only deposition is of interest. In Denmark deposition from sea spray constitutes a large part of the cation input to forests (e.g., Hovmand & Bille-Hansen 1999). Estimates of this input may be calculated by assuming that sodium in throughfall originates entirely from sea salt, and that the ratio $THF_{Na}/THF_X$ for any ion X was equal to the ratio $(Na/X)_{Sea\ salt}$ (Ulrich 1982). The sea salt contribution can then be calculated as

$$THF_x = THF_{Na} \cdot \left( \frac{X}{Na} \right)_{Sea\ salt} \qquad [8]$$

Jørgensen (1972) estimated the fraction $(X/Na)_{Sea\ salt}$ to be 0.277 mol/mol for $Mg^{2+}$, 0.044 mol/mol for $Ca^{2+}$, and 0.021 mol/mol for $K^+$.

Kreutzer *et al.* (1998) found the bulk precipitation concentration of $Na^+$ and $Cl^-$ to decrease logarithmically with distance from the coast. Based on the throughfall flux data from Kreutzer *et al.* (1998) the following relationship was established:

$$DEP_{Seasalt,Na} = THF_{Na} = \frac{b_{Na}}{z} + a_{Na} \qquad [9]$$

where $DEP_{Sea\ salt,\ Na}$ is the deposition of Na in sea salt, $b_{Na}$ and $a_{Na}$ are constants, and z is distance from the sea. $(X/Na)_{Sea\ salt}$-ratios were converted to g/g ($R_X$), and the corresponding relationships for potassium, calcium, and magnesium were established:

$$DEP_{Seasalt,X} = \frac{R_X \cdot b_{Na}}{z} + R_X \cdot a_{Na} = \frac{b_X}{z} + a_X \qquad [10]$$

where $b_X$ and $a_X$ are constants applying to the ion X.

# RESULTS AND DISCUSSION

## Nutrient Removal in Biomass

Measured diameters at breast height were between 10 and 20 cm and measured tree heights between 10.8 and 13.7 m. For Equation [2], the constant was calculated to be 4.64. A significant difference was observed between removed biomass in Fresh WTH and Dried WTH, taking the significant diameter effect into account ($p=0.0076$) (Fig. 1). Since there was a significant difference between amounts of biomass removed, there was also a significant difference between amounts of nutrients removed, even if nutrient concentrations were the same for chips from fresh and from dried trees (except in case of substantial immobilisation of nutrients in the biomass, which was not found here). For phosphorus and potassium there was a significant difference in concentrations between green chips and chips from dried trees ($p=0.0008$ and $p=0.0009$ respectively). For all nutrients, the estimated stem concentration, calculated from Table 1, was not contained within the 95% confidence intervals of mean nutrient concentrations in green chips or chips from dried trees (Fig. 2). In previous measurements of Danish wood chip samples from fresh or dried spruce trees from several site types, concentrations of nitrogen, phosphorus, potassium, calcium, and magnesium were within the ranges 1.4–5.8 mg N/g, 0.14–0.28 mgP/g, 0.6–1.8 mg K/g, 1.8–4.4 mgCa/g, and 0.23–0.76 mgMg/g (Anonymous 1994). Except for phosphorus, the nutrient concentrations

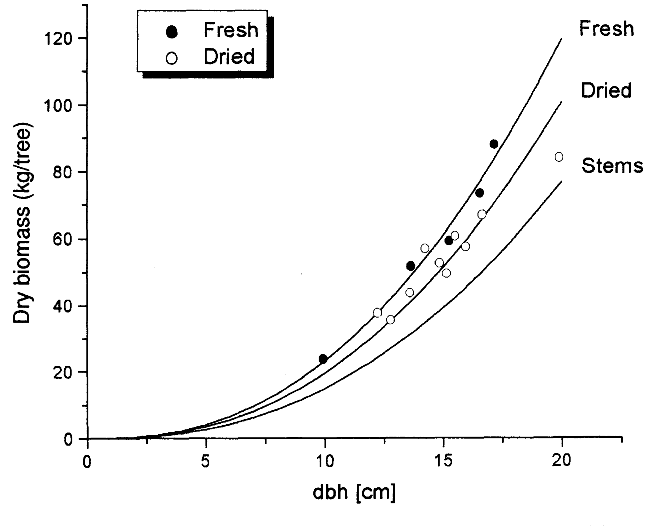

FIG. 1–Measured biomass of fresh and dried trees together with modelled biomass of fresh trees, dried trees, and stems only.

TABLE 1–Nutrient concentrations in stems (mg/g)—mean of measurements on sampled stem discs.

| | N | P | K | Ca | Mg |
|---|---|---|---|---|---|
| Stem wood | 0.52 | 0.044 | 0.52 | 0.66 | 0.12 |
| Stem bark | 4.65 | 0.527 | 2.78 | 7.44 | 0.83 |

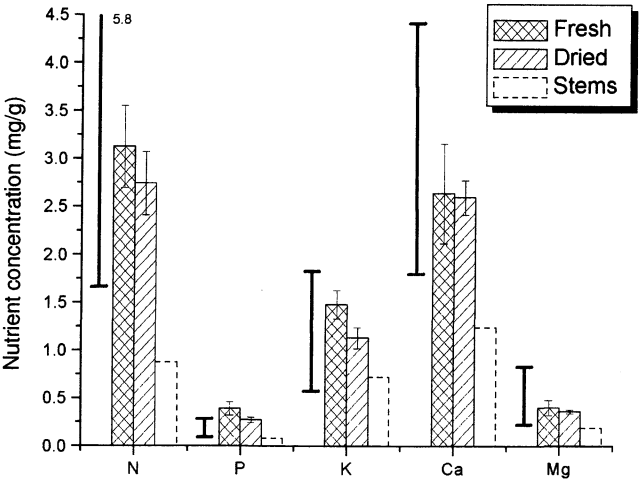

FIG. 2–Measured mean nutrient concentrations of wood chips from fresh and dried trees (bars) with 95% confidence intervals and stem nutrient concentrations, that are weighted averages of stem-wood and stem-bark nutrient concentrations. Intervals without bars are the range of nutrient concentrations of wood chips from fresh and dried Norway spruce trees from the BS/Elsam project (Anonymous 1994).

found in this study are within these ranges. Data from these sites also confirm that, in general, nutrient concentrations in chips from dried trees are more similar to nutrient concentrations in fresh chips than to nutrient concentrations in stems.

Calculated stocking reduction, dbh of thinned stems, and height from the growth model are listed in Table 2, together with other calculated stand data. Calculated values of the constant, $k_X$, for biomass and nutrient content equations are listed in Table 3. Biomass and nutrient contents in Tables 4, 5, and 6 were created from these calculated data and parameters. For Fresh WTH and Dried WTH, whole-tree harvesting was simulated if dbh was <20 cm—that is, WTH was simulated for the first two thinnings (Table 2).

Firstly, the increased biomass and nutrient removals were calculated for a single tree or for a thinning operation (Table 4). Fresh WTH and Dried WTH were compared to Stem harvest, and Fresh WTH was compared to Dried WTH. As expected, increased removals were greater for nutrients than for biomass. Compared to Stem harvests, 55% and 30% more

TABLE 2–Calculated stand data for a rotation of 90 years using a growth model developed by Skovsgaard (1995). N = stem number, DBH = breast height diameter, H = height, BT = before thinning, T = thinning.

| Operation | Stand age (yr) | $N_{BT}$ | $DBH_{BT}$ (cm) | $H_{BT}$ (m) | $DBH_T$ (cm) | $H_T$ (m) |
|---|---|---|---|---|---|---|
| 1. thinning | 39 | 2305 | 15 | 14 | 13 | 13 |
| 2. thinning | 47 | 1512 | 20 | 18 | 17 | 16 |
| 3. thinning | 57 | 1007 | 26 | 21 | 23 | 20 |
| 4. thinning | 71 | 692 | 34 | 25 | 31 | 24 |
| Clear-cut | 90 | 480 | 45 | 30 | 45 | 30 |

TABLE 3—Constants $k_X$ for biomass and nutrient content equations. Units in Equation [1] are: biomass (kg/tree), nutrients (g/tree), if inputs are dbh (cm), h (m).

| | Fresh WTH | Dried WTH | Stems |
|---|---|---|---|
| Biomass | $21.55 \times 10^{-3}$ | $18.15 \times 10^{-3}$ | $13.83 \times 10^{-3}$ |
| N | $70.46 \times 10^{-3}$ | $49.95 \times 10^{-3}$ | $11.14 \times 10^{-3}$ |
| P | $8.784 \times 10^{-3}$ | $5.055 \times 10^{-3}$ | $1.071 \times 10^{-3}$ |
| K | $32.25 \times 10^{-3}$ | $21.58 \times 10^{-3}$ | $9.418 \times 10^{-3}$ |
| Ca | $55.78 \times 10^{-3}$ | $46.00 \times 10^{-3}$ | $15.65 \times 10^{-3}$ |
| Mg | $8.823 \times 10^{-3}$ | $6.504 \times 10^{-3}$ | $2.410 \times 10^{-3}$ |

TABLE 4—Increased nutrient removal in a single thinning operation—e.g., removal of potassium was 3.5 times more in Fresh WTH than in Stems.

| | Biomass | N | P | K | Ca | Mg |
|---|---|---|---|---|---|---|
| Fresh WTH *v.* Stems | 1.55 | 6.5 | 8.0 | 3.5 | 3.5 | 3.5 |
| Dried WTH *v.* Stems | 1.30 | 4.5 | 4.5 | 2.5 | 3.0 | 2.5 |
| Fresh WTH *v.* Dried WTH | 1.20 | 1.40 | 1.75 | 1.50 | 1.20 | 1.35 |

biomass was removed in Fresh WTH and Dried WTH respectively. The amount of nitrogen, phosphorus, potassium, calcium, and magnesium removed increased about 3.5–8.0 times for Fresh WTH and 2.5–4.5 times for Dried WTH compared to Stems. In Fresh WTH the removal of nutrients was increased by 20–75% compared to Dried WTH. By drying trees in the stand, removals were thus reduced by 15%, 30%, 45%, 35%, 20%, and 25% for dry biomass, nitrogen, phosphorus, potassium, calcium, and magnesium respectively compared to Fresh WTH. Practising stem-only harvest reduced the removals by 35%, 85%, 90%, 70%, 70%, and 75% for dry biomass, nitrogen, phosphorus, potassium, calcium, and magnesium respectively compared to Fresh WTH. Note that when removals in Y are, for example, 5 times more than in X (Y/X=5), the removals are increased by 400% ((Y–X)/X=4).

Secondly, the increased biomass and nutrient removals were calculated for one rotation period of 90 years (Table 5). Fresh WTH and Dried WTH were compared to Stem harvest, and Fresh WTH was compared to Dried WTH. Compared to Stem harvest, 5.5% and 3.0% more biomass was removed in Fresh WTH and Dried WTH respectively. For nitrogen, phosphorus, potassium, calcium, and magnesium, removals increased 25–75% for Fresh WTH and 15–40% for Dried WTH. In Fresh WTH the nutrient removal increased 5–25% compared to Dried WTH. By drying trees in the stand, removals were thus reduced by 2.5%, 15%, 20%, 10%, 5%, and 10% for dry biomass, nitrogen, phosphorus, potassium, calcium, and magnesium respectively compared to Fresh WTH. Practising stem-only harvest reduced removals by 5.5%, 35%, 40%, 20%, 20%, and 20% for dry biomass, nitrogen, phosphorus, potassium, calcium, and magnesium respectively compared to Fresh WTH.

TABLE 5—Increased nutrient removal (%) during simulated rotation period scenarios.

| | Biomass | N | P | K | Ca | Mg |
|---|---|---|---|---|---|---|
| Fresh WTH *v.* Stems | 5.5 | 55 | 75 | 25 | 25 | 25 |
| Dried WTH *v.* Stems | 3.0 | 35 | 40 | 15 | 20 | 15 |
| Fresh WTH *v.* Dried WTH | 2.5 | 20 | 25 | 10 | 5 | 10 |

For a single thinning operation these rates of increased removals are slightly lower than rates obtained from studies based on stand data of a thinning experiment on poor soil in west Jutland, and biomass equations and nutrient concentrations from the literature (Andersen & Nord-Larsen 1997; Beier *et al.* 1995). For one rotation period, rates of increased removals were found to be consistent with or slightly higher than rates obtained from Andersen & Nord-Larsen (1997) and Beier *et al.* (1995).

The absolute annual mean removal of biomass and nutrients in one rotation period was calculated to be 6.3–6.7 Mg biomass/ha, 5.1–7.8 kg N/ha, 0.5–0.8 kg P/ha, 4.3–5.4 kg K/ha, 7.2–9.0 kg Ca/ha, and 1.1–1.4 kg Mg/ha (Table 6). Absolute mean nutrient removals calculated by Andersen & Nord-Larsen (1997) and Beier *et al.* (1995) were lower than found in the present study, possibly because production data in the earlier studies were from a site of low productivity. Biomass and nutrient removals were concentrated in the second half of the rotation period (Fig. 3).

TABLE 6–Annual mean nutrient removal during simulated rotation period scenarios.

| | Biomass (Mg/ha) | N | P | K | Ca | Mg |
|---|---|---|---|---|---|---|
| | | (kg/ha) | | | | |
| Fresh WTH | 6.7 | 7.8 | 0.8 | 5.4 | 9.0 | 1.4 |
| Dried WTH | 6.5 | 6.9 | 0.7 | 4.9 | 8.6 | 1.3 |
| Stems | 6.3 | 5.1 | 0.5 | 4.3 | 7.2 | 1.1 |

Weak points in the calculations are stem nutrient concentrations, the distribution between stem and bark volume, and the fact that tops of stems are included in stem biomass and nutrient removals. Not subtracting stem tops to create biomass and nutrient contents of merchantable stem only contributes to under-estimation of differences. Comparisons of WTH with stem harvest are sensitive to the estimated stem-wood and stem-bark nutrient concentrations, and these were measured for only two trees. However, compared to the variation found in Denmark (Danish Forest and Landscape Research Institute, unpubl. data), the two samples did show similar values for all nutrients.

Stem disc samples were furthermore removed at breast height, thereby ignoring the fact that stem nutrient concentrations increase with height above ground. If stem nutrient concentrations of both wood and bark were 50% higher than values shown in Table 1, nutrient removals in a single thinning operation would increase 2.5–5.5 and 2.0–3.0 times for Fresh WTH and Dried WTH respectively compared to Stems. This increase is inherently lower than rates found using nutrient concentrations of Table 1 (nutrient removals increased 3.5–8.0 times and 2.5–4.5 times for Fresh and Dried WTH respectively compared to Stems). The reduction in nutrient removals in Stems compared to Fresh WTH would be 70–90% and 60–80%, respectively, for nutrient concentrations in Table 1, and nutrient concentrations which are 50% higher than these.

There is some question how general the relationship in Equation [3] is, and whether methods applied in the study by Holmsgaard & Jakobsen (1970) can be applied to this study. Measurements of 12 old Norway spruce trees at Klosterheden showed values of the constant from 0.77 to 1.58 (Danish Forest and Landscape Research Institute, unpubl. data). But, using the value 2.11 found by Holmsgaard & Jakobsen (1970), the estimated stem-wood and stem-

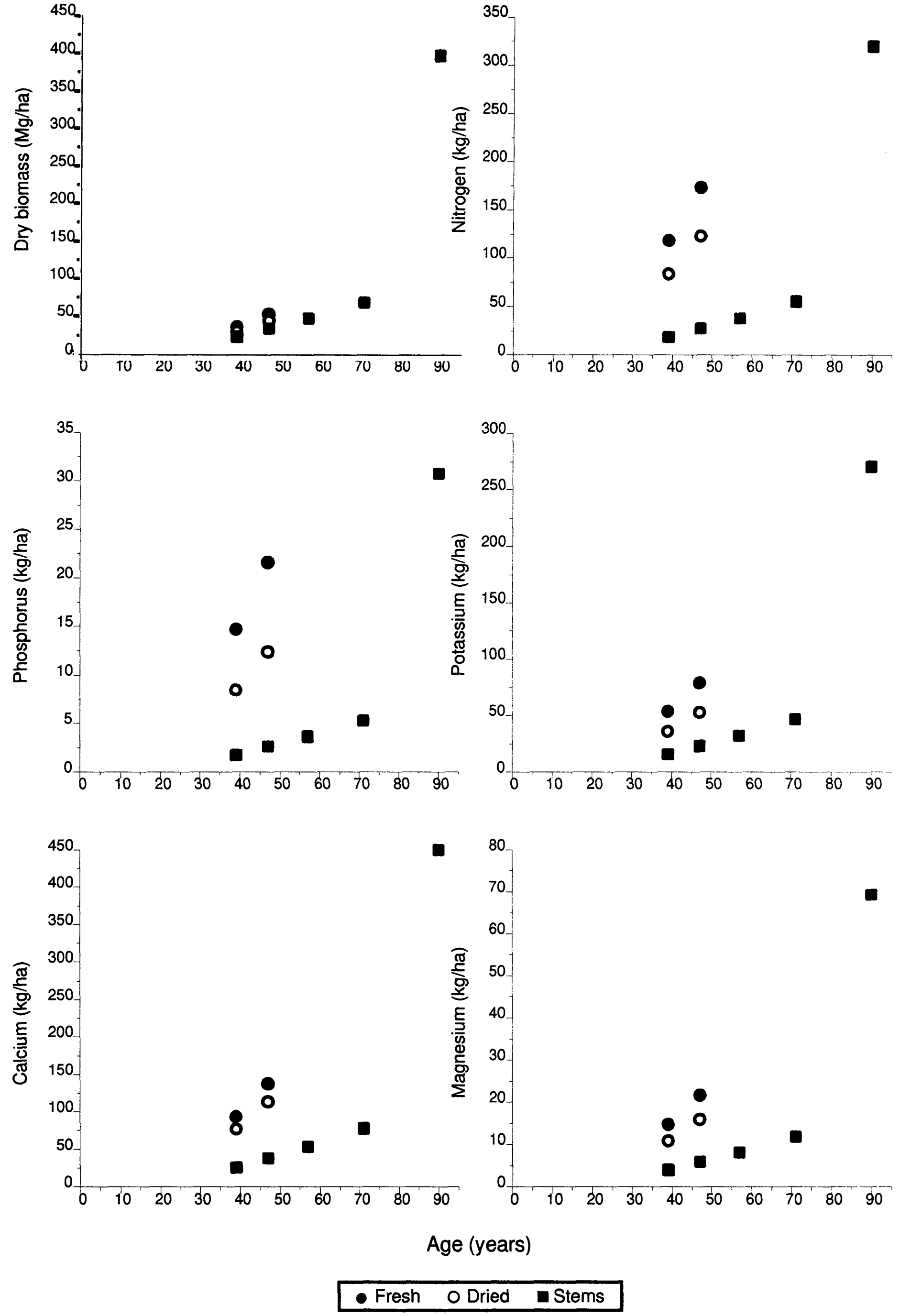

FIG. 3—Calculated biomass and nutrient removals in thinnings and clear-cut during a rotation period scenario for the three harvesting intensities.

bark biomass seem to the fit stem-wood and stem-bark biomass equations of Marklund (1988).

For the data in Tables 5 and 6, the combination of single tree biomass and nutrient concentrations from one site type and stand, with growth model calculations fitted for other site types and stands, introduces a major obstacle to a far-reaching interpretation of rotation level results. In particular, the interaction between crown biomass, initial stocking number, and thinning regimes could be of great importance. Disregarding the variation in stand diameters and heights might also introduce bias to the results. Most importantly, results found in this study originate from one single stand.

## Nutrient Budgets

A common way of evaluating long-term effects of intensive harvesting on the nutrient status—and thereby the production potential—of a site is to draw up input-output nutrient budgets. Inputs such as deposition and weathering are compared to outputs from leaching and removal in biomass. Depending on the conditions of the specific site, more or fewer inputs or outputs are included. The evaluation becomes increasingly complicated and increasingly relevant when moving from input-output budgets to dynamic considerations and further to questions of availability. To some extent, however, input-output budgets do characterise the system and are rather simple to construct.

In Denmark large inputs of calcium, magnesium, and potassium come to the forests from sea salt. Data from Kreutzer *et al.* (1998) were remodelled as described above. Provided all nutrients from sea salt inputs are taken up by the stand, atmospheric deposition can compensate for removals of potassium in Fresh WTH, Dried WTH, and Stems up to a distance of 15–20 km from the sea, and for removals of calcium up to 20–25 km from the sea (Fig. 4). Magnesium inputs from sea salt would be able to compensate for removals at all sites in Denmark. However, nutrient inputs from sea salt are partly leached from the root zone. This means that the critical distances for full nutrient compensation will be shorter than mentioned above. On the other hand, annual removals of nutrients on poor soils in western Jutland are probably somewhat lower than calculated here (cf. Andersen & Nord-Larsen 1997; Beier *et al.* 1995).

As an illustration, the calculated base cation removal in biomass was compared to nutrient budgets from two well-described forests—Klosterheden in western Jutland (18 km from the sea) and Solling in northern Germany (230 km from the sea) (Table 7). The soil texture at Klosterheden is coarse sand, and at Solling it is silty loam. For a more thorough description of the sites, *see* Kreutzer *et al.* (1998). For Klosterheden, the deposition was calculated based on Equation [8]. For Solling, the bulk precipitation was used, as this location has contributions from fly ash. Some of this is found in bulk precipitation, but dry deposition from fly ash and other sources was not included. Reynolds *et al.* (1998) gave estimates of annual weathering rates of potassium, calcium, and magnesium for six sites in Europe, including Klosterheden and Solling. The range of the six sites was 0.0–4.8 kg K/ha, 0.0–3.6 kg Ca/ha, and 0.0–4.2 kg Mg/ha. When these figures are compared with calculated "weathering needs" (Table 7), it appears that the two ecosystems can scarcely support utilisation and that the demand on soil nutrients will be highest at the continental site (Solling). However, weathering estimates are uncertain and nutrient budgets are subject to many possible errors. Leaching estimates can vary a lot within a few metres or less (P.Gundersen, Danish Forest and Landscape

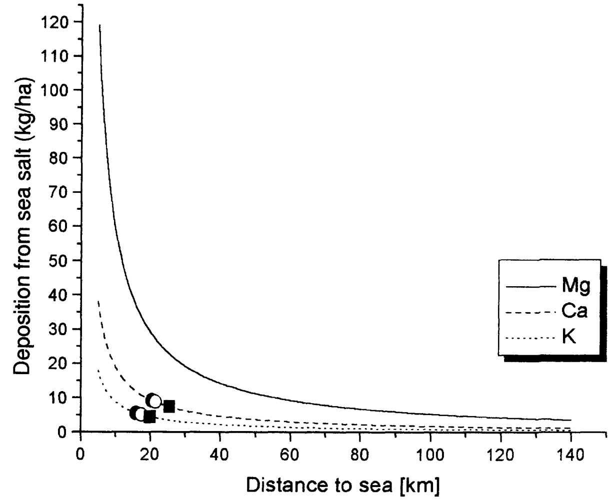

FIG. 4–Modelled deposition of potassium, calcium, and magnesium from sea salt in relation to the distance from the sea. Filled circle, empty circle, and filled square are calculated mean annual removals over a rotation period for scenarios of Fresh WTH, Dried WTH, and Stem harvesting respectively. Mean annual removals for magnesium were 1.1–1.4 kg/ha—less than deposition from sea salt in Denmark.

TABLE 7–Annual nutrient budget (kg/ha). Deposition and leaching data are calculated from Kreutzer *et al.* (1998).

| | Klosterheden | | | Solling | | |
|---|---|---|---|---|---|---|
| | K | Ca | Mg | K | Ca | Mg |
| Deposition | 4.3 | 9.3 | 29.2 | 2.7 | 8.8 | 2.8 |
| Leaching | 10.9 | 4.8 | 28.9 | 6.6 | 16.0 | 7.5 |
| Removal (Fresh WTH ) | 5.4 | 9.0 | 1.4 | 5.4 | 9.0 | 1.4 |
| Weathering need* | **12.0** | **4.5** | **1.2** | **9.3** | **16.2** | **6.5** |
| Removal (Stems) | 4.3 | 7.2 | 1.1 | 4.3 | 7.2 | 1.1 |
| Weathering need* | **10.9** | **2.7** | **0.9** | **8.2** | **14.4** | **6.2** |

* Weathering estimates are not included, as it is difficult to obtain reliable estimates. Instead, "weathering needs" are calculated by subtracting nutrient leaching and nutrient removals in biomass from the atmospheric deposition of nutrients.

Research Institute, pers. comm.), deposition—and hence also leaching—is highly dependent on the age and structure of the stand (T.Bille-Hansen, Danish Forest and Landscape Research Institute, pers. comm.), and estimates of nutrient removals in harvesting are not related to these sites.

The deposition of ammonium-nitrogen is mainly dependent on the distance from animal farming, from which large amounts of ammonia are released into the atmosphere. Contributions of nitrate-nitrogen from combustion gases are also significant, but less variable over the country. According to Bak (1996), annual deposition of nitrogen ranges from about 10 to about 40 kg/ha in Denmark. The largest deposition of nitrogen occurs in the southern parts of Jutland, whereas the smallest deposition of nitrogen is found in the most western parts of Jutland and the most northern parts of Zealand along the coastline. Deposition of nitrogen thus exceeds nitrogen removals, even when whole-trees are harvested fresh. However, Jacobson & Kukkola (1999) found that fresh whole-tree harvesting in the first thinning at 10 years had caused significant increment losses in Norway spruce and Scots pine compared to stem-only harvest on a number of Swedish and Finnish sites. Losses could be counteracted by fertiliser application with compensatory amounts of nitrogen, indicating that increment losses occurred as a consequence of less available nitrogen. Nitrogen is normally believed to be in excess in south Sweden, so it is interesting that relative increment losses on sites in south Sweden were as high as on more northern sites. Deposition of nitrogen in forests in south Sweden has been calculated to be 10–20 kg/ha annually (Vinterbäck *et al.* 1998) and should therefore be comparable to the nitrogen deposition in some parts of Denmark.

Deposition of phosphorus has been measured at 0.5 kg/ha annually at Klosterheden (P.Gundersen, pers. comm.). Based on the geology of the EXMAN sites, Reynolds *et al.* (1998) assumed that there were no sources of phosphorus from weathering. Removals of phosphorus therefore seem to exceed inputs and, as for potassium and calcium, the system might be sensitive to phosphorus removals.

### Communication of Guidelines

A long-term objective is to be able to give site-specific guidelines for the removal of biomass and nutrients in thinnings and clear-cuts based on scientific knowledge. So far, available information is inadequate. General information is necessary on soil weathering capacity, on leaching, on inputs from atmospheric deposition (e.g., in relation to stand parameters), and on nutrient removals at rotation level in relation to harvesting practices. Furthermore, the information needs to be transformed into practical guidelines in a satisfactory way. Jacobson & Mattsson (1998a, b) produced an elegant means of synthesising existing knowledge and of acquainting forest managers with the way in which they influence the ecosystem quantitatively. They developed a simple spreadsheet model for Swedish conditions, which estimates the amounts of biomass and nutrients removed and the compensatory amounts of ashes to be recycled under different harvesting intensities. The user can adjust the model using realistic inputs for specific sites. A similar model developed for Danish conditions will soon be available at the Danish Forest and Landscape Research Institute.

## CONCLUSION

The amounts of nutrients removed during whole-tree harvesting in thinnings were significantly higher than removals in stem harvest only, both when trees were harvested fresh and when they were harvested after drying for 6 months in the stands during the summer. Drying of trees reduced the amount of nutrients removed by 20–45% compared to fresh whole-tree harvesting. Reduction in biomass yield was found to be 15%. Harvesting of stems-only reduced the amount of nutrients removed by 70–90 % compared to fresh whole-tree harvesting. The decrease in biomass yield was 35%. Nutrient removals in harvests of fresh and dried whole-trees increased 3.5–8.0 times and 2.5–4.5 times respectively compared to stem-only harvest. When whole-tree harvesting was simulated for the first two thinnings and stem harvest in all later thinnings and clear-cut, differences in nutrient removals inherently decreased. However, differences were still observed. Nutrient budgets indicate that when weathering capacity is low, a decrease in long-term production potential at sites similar to Klosterheden is more likely to be a consequence of diminished potassium, calcium, and phosphorus pools and availability, than a consequence of nitrogen and magnesium deficiency.

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