Estimation, availability and production of tree biomass resources for energy purposes – a review of research challenges in Norway

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Preface

The Bioenergy Innovation Centre (CenBio) is cooperation between the Norwegian University of Life Sciences, Norwegian Institute of Forest and Landscape, Norwegian Centre for Agricultural and Environmental Research, The Foundation for Scientific and Industrial Research (SINTEF), and the Norwegian University of Science and Technology (NTNU). The project is funded by The Research Council of Norway, a number of industrial partners and participating research institutions.

The project started in year 2009 and will continue at least until 2013. The present report is a review of the state of the art regarding the main issues that will be handled by Working Package 1.1 (Feedstock supply) in the CenBio project. The aim of the report is to indentify knowledge gaps and challenges, and thus facilitate appropriate focus, development and priorities regarding development and research within this subject area for the coming years.

Ås, 1th of November 2010

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Summary

Eid, T., Brunner, A., Søgaard, G., Astrup, R., Tomter, S., Løken, Ø. & Eriksen, R. 2010. Estimation, availability and production of tree biomass resources for energy purposes – a review of research challenges in Norway [Estimering, tilgjengelighet og produksjon av biommasse i skog for bioenergiformål – en gjennomgang av forskningsutfordringer i Norge]. INA fagrapport 15, 91 pp.

Ambitious targets for renewable energy production in Norway draw attention to biomass potentials. The objective of this report is to review the state of the art regarding research on estimation methods, the availability and production of tree biomass resources for energy purposes in Norway in order to indentify knowledge gaps and thus facilitate appropriate focus, development and priorities regarding research for the coming years. The review focuses on biomass from primary forest production with emphasis on Norwegian conditions, but also considers international research, especially from the other Nordic countries. Three main subject areas are considered:

- biomass estimation
- biomass resources and availability
- biomass production.

The first part of this report comprises an overview of existing biomass equations and associated inventory methods applied for estimating biomass in Norway. The overview includes a description of the Norwegian National Forest Inventory data as a basis for large-scale biomass assessments. The second part of the report comprises an overview of previous Norwegian assessments of biomass as an energy supplier as well as suggestions for improvements in such assessments. Improvement possibilities regarding the impacts of environmentally oriented restrictions, appropriate models for productivity and cost calculations regarding biomass harvesting systems, and implementation of biomass-related features in existing decisions support systems to facilitate analyses, where timber production and biomass production for energy purposes are equally important, are identified. The final part of the review focuses on silvicultural options aiming at optimizing the value of total biomass instead of the conventional approach to silviculture where the main focus is timber values.

Key words: forest biomass, energy, estimation, availability, production

Sammendrag

Eid, T., Brunner, A., Søgaard, G., Astrup, R., Tomter, S., Løken, Ø. & Eriksen, R. 2010. Estimation, availability and production of tree biomass resources for energy purposes – a review of research challenges in Norway [Estimering, tilgjengelighet og produksjon av biommasse i skog for bioenergiformål – en gjennomgang av forskningsutfordringer i Norge]. INA fagrapport 15, 91 pp.

Nye og ambisiøse mål for produksjon av fornybar energi i Norge setter fokus på biomasse i skog. Hovedformålet med denne rapporten er å kartlegge kunnskapsstatus med hensyn på estimerings-metoder, tilgjengelighet og produksjon av biomasse i skog i Norge. Denne kartleggingen er tenkt å danne grunnlaget for en prioritering av utviklings- og forskningsoppgaver innen dette fagområdet for de kommende årene. Rapporten legger vekt på norske forhold, men også internasjonal forskning og utvikling, særlig fra de andre nordiske landene, blir tatt opp. Tre hovedområder blir fokusert:

- biomasseestimering
- biomassetilgjengelighet
- biomasseproduksjon.

Den første delen omfatter en oversikt over eksisterende biomassefunksjoner og takstopplegg som brukes i forbindelse kartlegging av biomasse i Norge. Oversikten inkluderer en beskrivelse av Landsskogtakseringens opplegg og data som grunnlag for kartlegging av biomasse for større områder. Den andre delen omfatter en oversikt over tidligere kartlegginger av tilgjengelig biomasse i Norge, samt forslag til forbedringer som kan gjøres for slike analyser. Som viktige områder for forskning og utvikling pekes det her på konsekvenser av miljørestriksjoner, modeller for produktivitet og kostnader ved uttak av biomasse fra skog og tilrettelegging av eksisterende prognoseverktøy slik at tømmerproduksjon og biomasseproduksjon til energi i større grad kan sidestilles i analyser. Den siste delen av rapporten tar for seg skogskjøtselmetoder der en fokuserer på verdien av total biomasse i stedet for den tradisjonelle tilnærmingen der en fokuserer på verdien av tømmer.

Nøkkelord: biomasse fra skog, energi, estimering, tilgjengelighet, produksjon

1. Introduction

New and ambitious targets for renewable energy production in Norway draw attention to biomass potentials in the country. The Government has proposed to increase the annual use of bioenergy by 14 TWh by year 2020 (St.meld. nr. 34 (2006-2007). Forest resources represent the main biomass source for energy in Norway, partly as feedstock directly from forests, partly as residues from the forest industry, and as a small portion of waste wood from, for example, packaging goods and demolition of houses. In addition to forest biomass, biomass from agricultural production and wet organic waste are important sources for renewable energy in Norway.

The targets for future energy production from biomass have several challenging implications. Suplies will have to be increased substantially compared to present use. Increased competition for use of land and for biomass resources imply that present efficiencies must be improved. Economic and ecological sustainability must be addressed throughout the value chain. To determine how the quantities of biomass harvested for energy purposed may be doubled by the year 2020 there is a need to implement research on several issues.

The main objective of the present report is to review the state of the art regarding research on estimation, availability and production of tree biomass resources for energy purposes in Norway. The aim is to indentify knowledge gaps and challenges, and thus facilitate appropriate focus, development and priorities regarding research within these subject areas for the coming years. The review is based on existing literature and ongoing research. The main focus is on Norwegian conditions, but also international research and literature are considered.

Biomass derived from forest production applies to primary forest production (standing forest), residues from the forest industry (secondary production), and waste wood from other activities. This review focuses on biomass for energy from primary forest production. Based on these priorities the following main subject areas are considered:

- biomass estimation
- biomass resources and availability
- biomass production.

Biomass estimation of a stand, forest property, or certain geographical unit or stratum is generally done by multiplying biomass ha^{-1} by the total area under consideration. Biomass equations and their application in Norway are described and discussed. Since the most important source for biomass estimation at national and regional levels in Norway is National Forest Inventory (NFI) data, the procedures applied to the Norwegian NFI are described, with emphasis on biomass estimation. Also biomass resources related to areas normally not considered appropriate for forest production (e.g. densely populated areas, pasture, power lines, roadsides, border zones surrounding agriculture land) are discussed. Finally, the review examines inventory methods and sampling designs relevant also for other purposes than national and regional assessments, such as purposes related to practical management planning at different levels.

Assessments of biomass resources and the potential of biomass as a source of energy at national and regional levels in Norway have been carried out by several projects over the past 10 years. Most of these assessments have been relatively simple, and are therefore reviewed here in order to identify knowledge gaps and suggest improvements. In addition to the basic biomass estimation mentioned above, biomass resources are also considered with regard to environmental, technical and economic restrictions. To assess the potential future availability of biomass resources it is necessary to consider growth dynamics, temporal and spatial aspects, harvesting costs, and biomass fraction prices. Forest management decision support systems (e.g. a forest simulator and a decision module coupled with GIS functionality) already developed in Norway comprise functionality that partly can deal with such aspects. There are obvious shortcomings, however, for example related to new biomass harvesting methods and systems. Previously developed decision support systems are described and possible measures for improving them are discussed. The focus is on resources available at roadsides. Challenges related to transport and logistics from roadsides to energy user are not considered. Questions related to the market for biomass are only superficially considered in this review.

Biomass production may result from conventional forest production applying silvicultural alternatives to optimize the value of timber. However, it may also result from conscious management aiming to optimize the value of the total biomass. Such management could be applied on sites previously used for conventional forest production but also for other areas, such as those previously used for agricultural production. Accordingly, silvicultural aspects of biomass production constitute the third main part of this review.

2. Biomass estimation

Estimations of tree biomass quantities may be required for general forest planning or for studies of energy and nutrients flows in ecosystems. Currently, however, the focus is on tree biomass both as carbon stocks as a means to reduce atmospheric CO_2 concentration and as an energy source.

The total biomass of a given stand, forest property, geographical area, or stratum is generally estimated by multiplying biomass ha^{-1} by the area under consideration. The basic requirement in biomass estimation is the availability of appropriate species-specific biomass equations for individual trees. A biomass equation may in general be used to estimate the dry weight of the biomass for a whole tree or fractions of a tree by means of tree-level measured data (tree species, diameter, height, etc.). The most common method for estimating biomass ha^{-1} is to take measurements for all trees within the unit, thereafter apply biomass equations for individual trees, and finally sum up biomass for all trees located in the unit.

If only a sample of trees within a given unit is measured there are principally three ways to estimate biomass ha^{-1}. First, the area unit can be characterized through stand-level variables (e.g. species distribution, basal areal ha^{-1}, mean height) and the biomass estimated by means of stand-level biomass equations. Second, individual tree-level information can be generated by means of diameter distribution models and/or height curves, and biomass can be estimated from equations for individual trees. This method, however, requires available information on number of trees ha^{-1}. A third method is to apply stand-level volume equations and corresponding biomass expansion factors (BEF) to estimate total biomass ha^{-1}. A biomass expansion factor is a factor that converts timber volumes into the dry weight of the biomass.

The choice of method for estimations of biomass ha^{-1} is closely related to the general inventory design. In the Norwegian NFI or in procedures applied for airborne laser scanning, where all diameters are measured within a sample plot, biomass equations for individual trees are applied. For inventories based on ground-based laser scanning, photo interpretation, airborne radar techniques, and satellite images it may be necessary to apply some of the other methods for biomass estimation described above.

The first part of this chapter comprises a state-of-the-art description regarding biomass equations and their application in Norway. Secondly, a description of procedures applied by the Norwegian NFI, with emphasis on biomass estimation, is given. Finally, inventory methods, relevant for smaller areas and practical planning, or for other purposes, are discussed.

2.1. Biomass equations and biomass expansion factors

2.1.1. Existing equations and their application

Extensive reviews of tree-level European volume and biomass equations have been given by Zianis et al. (2005) and Muukkonen & Makipaa (2006). The total numbers of the compiled equations for biomass estimation in these two reviews are 607 and 188, respectively. Many of these biomass equations are developed for above-ground tree components only and most of them are based on relatively few sampled sites, reflecting only limited variation regarding growing conditions and silvicultural treatments, and a very limited number of sampled trees.

Most of the tree-level biomass equations developed in Norway are described in Table 1. In general, they cover a relatively large number of species and fractions. The number of trees used for developing models is also in most cases relatively high compared to the numbers reported by Zianis et al. (2005) and Muukkonen & Makipaa (2006). However, the main problem with most Norwegian equations is their general validity, i.e. most of them have been developed from data covering limited variation regarding growth conditions and silvicultural treatments. For example, the equations developed for birch (Opdahl 1987, Bollandsås et al. 2009) are based on data from high altitude areas in southern Norway. This means that they should not be applied at low altitudes or in other parts of the country, at least not before they have been tested for such sites. Similar problems relate to the equations developed by Brække (1986) and Korsmo (1995), where the data were based on sites subjected to certain silvicultural treatments, i.e. ditched peatlands and regeneration by coppicing only, respectively.

The most widely applied biomass equations in Norway (Table 2) (see also section 2.2.3) have been developed in Sweden (Marklund1987, 1988, Petersson & Ståhl 2006). Among the almost 800 biomass equations in Europe reviewed by Zianis et al. (2005) and Muukkonen & Makipaa (2006), only Marklund's (1987, 1988) equations were based on a sample size of several hundred felled trees. Since these reviews, however, biomass equations have been developed in Finland based on representative data material from several hundred trees for each of the three tree species Norway spruce, Scots pine, and birch (Repola 2008, 2009).

In general, the trees used for the development of Marklund's (1987, 1988) biomass equations cover large variations regarding growing conditions and treatments in Sweden. The only reservation made for the application of the equations was for treatments that 'considerably deviate from the normal'. When applied in Norway, the equations are definitely used outside their geographical range. However, since they cover a wide range of conditions and treatments in Sweden there is reason to believe that they will also be appropriate for use in Norway, at least in southern and eastern Norway, and probably also in the central part of the country. Since wood density and biophysical stem properties vary according to growing conditions, one should probably be more careful when applying the equations in coastal regions in the western and northern part of Norway without first checking their performance. Marklund's equations for birch are also frequently applied for other broadleaved tree species in Norway. This is clearly a violation of the 'data range'.

Wilhelmsen & Vestjordet (1974) developed stand-level biomass equations for Norway spruce in Norway. These equations can be used to estimate biomass (dry weight) based on stand-level variables such as basal area and mean height. However, since only the weight of the merchant-able part of the stems can be estimated, the models have only limited value regarding biomass estimation for energy purposes. No other stand-level biomass equations have been developed in Norway.

The typical procedure when developing stand-level biomass equations, however, is to sum up the biomass from all trees, estimated from individual-tree biomass equations, within a number of stands, and thereafter regress the estimated biomass for the stands with different stand variables (e.g. basal area and mean height). Example of such equations are given by Doruska et al. (2004), used in the United States. Such an approach to the development of stand-level biomass equations implies that the appropriateness and error structure of stand-level equations to a large extent rely in turn on equations for individual trees. However, stand-level equations may be an appropriate solution when no information on individual trees is available, such as in cases when forest simulators based on area-based growth models are applied (see also section 3.4).

Table 1. Biomass equations developed in Norway.

Tree species	Units			No. of trees	Range of		Fractions*	R-square (according to fractions)	Reference
	Biom.	D	H		D (cm)	H (m)			
Norway spruce (*Picea abies*)	g	cm	-	35	2-15	-	AB, BR, DB, FL, SB, SW	0.99, 0.98, 0.80, 0.97, 0.98, 0.98	Brække (1986)
Sitka spruce (*Picea sitchensis*)	kg	cm	-	10	2-43	2.6-34	AB, BR, DB, FL, SB, SW	0.97, 0.73, 0.51, 0.51, 0.99, 0.97	Johnsen (2009)
Scots pine (*Pinus sylvestris*)	g	cm	-	16	2-15	-	AB, BR, CO, DB, FL, SB, SW	0.99, 0.97, 0.69, 0.99, 0.95, 0.99, 0.99	Brække (1986)
Scots pine (*Pinus sylvestris*)**	g	cm	-	16	2-20	-	AB, BR, CO, DB, FL, SB, SW	0.99, 0.97, 0.71, 0.93, 0.95, 0.99, 0.99	Brække (1986)
Birch (*Betula pubescens*)	kg	cm	-	133	1-8	-	AB	0.97	Opdahl (1987)
Mountain birch (*Betula pubescens* spp. czerepanóvii)	kg	mm	-	80	3-22	1.8-12	AB, CR, ST	0.85, 0.60, 0.91	Bollandsås et al. (2009)
Mountain birch (*Betula pubescens* Ehrh, subsp. Tortuosa Ledeb.)	kg	cm	cm	16	4-12	3.7-8	SW, SB, BR, SR	0.88, 0.79, 0.92, 0.94	Kjelvik (1974)
Silver birch (*Betula pendula*)	kg	cm	-	34-88	1-13	1.5-16	BR, FL, ST	0.92, 0.75, 0.99	Korsmo (1995)
Black alder (*Alnus glutinosa*)	kg	cm	-	130-137	1-14	1.5-14	BR, FL, ST	0.86, 0.77, 0.98	Korsmo (1995)
Grey alder (*Alnus incana*)	kg	cm	-	48-54	1-15	1.5-15	BR, FL, ST	0.89, 0.84, 0.99	Korsmo (1995)
European ash (*Fraxinus excelsior*)	kg	cm	-	18-32	1-11	1.5-14	BR, FL, ST	0.93, 0.96, 0.98	Korsmo (1995)
European aspen (*Populus tremula*)	kg	cm	-	70-132	1-15	1.5-12	BR, FL, ST	0.92, 0.94, 0.99	Korsmo (1995)
Rowan (*Sorbus aucuparia*)	kg	cm	-	42-43	1-10	1.5-12	BR, FL, ST	0.90, 0.81, 0.99	Korsmo (1995)

*AB = Total above-ground biomass, BR = Branch biomass, CO = Biomass of cones, CR = Crown biomass, DB = Biomass of dead branches, FL = Total foliage biomass, SB = Biomass of stem bark, SW = Stem wood biomass, ST = Total stem biomass (including bark), SR=biomass of the stump root system, ** = Fertilized

Table 2. Biomass equations usually applied in Norway.

Tree species	Units			No. of trees	Range of		Fractions*	Function ID	R-square (according to fractions)	Reference
	Bio-mass	D	H		D (cm)	H (m)				
Norway spruce (*Picea abies*)	kg	cm	m	551	0-50	1-30	CR, DB, FL, RC, RF, SB, SR, ST, SW, SU	12, 20, 16, 28, 31, 8, 23, 1, 5, 26	0.99, 0.87, 0.97, 0.98, 0.97, 0.99, 0.99, 0.99, 0.99, 0.98	Marklund (1987, 1988)
Scots pine (*Pinus sylvestris*)	kg	cm	m	493	0-48	1-28	CR, DB, FL, RC, RF, SB, SR, ST, SW, SU	14, 22, 18, 31, 34, 10, 25, 2, 6, 28	0.98, 0.88, 0.95, 0.96, 0.95, 0.97, 0.98, 0.99, 0.99, 0.98	Marklund (1987, 1988)
Birch (*Betula pubescens*)	kg	cm	m	242	0-36	1-24	CR, DB, SB, ST, SW	11, 16, 8, 2, 5	0.96, 0.79, 0.98, 0.99, 0.99	Marklund (1987, 1988)
Norway spruce (*Picea abies*)	kg	mm	-	342	0-63	1-35	SR	A-i	0.97	Petersson & Ståhl (2006)**
Scots pine (*Pinus sylvestris*)	kg	mm	-	330	1-49	1-27	SR	A-i	0.98	Petersson & Ståhl (2006)**
Birch (*Betula pubescens*)	kg	mm	-	14	1-27	2-21	SR	A-i	0.95	Petersson & Ståhl (2006)**
Norway spruce (*Picea abies*)	kg	mm	-	342	0-63	1-35	SR	B-i	0.97	Petersson & Ståhl (2006)***
Scots pine (*Pinus sylvestris*)	kg	mm	-	330	1-49	1-27	SR	B-i	0.98	Petersson & Ståhl (2006)***
Birch (*Betula pubescens*)	kg	mm	-	14	1-27	2-21	SR	B-i	0.95	Petersson & Ståhl (2006)***

* CR = Crown biomass, DB = Biomass of dead branches, FL = Total foliage biomass, RC = Biomass of coarse roots (defined in the study), RF = Biomass of fine roots (defined in the study), SB = Biomass of stem bark, SR = biomass of the stump root system, ST = Total stem biomass, SU= Stump biomass, SW = Stem wood biomass,
>5mm, *>2mm

A simpler method for estimating stand-level biomass was provided by Johansson (1999a, 1999b) for Norway spruce and aspen growing on abandoned farmland. In this approach biomass equations were first developed based on individual trees, and then the equations were applied based on stand-level parameters (i.e. basal area mean diameter). Johansson (1999a) argued for such a procedure based on the assumption that the variation in size between trees on abandoned farmland where all trees have been planted was very low. Theoretically, a similar approach could be applied also for other forest types in order to estimate stand biomass in cases where information on individual trees does not exist. In Norway, information on basal area mean diameter (D_g), mean height by basal area (H_L), and number of trees ha^{-1} (N) is quite often available in forest management plans and in area-based forest simulators. By applying these variables as input in, for example, Marklund's (1987, 1988) tree-level biomass equations, an estimate can be obtained for biomass for a given stand. It is, however, obvious that such a procedure will cause biased estimates at stand level due to variations in tree sizes. Even if the diameter distribution is narrow and normally distributed, there will be a bias because of the non-linear relationship between diameter and weight in the biomass equations. In most 'normal' stands considered as even-aged, and particularly in uneven-aged forests, with a typical inverse J-shape in size distribution, care should be taken in applying this approach as long as there have not been any systematic tests of how large any biases will be that appear under different conditions.

As previously stated, biomass equations may be replaced by stand-level volume equations and biomass expansion factors in order to estimate biomass. A biomass expansion factor (BEF) converts timber volumes into the dry weight of biomass (see e.g. Lehtonen et al. 2004). Individual tree volume and biomass equations are required as a basis to develop biomass expansion factors. Since wood density and biophysical stem properties, among other characteristics, vary according to the size and age of trees, it is necessary to establish relationships between the BEF and certain stand characteristics. Lehtonen et al. (2004) in Finland and Jalkanen et al. (2005) in Sweden, for example, established factors varying according to stand tree species and stand age. Although applying BEFs is a good alternative for estimating stand-level biomass when information for individual trees is not available, several authors have reported challenges related to this approach. Jalkanen et al. (2005), for example, pointed to certain discrepancies relating to different geographical regions and young age classes when testing the factors. Similar problems were reported by Levy et al. (2004), who tested a number of biomass expansion factors for several conifer species in Great Britain. Also, Albaugh et al. (2009) pointed to problems when applying

general (not site-specific) BEFs for sites in Sweden that had been subjected to certain treatments (e.g. irrigation and fertilization).

2.1.2. Research challenges

Biomass estimation for carbon stock versus bioenergy

The main body of literature regarding biomass estimation over the past 10 years has focused on biomass as carbon stocks, while less attention has been paid to biomass as an energy source. In some cases, the two approaches coincide and equations can be applied irrespective of the intended purpose. It is, however, important to be aware of differences between the approaches. In carbon estimations the aim is to calculate the total biomass, while quantification of different biomass fractions is less important. In estimations related to bioenergy it is important to quantify the biomass that actually can be used for energy purposes. It is also important to distinguish between different fractions since their potential for producing energy differs. In a study made by Palander et al. (2009), for example, Marklund's (1987, 1988) equations were tested at the operational level of stump wood procurement and a calibrated biomass equation was developed to predict stump biomass. The motivation for Palander's study was to produce more accurate information for planning and business management in energy production. Further examples of challenges related to estimating biomass for energy production are described in the following:

- Norwegian national reporting on carbon stock (see section 2.2.3) is based on Marklund's (1987, 1988) equations for all above ground biomass fractions, while Petersson & Ståhl's (2006) equations are applied for below ground biomass. Petersson & Ståhl (2006) found that their equations gave 11% higher below ground biomass compared to Marklund's (1987, 1988) equations. The reason for this difference is the proportion of the roots included in the equations. Petersson & Ståhl (2006) included all roots down to 2 mm, while Marklund (1987, 1988) focused on biomass for bioenergy and, when excavating the stumps and roots, an unknown proportion of roots was left in the ground. Although the latter approach probably is the most realistic regarding biomass for energy, some conscious considerations on these differences should be done.

- Marklund's (1987, 1988) equations for birch did not include any equations for below-ground biomass. Therefore, his equations for pine have been applied in Norway to estimate below-ground biomass for birch. The fact that pine equations are applied implies an uncertainty that should be considered.

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- Marklund's (1987, 1988) equations for stem and bark biomass also include the top. When estimating forest residues (top and branches) after a conventional harvest for timber production, the stem and bark proportion of the top have to be deducted from the stem and added to the branch biomass. This proportion varies according to the stem taper and the grading and scaling regulations for sawn logs and pulpwood (e.g. minimum top diameter required for pulpwood). Proper analyses of the variation of this proportion based on Norwegian taper curves (Eide & Langsæter 1954, Strand 1967, Blingsmo 1985) should therefore be carried out. Such analyses should also consider other top-diameter requirements than those currently prevailing in order to analyse variations in resources available for pulpwood and forest residues under different assumptions for grading regulations.

- Several questions related to the proportion of needles, leaves and bark left in forests or at roadsides and the proportion that actually can be utilized for energy purposes need to be answered. Also the proportions of remaining wood in forests (short logs, small trees, etc.) have to be considered in this context (see e.g. Gulbrandsen 1980, 1981, Asper 2007). Previous studies, however, have covered only small areas and focused on traditional timber harvesting systems. More research is therefore necessary to arrive at appropriate estimates according to harvesting systems related to biomass for energy purposes.

Systematic evaluation of existing biomass equations for application in Norway
None of the Norwegian biomass equations are based on data covering a wide range of geographical locations, conditions and treatments. Because of this, Marklund's (1987, 1988) equations, developed for Sweden, have been applied in Norway. Complemented with the equations for below-ground biomass developed by Petersson & Ståhl (2006), there is reason to believe that biomass is estimated in an appropriate way under most conditions and for the most important tree species (Norway spruce, Scots pine and birch) also in Norway. Representative biomass equations for the three most important tree species in Finland have been developed (Repola 2008, 2009) and, in the same way as for the Swedish equations, these have potential for covering most Norwegian conditions if applied.

The fact that comprehensive Swedish and Finnish biomass equations already exist implies that large and expensive projects aiming at developing representative equations for Norway should not be nesseary, at least not for spruce and pine. However, the performance of the Swedish and

Finnish equations under Norwegian conditions has never been systematically evaluated. Research in Norway should therefore focus on a systematic evaluation of existing equations. The evaluation should be approached in two different ways: qualitatively and based on empirical data. A qualitative approach should include questions related to the representativeness and structure of the data, the statistical methods used, the capability of the equations to describe the different components of a tree, and the capability of applied independent variables to describe the biomass of different fractions of a tree. The output from Marklund's (1987, 1988) and Repola's (2008, 2009) set of equations could be evaluated in relation to each other and compared with other studies. The comparisons could be done for different conditions (e.g. productivity, treatments) and geographical areas. A similar evaluation of Marklund's equations has previously been done for Finland by Kärkkäinen (2005).

An evaluation based on empirical data should also be carried out. Although no data exist that facilitate systematic tests covering all conditions, there are several existing Norwegian datasets from previous (see Table 1) and ongoing research that could be used for this purpose. In total, these data sets could provide valuable input regarding the performance of the Swedish and Finnish equations when applied in Norway.

The evaluation should, of course, cover as much as possible regarding the three tree species and geographical areas. Since the coastal western and northern parts of Norway vary most from Swedish and Finnish conditions, special attention should be paid to those areas. Also the mountainous and high altitude areas in Norway should be paid attention in this respect. Norway spruce, Scots pine and birch constitute approximately 92% of the growing stock in Norway (Larsson & Hylen 2007). Most of the remaining volume is made up of different broadleaved tree species. The fact that biomass equations for birch are applied also for other broadleaved tree species requires special attention.

Biomass equations for birch in Norway

In Norway, downy birch (*Betula pubescens* Ehrh.) is the dominant broadleaved tree species from sea level to the treeline. In addition, silver birch (*Betula pendula* Roth.) is abundant in eastern parts of the country. Within the productive forest regions, birch makes up 14% of the country's total above-ground volume and approximately 25% of the forested area (Larsson & Hylen 2007). Additionally, birch is the dominant species on approximately 2.5 million hectares of unproductive

forest. Historically, unproductive forest has not been covered by the national forest inventory and neither volume nor biomass estimates are currently available.

It is well established that tree allometry and hence biomass fractions vary between tree species, tree sizes, site types, stand types, and along environmental gradients. Consequently, to develop biomass functions with reasonable precision and broad applicability, it is necessary to have data from the same range of site type, stand type, geographic region, and environmental conditions spanning a range of tree sizes (Marklund 1987). For example, a recent comparison between birch below-ground biomass functions from Sweden and Finland showed differences in predicted values of 15-20% (Repola et al. 2007). Some main objectives in a project related to biomass estimation for birch could be to:

- Sample below- and above-ground biomass of individual trees of birch across a geographical and
   environmental gradient.
- Characterize the error and variation associated with the currently applied biomass functions
   through testing against the collected dataset.
- Develop new below-ground biomass functions that include environmental parameters as
   predictor variables.

Biomass expansion factors for Norwegian conditions

As long as information on individual trees exists, tree biomass equations should be applied directly and summarized to estimate stand-level information. In many cases, however, only stand-level information is available, most commonly as volume ha^{-1}, but also as basal area ha^{-1} and mean height by basal area or as basal area mean diameter, mean height by basal area, and number of trees ha^{-1}. This applies to several management-oriented inventory methods as well as to analyses required as input for decision support systems using area-based growth models (AVVIRK-2000 and Gaya-SGIS, see section 3.4.1). For all these cases the best option for estimating stand-level biomass is probably to apply stand-level biomass expansion factors.

Biomass expansion factors for Norway spruce, Scots pine and birch under Norwegian conditions could quite easily be developed from the combined tree and plot database of the Norwegian NFI by applying volume equations (Braastad 1966, Brantseg 1967, Vestjordet 1967) and biomass equations (Marklund 1987, 1988, Petersson & Ståhl 2006, Repola 2008, 2009) for individual trees.

Relationships (models) could then be established between plot-level (stand-level) information (e.g. volume ha^{-1}) and biomass expansion factor and biomass ha^{-1}.

It is obvious that variations in biomass expansion factors according to tree species and stand age need to be considered (see e.g. Lehtonen et al. 2004, Jalkanen et al. 2005). However, also forest structure (e.g. even-aged versus uneven-aged), treatment history and regional differences should also be considered. Further, special attention should be paid to young forests (development class II) in this respect. Evaluations of such models to a large extent need to be based on qualitatively based expectations regarding performance and previous research on, for example, variation in wood density (e.g. Wilhelmsson 2001, Molteberg & Høibø 2007). However, as far as possible, independent data from destructive sampling should also be applied in empirical testing.

2.2. National forest inventory data in Norway

2.2.1. Background and present use of results

The Norwegian National Forest Inventory (NFI) has been producing large-area forest resource information since 1919. The first inventory was carried out in the period 1919–1930. The main reason for the start of the inventories was concern about the forest situation and concern about the possible lack of forest resources in future. To date, nine inventory cycles have been completed, of which the most recent is for 2005–2009.

The inventory system and sampling design have changed considerably over the years. From 1986 to 1993, fixed-area circular permanent sample plots were installed in all counties except Finnmark. The sixth NFI inventory (NFI6) was carried out on a county-by-county basis. In 1994 the concept of continuous forest inventory was introduced, with 20% of the sample plots inventoried each year. Since 1995, county-based inventories have been carried out together with reassessment of the permanent plots in such a way that temporary plots have been measured in selected counties and completed over a 5-year period. All counties (except Finnmark) have been covered during the period 1995-2009. Limited inventory work in Finnmark County was started in 2005. The primary aim was to provide data for carbon reporting (UNFCCC's Kyoto Protocol), but it will also contribute to more complete general forest statistics for Norway. This work is still ongoing (2010).

The field sampling intensity for permanent plots is basically the same throughout the entire country, i.e. one sample plot represents the same forest area size regardless of the location of the plot. There are, however, some exceptions to this principle. The number of temporary plots and

the distance between them has been adapted to the forest area in the county and to terrain constraints.

The Norwegian NFI covers forests of all ownership groups, including protected forests and all other land-use classes, and serves as a central forest information source for forest industries and forest environment decisions and policy making. Information generated by the NFI has traditionally been used for large-area forest management purposes such as harvest planning, silviculture and forest improvement regimes at regional and national levels, and to some extent decisions concerning development of forest industries. It also provides information to international bodies such as the Food and Agriculture Organization of the United Nations (FAO) and its Global Forest Resources Assessment (FRA) programme and Forest Europe (earlier the Ministerial Conference on the Protection of Forests in Europe) (FAO 2007, MCPFE 2007). In addition, the NFI provides information on forest health status and damage, biodiversity and carbon pools, and changes for the Land Use, Land-Use Change and Forestry (LULUCF) reports of the United Nations Framework Convention on Climate Change (UNFCCC). The Norwegian NFI has been the main source of information for greenhouse gas reporting by the LULUCF sector to the UNFCCC since the mid-1990s, and it will also play a central role in reporting LULUCF activities under Articles 3.3 and 3.4 of the Kyoto Protocol.

Land-use categories reported by Norway are consistent with the IPCC Good Practice Guidance (Penman et al. 2003). Area estimates by land-use categories, excluding some sub-categories of cropland, are based on NFI data. IPCC land-use categories are formed on the basis of national land classes using other variables assessed in the NFI. Data from the current inventory (2005–2009) and three most recent NFIs have been used for estimating time series of areas for land-use categories from 1990 to the present (2009).

Some new land-use related variables and classifications were included in NFI9 because data from previous inventories did not provide adequate information about transitions between IPCC land-use categories. These additions are expected to provide more accurate data for reporting emissions and removals from afforestation, reforestation and deforestation (ARD) activities under the Kyoto Protocol. All the LULUCF related carbon pool change estimates are based either directly or indirectly on NFI data, with the exception of emissions ha^{-1} from organic soils (Rypdal et al. 2005).

In addition to conventional NFI variables such as stand and tree age, the following have been introduced to the NFI: tree species composition, diameter distribution of the growing stock, number of trees, soil and site variables, and variable groups describing forest biodiversity. Assessments of the volume, diameter, tree species, decay class, and appearance class (categories include broken snags, uprooted stems, broken lying stems, logging residues) of dead wood were introduced for NFI7 (1994–1998) for all permanent plots. In subsequent inventories, only trees that have died since the previous assessment have been recorded.

2.2.2. Sampling design

Norway is divided into 17 regions (counties) and for NFI7–NFI9 (1994–2009) each region has had a different sampling intensity based on experiences from previous inventories, especially the total land area of the county and the relationship between forested areas and total land area. The regional sampling designs to some degree also reflect the variability in land-use classes and the values of forest variables (growing stock by tree species). The basic observation unit is an individual field plot. However, for practical reasons and for purposes of increasing the efficiency of fieldwork, field plots are organized into clusters. The shape of the clusters may vary between counties. The cluster design basically applies only to the temporary plots, while the permanent plots are installed in a regular grid of 3x3 km in most parts of the country. An exception is mountain areas (above the previously defined coniferous forest limit), where the spacing between plots is 3x9 km. Multiple plot types were used in NFI9. The plot radius depends on the variable to be recorded, and in some cases, also the value of the variable. The plots used in NFI9 are described as follows:

1. For forests (productive and non-productive), other wooded land, and other land-use classes where trees are assessed, the radius of the sample plot for tally trees is fixed at 8.92 m (area 250 m^2). This plot type has been used for all permanent plots since 1994 for measuring trees with dbh (diameter at breast height) $\geq$ 50 mm. Sample trees are now being selected using an adjustable basal area factor that selects approximately 10 trees in each sample plot, when possible.

2. Temporary plots are circular with an area of 250 m^2 and include a smaller inner plot with an area of 100 m^2. All trees with dbh $\geq$ 200 mm are measured in the larger plot, whereas only trees with dbh $\geq$ 50 mm are measured in the smaller, inner plot. In temporary plots, all trees are considered tally trees, for which only species are observed and dbh is measured. No

sample trees are measured in temporary plots, because the same strata are represented by permanent plots.

3. For all permanent plots with tree assessments, data for trees with dbh < 50 mm are collected in four sub-plots of radius 1.3 m with centres located 5 m from the plot centre in directions north, east, south, and west.

4. Circular sample plots of radius 17.84 m (1000 m^2) centred at the centres of both permanent and temporary plots are used to assess area-related data such as land-use class, crown cover, development class, and site quality class. If a forest edge or stand boundary crosses the plot, the plot shape may be altered to obtain the minimum area of 1000 m^2 within the stand.

5. "Environmental Inventories in Forests" (manual for field work) also uses the NFI permanent plots, but areas of 2000 m^2 (radius 25.23 m) around plot centres are considered. The 2000 m^2 plot should completely or partially overlap a specifically defined environmental unit (habitat) in order for the plot to be used to assess the unit.

2.2.3. Volume and biomass estimation

Area estimates are based on the total land and inland water areas, which are known or assumed to be error-free, and on the number of plot centres. In brief, the area estimate of a land stratum is the product of the known land area and the ratio of the number of sample plots in the stratum and the total number of plots. Because the number of plot centres on land is a random variable, area is estimated using ratio estimators (Cochran 1977):

$$a_s = A \frac{\sum_{i=1}^{n} y_i}{\sum_{i=1}^{n} x_i} = A \frac{\overline{y}}{\overline{x}},$$

where a_s is the area estimate of stratum s, A is the land area on the basis of the official statistics of the Norwegian Mapping Authority, y_i is 1 when the plot centre belongs to the stratum in question and 0 otherwise, x_i is 1 when the plot centre is on land, and n is the number of plot centres on land. Some examples of land strata are forest land, spruce-dominated forest land, and forest land thinned during the last five years.

The stem volume of trees in the Norwegian NFI is defined as the volume of the stem wood above stump to the top of the tree. Volume estimation of individual trees from dbh and height is based on traditional volume functions (Braastad 1966, Brantseg 1967, Vestjordet 1967, Bauger 1995). The functions are available for individual tree species (spruce, pine, birch) and also to some degree for

various regions (i.e. separate functions for western Norway exist). Both volume under bark and over bark are calculated and stored in the database, but for national purposes volume under bark is commonly used. Growing stock includes stem volumes of all living trees, independently of species. For national reporting only the volume of trees with dbh ≥ 50 mm is usually included, but from NFI9 it will be possible to report volume for all trees with dbh > 0 and a minimum height of 1.3m. The estimates of dead wood are intended mainly for biodiversity assessment, but will also be of importance for estimations of carbon pools. A complete assessment of dead wood was carried out 1994–1998. Subsequently, only the trees that have died during the periods between two assessments of the permanent plots have been recorded.

Volumes of individual trees and volumes by various strata are predicted for sample trees (approximately 10 in each sample plot) using volume functions based on dbh and h. These volume estimates are used directly in the following calculations. From the sample trees, an average tariff is calculated individually for tree species classes 'spruce', 'pine' and 'broadleaved trees' occurring in the sample plot. Assuming a reasonably constant diameter-height relationship on the plot, volume can be estimated using only dbh. The volumes of tally trees are predicted by sample plots, applying the tariffs from the sample trees:

1. Volume ha^{-1} and total volume represented by each sample plot are calculated from volume per tree (and plot), sample plot size and area represented by each plot.
2. Mean volumes are tabulated by computation strata.
3. Total volumes are tabulated by computation strata.

The volume estimators are ratio estimators similar to the area estimators. Briefly, to obtain the mean volume for a given stratum, the mean volumes of all trees belonging to that stratum are added and the total is divided by the number of field plots in the stratum. The mean volume of a tree for this purpose is volume ha^{-1} represented by the tree. The indicator variable y_i in the numerator of (1) is replaced with the volume ha^{-1} represented by a tree, or the volume ha^{-1} of timber class of interest represented by the tree, on field plot i when computing volume ha^{-1} or total volume estimates. For total volumes, the volumes ha^{-1} must be multiplied by the area estimate for the stratum in question. This operation has normally been performed for each sample plot and is available in the NFI database; hence the total volume can be estimated by summing up the values for all plots in the stratum.

The estimation procedure for biomass refers to all living trees with a height of at least 1.3 m. Thus, small trees, shrubs and other vegetation, such as herbs are not included in the figures. The biomass of trees with a stem diameter larger than 50 mm measured 1.3 m above the ground is individually monitored.

Both above-ground biomass and below-ground biomass are reported. Above-ground biomass is defined as living biomass above stump height (1% of the tree height). The Swedish biomass equations for individual trees developed by Marklund (1987, 1988) are applied for predicting the various tree biomass components: stem, stem bark, living branches, dead branches, and needles (not leaves) of Norway spruce, Scots pine and birch. These species (including approximately 1% other coniferous species than Norway spruce and Scots pine) constitute 92% of the growing stock (Larsson et al. 2007). Other broadleaved species than birch constitute the remaining 8%, and the birch functions are applied to all these broadleaved species. Below-ground biomass is defined as living biomass below stump height down to a root diameter of 2 mm and is estimated using biomass equations (Petersson & Ståhl 2006) for the same tree species as for above-ground living biomass. The living biomass is estimated consistently based on the same monitoring design, by using the same functions for the same tree species from the base year 1990 and onward.

The biomass for all trees larger than 50 mm in dbh was estimated from their diameter and height assessments. Trees with a diameter less than 50 mm may be included in estimates after 2009, when a full cycle of assessments of small trees has been completed.

NFI6 (1986–1993) was the last inventory where fieldwork proceeded by regions. Since 1994, the inventory has been performed continuously with all permanent plots reassessed every 5 years. For example, the reference year for data collected over the period 2001–2005 is 2003, and for the period 2002–2006 it is 2004. By using such a moving average, both volume and biomass changes have been estimated. The reference year moves forward one year when data for a new season is included in the calculations and data for the oldest season is excluded.

Error estimates are usually based on formulas traditionally used for random sampling, under the assumption that they provide an adequate approximation to the errors for systematic sampling. For the sampling error of area estimates, the normal approximation to the binomial distribution (Snedecor & Cochran 1989) is used, and area standard errors, and volume/biomass standard errors are combined in order to obtain the standard error of the total volume or biomass estimates.

2.2.4. Challenges in estimating biomass for energy purposes

There is no other source better suited for providing large area estimates of biomass for energy purposes than the NFI data (see section 2.3 for alternative inventory methods). These data are based on a well-documented sampling design and on detailed fieldwork instructions. The sample plots cover most of the land area of Norway in a systematic grid providing representativeness in terms of the estimates, and many variables are recorded for each plot describing forest and site conditions. These data therefore provide a solid basis for estimating current biomass resources as well as for assessing future potential.

For biomass assessments related to bioenergy it may be necessary to quantify the biomass according to different strata. Examples of such strata are geographical units, land cover and land-use categories, forest characteristics, site characteristics, and biomass fractions. Some challenges when quantifying biomass according to these strata are discussed in the following:

- Geographical units

  The Norwegian NFI regularly reports on growing stock and biomass resources for the country as a whole, for regions (i.e. several counties), and for individual counties. Results for smaller geographical units than a county are usually not reported because the requirements for maximum standard errors may be violated due to low numbers of sample plots.

  The size of the land area, and accordingly also the number of sample plots distributed, varies considerably between counties. In Hedmark County, for example, the total number of permanent sample plots is approximately 2400, while in Vestfold County the number is approximately 200. Stratification within a county according to, for example, land cover and land-use categories, or according to forest and site characteristics therefore has to be considered carefully in each individual case. For strata with few sample plots (e.g. certain land-use categories) volume and biomass estimates can only be presented at a regional level.

  Since all plots are georeferenced, it is possible to do specific analyses by for example estimating the biomass resources present within certain distances from an anticipated location of an energy producer. In such cases it is important to consider especially the number of sample plots within the area, and the corresponding standard error for the estimated biomass.

- Land cover and land-use categories

The public debate on bioenergy resources in Norway is quite often related to high expectations regarding marginal areas (e.g. pasture, power lines, roadsides, border zones surrounding agriculture land). There is a lack of proper definitions and descriptions for such areas, and there is also confusion related to whether or not such areas are included in NFI assessments.

Over several years, the NFI has covered forest and other wooded land below the coniferous forest limit. However, inventorying sub-alpine forests and other wooded land was not started until 2005, and the first cycle was completed in 2009. An inventory of Finnmark County was not started until recently, and so far only the coniferous forests have been completed and the work is still ongoing in the broadleaved forests.

For the land cover and land-use classes 'productive forest', 'non-productive forest' and 'other wooded land', where land use is classified as 'forestry', 'forest reserves' and 'outdoor recreation area', all living trees with dbh ≥ 5 cm are measured. In addition, assessments are done for smaller trees (on sub-plots) and for dead standing trees. A complete assessment of dead lying trees has not been carried out since the mid-1990s, but are introduced again in 2010. Currently, only a rough estimate can be made for lying trees. However, this means that practically all biomass can be estimated for all these land cover and land-use categories.

Some areas outside forests and other wooded land are surveyed or partly surveyed by the NFI. Thus, an estimate of the potential of these areas for biomass supply may be obtained from existing data. To these belong areas designated for holiday cabins, pastures, *Calluna* heath (near the western coast), power lines, and gardens. Still absent from the NFI inventories are trees in built-up areas, military areas for weapons training and shooting, roads, railways, and airports. Some of these areas are not accessible, neither for inventory, nor for utilization of wood and biomass resources. It may be possible to provide some rough estimates based on their extent, together with an estimated growing stock and biomass ha^{-1}, but the significance of such areas should be expected to be fairly low.

- Forest characteristics

For several reasons, information on quantities of biomass resources according to different forest conditions (e.g. tree species, development class, density) may be interesting from an energy point of view. Tree species, for example, are directly related to the efficiency of energy production,

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density (biomass ha^{-1}) is related to harvesting costs, and development classes are related to availability of resources. Sample plots may be stratified according to such variables. However, also here the main challenge is to avoid violating the requirements for maximum standard errors.

- Site characteristics

Many variables characterizing the growing site conditions for sample plots are directly recorded in the field or are indirectly available through databases or digital maps. Examples are site quality, altitude, latitude, longitude, soil and rock properties, and climate variables like precipitation and temperature. A link between these variables and the associated biomass quantities and qualities may provide interesting data related to different uses of the biomass. Variations in, for example, moisture content, wood density, wood structure, and ash content according to growing site characteristics may have a practical impact on fuel quality and heat value or on potential use of residues, i.e. ashes, for fertilizing (see e.g. Sikström et al. 2009). Here, too, the main challenge is to avoid violating the requirements for maximum standard error when stratifying NFI data.

- Biomass fractions

When considering carbon sequestration, all above- and below-ground biomass should be included. For bioenergy it is important to quantify the biomass that actually can be used for energy. All roots, for example, can hardly be expected to be used for energy. It is also important to distinguish between fractions because they have different potential in producing energy. There is also uncertainty related to the proportion of needles, leaves and bark that can be utilized for energy purposes, and to the proportions of waste left when harvesting biomass.

In general, for the permanent sample plots, all trees with dbh ≥ 5 cm are measured for diameter. However, smaller trees are also measured for sub-plots (see section 2.2.3), and biomass can be estimated. Also biomass of dead standing and fallen trees may be estimated. For both these categories, smaller trees and dead trees, there are several challenges regarding the proportions that can be utilized for energy purposes.

2.3. Inventory methods for biomass estimation

There are several available approaches to biomass estimation that vary in cost, spatial resolution, and associated error levels. The appropriateness of a given forest biomass inventory method will depend on the intended use and associated willingness to pay and accept errors. The historically most common approach for biomass estimation is to combine field plots with biomass equations

or biomass expansion factors (see section 2.1). For sampling-based biomass estimates for large regions or nations, such as provided by the Norwegian NFI (see section 2.2), field measurements combined with biomass equations is the approach applied in all Scandinavian countries. On the other hand, for applications where a full census of stand-level biomass is required, utilization of field-based methods may often be associated with high costs. Thus, remote sensing based approaches are often preferred for inventories associated with strategic and operational planning of forest estates. In the following sections we provide a brief overview of different inventory methods and their applications and future research possibilities.

All remote sensing based methods mentioned in this report are dependent on field plots for calibration and validation. A remote sensing method will never be better than the field data used for calibration. Thus, to obtain good results with remote sensing methods high quality field plots in combination with good biomass equations are required.

2.3.1. Airborne and terrestrial LiDAR

Airborne LiDAR (Light Detection and Ranging) as an inventory tool has seen large development in the past 10 years (see reviews in Næsset 2007 and Næsset & Gobakken 2008) and is now an operational tool used for most forest planning in Norway (Næsset 2007). Biomass estimates can either be obtained from LiDAR data by single tree segmentation (e.g. Solberg et al. 2006) or by the area-based method (e.g. Næsset 2007). In single tree segmentation, individual crowns are detected and variables such as tree volume and biomass are regressed based on tree height and crown characteristics extracted from the laser data. In the area-based method, plot-level variables such as biomass and volume are regressed directly from plot-level height percentiles in the laser data. Single tree segmentation requires laser data with more laser pulses per area than the area-based method and single tree segmentation is hence associated with substantially higher costs.

The stand-level error associated with an airborne LiDAR-based biomass estimate will vary between individual projects and depend on the actual LiDAR acquisition, the quality and quantity of data for calibration, and the applied algorithms. Still, when implemented in a reasonable way, LiDAR-based stand-level volume and biomass estimates have been reported with mean squared errors of about 10-14%, which compares favourably with most other methods (Næsset 2007).

In Norway, the cost of airborne LiDAR-based inventory compares favourably with field-based approaches. Still, large regions wall-to-wall coverage of LiDAR data is associated with very high

cost. Thus, this technique may only be applied in limited areas, or in sampling-based schemes for routine inventories of large areas such as countries (Næsset et al. 2009). The high cost has given rise to research into sampling-based inventorying with LiDAR (Hedmark prosjektet, UMB) and lower cost satellite-based approaches.

Terrestrial LiDAR has received less attention in Norway than airborne LiDAR. While airborne laser scanning has the potential to cover large areas at a reasonable cost, terrestrial LiDAR has the potential for giving detailed estimates for small areas. Internationally, terrestrial LiDAR has been used to measure tree diameters (e.g. Henning & Radtke 2006a), crown attributes (e.g. Henning & Radtke 2006b), and responses to silvicultural treatments (e.g. Huang et al. 2007).

Recently, research activities related to terrestrial LiDAR has commenced in Norway. The BALABU (Bakkemontert laser som verktøy for bedre utnyttelse av skogressursene) project (owned by Viken skog) is investigating inventory methodology with terrestrial LiDAR and how terrestrial LiDAR can be utilized in combination with airborne LiDAR. The BALABU project is carried out in collaboration with the Irish company Treemetrics which bases its business on carrying out forest inventory with terrestrial LiDAR.

2.3.2. Optical satellite imagery and satellite-based radar

There is a wide range of remote sensing techniques that utilize optical imagery from satellites to create wall-to-wall maps of forest conditions and resources (e.g. Luther et al. 2006, Gjertsen 2007, Olander et al. 2008, Tomppo et al. 2008). The advantages of optical satellite imagery are competitive prices (many data sources, such as Landsat TM imagery, are free), coverage of large areas, and repeated coverage. The disadvantages are problems with cloud coverage (see e.g. Olander et al. 2008), problems with distinguishing trees from other vegetation, and a saturation effect for biomass that makes it hard to distinguish biomass concentrations above a certain threshold (e.g. Nilson et al. 2003, Eriksson et al. 2006).

In Scandinavia, the most developed application of satellite imagery for forest recourses is Multi-Source National Forest Inventory (MSFI) (e.g. see review of method and applications in Tomppo et al. 2008). MSFI was developed in Finland to provide forest statistics for small areas that are equivalent in quality to the regional or national estimates provided by national forest inventories (Tomppo et al. 2008). In MSFI, plot data are combined with satellite images (Landsat) and the K-Nearest Neighbor estimation method. The product of MSFI is statistics for small areas and wall-

to-wall forest maps. Due to the estimation method, all variables included in the field plots are estimated in the MSFI. The root mean squared error of the MSFI is substantial (> 12%) for small areas (< 100 ha) but becomes smaller as the area of interest increases (Tomppo et al. 2008). The Norwegian MSFI product (Gjertsen 2007) is named SAT-SKOG, and maps with coverage for southern and eastern Norway are currently available on the Internet (www.skogoglandskap.no).

The use of radar as a tool in forest monitoring is currently an international research topic associated with high expectations (e.g. Olander et al. 2008). Synthetic Aperture Radar (SAR) is an active sensor that "sees" through clouds and works in any weather. Data can hence be obtained more reliable in cloudy regions such as the tropics or parts of Norway. Recently, several types of radar data from both airborne and satellite platforms have been investigated for mapping forest attributes (e.g. Magnusson & Fransson 2004, Eriksson et al. 2007, Sexton et al. 2009). In Norway, Weydahl et al. (2007) utilized SRTM X-band InSAR to derive vegetation heights that corresponded to between one-half and two-thirds of the tree heights. Simultaneously, initial studies have shown that x-band InSAR has potential for mapping forest biomass (Solberg et al. 2010a, 2010b) with a relatively low level of associated errors. A newly founded study (Research Council of Norway project led by Solberg and Astrup) will further investigate the utility of radar in forest inventorying in Vestfold County.

2.3.3. Research challenges

The main research challenge for biomass estimation is to improve current methods or create new and better methods. Such improvements can result in better coverage of biomass inventories, decreases in errors associated with existing methods, and cost reductions relating to methods. Selected research opportunities could include the following:

- *Terrestrial LiDAR and biomass estimation*. Given that terrestrial LiDAR can be utilized to estimate detailed crown attributes it is very likely that the technology can be utilized directly to estimate biomass in crowns and stems without utilization of biomass functions or biomass expansion factors. Given the uncertainty associated with existing biomass functions and biomass expansion factors, a direct field measurement tool may be very useful for field-based inventories, in research plots, and for calibration plots for airborne remote sensing techniques.

- *Radar and biomass mapping*. Given the initial Norwegian results from biomass estimation with radar, further research may result in a cost-efficient method for biomass mapping of large areas.

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Satellite-based InSAR data can be provided for the whole of Norway at a relatively low cost and can potentially be utilized to provide biomass estimates with a relatively low error level.

- *Improvement of MSFI and use of maps*. The SAT-SKOG product is the only biomass map that provides a uniform coverage of a substantial part of Norway. Utilization of SAT-SKOG to analyse biomass availability in different regions and in relation to bioenergy production facilities may be of interest to the industry. Improvement of SAT-SKOG with error estimates and extension of SAT-SKOG to cover all of Norway may also be a topic for development.

- *Airborne LiDAR*. Airborne LiDAR and forest resource mapping has been the topic of much research in recent years and much research is currently in progress. Given the wide operational application of this technique, research that leads to improved LiDAR-based estimates or reduce costs may be very beneficial for the forestry sector in Norway.

3. Biomass resources and availability

3.1. Assessing present resources and future potential

3.1.1. Previous studies

Over the past 10 years several national studies related to potential use of biomass for energy production in Norway have been reported (OED 1997, NOU 1998, KanEnergi 2003, 2007). These studies have several aspects in common. In addition to assessment of the potential from primary forest production (standing forest), they have also considered biomass-related residues from the forest industry, and partly also biomass from agricultural production of plants and biomass from wet organic waste and other sources. The studies have also compared the present use of biomass for energy purposes with the assessments they have made on the potentials. The main conclusion has been that there is a large gap between use and potential, i.e. technically it is possible to increase biomass production for energy purposes considerably, especially from primary forest production. However, a further conclusion made in the studies is that such an increase hardly will be seen without changes in external conditions (prices, costs, subsidies, taxes, prices for alternative products, etc.).

The analyses of the studies on the assessment of potential biomass from forest production have been relatively simple. In general, the starting point has been national (in some cases regional) estimates of total annual growth. From these estimates of total growth, a net annual potential for biomass production has been estimated based on quite rough assumptions related to environmental considerations, present harvesing methods and levels, and residues from this harvesting activity. To some extent harvesting costs and prices for different biomass qualities and quantities have been considered.

Applying annual growth estimates as a starting point in the assessments of potential biomass production is a rather static approach. Changes over time in harvest and growth levels, and relative changes between harvest and growth levels, and the subsequent long-term consequences of such changes, can hardly be considered appropriately in this respect. A more dynamic approach is necessary to capture the changes. Using aggregated growth estimates at national level also means that no real spatial considerations are done. To capture temporal as well as spatial aspects, a decision support system with a growth simulator describing the forest dynamics is required.

A more comprehensive approach to assessing the potential of biomass production for energy purposes has been done by Langerud et al. (2007). In their study, they applied the AVVIRK-2000 model to describe potential future forest resources and harvests. The present state of Norwegian forests was described by means of 8700 sample plots from the NFI covering all productive forests with area utilization 'forestry' in Norway. To assess the biomass potential they first estimated the long-term maximum sustained yield. Secondly, they reduced this quantity based on environmental and economical (harvesting costs) considerations to a net maximum sustained yield. This was finally compared to the actual harvest level observed over the past 10 years, and the difference between the net maximum sustained yield and the current harvest level was regarded as the potential for increased production of biomass for energy purposes. Similar approaches for different regional levels with the application of AVVIRK-2000 have been described by Hobbelstad (2007a, 2007b). In the most recent national assessments carried out according to the methods described by Langerud et al. (2007), the annual potential harvest of biomass for energy purposes in Norway was estimated to be equivalent to 26.8 TWh (Gjølsjø & Hobbelstad (2009).

Rørstad et al. (2010) provided a new dimension to biomass availability analyses in Norway when they developed cost-supply curves for a region. In their study, firstly Gaya-SGIS was applied to optimize conventional timber harvesting level alternatives according to net present value, and secondly cost-supply curves for forest residues following as a consequence of the conventional timber harvesting were developed by means of productivity models and costs related to the harvesting and transport of residues. The analyses comprised spatial as well as temporal aspects since stand-level data from 40,000 hectares of forest were considered for a period of 50 years. The main improvement achieved in the project was the addition of cost-functions describing variation in residues, harvesting costs according to forest conditions, and geographic dispersion.

In order to assess the future potential utilization or availability of biomass resources it is important to consider growth dynamics, temporal and spatial dimensions, environmentally oriented restrictions, and harvest costs and prices, and also to optimize the linkages between all these aspects. To some extent, Gaya-SGIS comprises functionality to deal with this. Previously, comprehensive analyses have been done applying this model at national and regional level based on data from the Norwegian NFI (Hoen et al. 2001, Eid et al. 2002). These studies focused on optimization, cost-efficiency and potential supply according to conventional timber production. No considerations, however, were made of biomass supply for energy purposes, i.e. the concepts, methods and assumptions made were directed towards timber production (see Hoen et al. 1998).

The body of international literature on assessments of biomass resources, availability and supply potential is vast. The approaches and tools applied for such analyses cover a wide range regarding comprehensiveness and sophistication. Assessments of biomass potential supply have been provided even at global and European level (e.g. Berndes et al. 2003, Karjalainen et al. 2004, Ladanai & Vinterbäck 2009). In the following, a few examples from neighbouring countries to Norway are described.

The Swedish Forest Agency (2008) in Sweden has provided extensive long-term scenarios assessing potential timber and fuel biomass resources by means of NFI sample plots and the HUGIN decision support system. The main aim of the analyses was to study the timber production potential, and therefore the bioenergy potential was assessed according to a reference scenario based on present ambitions for timber production and present environmentally oriented legislation. The biomass quantities assessed were branches and tops from final felling, stumps from final felling, branches and tops from thinning, stumps from thinning, and total above-ground biomass from young growth tending. In addition, to the general environmentally oriented considerations certain assumptions were made regarding biomass to be left in the forest to secure sufficient nutrient supply in the long run. The HUGIN analyses were also followed up by a study where marginal cost curves (accumulated biomass according to increasing harvesting cost) at national level were constructed for forest residues and stumps for a given final harvest level (Athanassiadis et al. 2009).

An interesting study from Denmark was provided by Nord-Larsen & Talbot (2004), where they estimated potential fuel wood resources based on NFI data. In the first stage they estimated the total potential of biomass resources. In the second stage the economically available resources were quantified by coupling biomass data from NFI sample plots data with location of conversion facilities and projected consumption. The data were incorporated into an economic model based on GIS that formed industrial marginal cost-of-supply curves from an optimization (linear programming) of the allocation of fuel wood. The main conclusion of the assessment was that resources in Denmark were able to meet 57–100% of the projected future consumption.

Padari et al. (2009) has estimated Estonian wood fuel resources in a study based on field measurements (not NFI data), digital national map layers (base map, soil map, forest cover, etc.), models for growth, and a number of assumptions related to rotation ages for different site classes

and tree species. Also different environmental restrictions and harvesting systems were considered. Theoretical long-term average annual yield estimates were presented for merchantable timber resources as well as energy resources from harvesting residues and stumps. Attempts to provide assessments of forest energy resources at national level have also been provided in Lithuania by Kairiūkštis & Jaskelevičius (2003). In Finland and Sweden many studies on biomass availability have been carried out focusing on developing new methods as well as providing updated quantifications (e.g. Malinen et al. 2001, Bååth et al. 2002, Ranta 2005).

When discussing potential biomass availability it is, of course, also important to consider the interaction between forestry and forest industry. The development of forest-sector models (see e.g. Bolkesjø 2004) has provided possibilities to perform analyses related to, for example, marketing (prices, costs), external conditions (subsidies, different rates of economic growth, currency fluctuations), large-scale transport logistics, and location of the industry. Examples of such analyses where biomass for energy purposes have been considered have been provided by e.g. Bolkesjø et al. (2006) and Trømborg et al. (2007a, 2007b). The forest-sector approach, however, is not considered further in this review.

3.1.2. Research challenges

Although the above-described Norwegian analyses in many respects capture a wide range of challenges related to the estimation of available bioenergy resources, there are many aspects that could be considered to improve the estimates and provide new information. In addition to productive forest areas, also non-productive forest areas and 'other forested areas' should be included. The same applies to more to marginal areas, such as densely populated areas, pasture, power lines, roadsides, and border zones surrounding agriculture land.

The environmentally oriented restrictions (ranging from e.g. forest reserves where no harvest is allowed to management activities adapted to the Living Forest standards (Living Forest 2010)) should preferably be applied as spatially explicit (i.e. located to individual sample plots) instead of as a generally imposed percentage reduction of areas or biomass as in previous analyses (see section 3.2).

Quantifications of the potential availability of tree biomass resources should also aim at presenting results according to different strata, depending on the purpose of the analyses. Different

geographical units, land-use and land-type categories, forest conditions, growing site characteristics, and biomass fractions are examples of strata that could be considered.

Previously, also only a limited range of alternatives regarding harvesting systems (harvest residues according to conventional timber harvesting and to some extent early thinning) have been considered. Also, additional harvesting systems, such as whole tree harvesting and stump harvesting, should be included. In particular, productivity and the associated costs related to the harvesting systems should be investigated, and corresponding models should be developed (see section 3.3).

3.2. Environmental considerations

3.2.1. Background and previous research

The same environmental restrictions and considerations apply to conventional timber production as to production of biomass for energy purposes. The environmental restrictions are materialized in legislation and certification regimes focusing on forestry in general. Harvesting of forest residues (branches and tops) and below-ground biomass (stumps and roots) for energy purposes, however, raise some additional concerns (see e.g. Bohlin & Roos 2002, Rudolphi & Gustafsson 2005, Stupak et al. 2007, Lattimore et al. 2009, Lauren et al. 2008, Rabinowitsch-Jokinen & Vanha-Majamaa 2010). Since a large proportion of all nutrients in trees is located in their needles, removing residues will reduce nutrient supply to soils, and in the long run this may increase the risk of nutrient imbalance and reduced productivity (Raulund-Rasmussen et al. 2008). Removing residues may also affect biodiversity and change species composition (Åström et al. 2005). The removal of stumps and roots raises concerns regarding risks of landslides, less organic matter in soils, and decreases in substrates important for some species (Stupak et al. 2007, Lindhe 2009). A few European countries have developed guidelines or recommendations for harvesting forest residues and below-ground biomass (Stupak et al. 2007), but currently there are no guidelines in Norway. However, in future it is expected that such guidelines will be developed as a part of certification standards.

Environmental considerations in previous Norwegian assessments of potential biomass resources for energy have in general been relatively simple, and only very rough estimates of the impacts have been done (OED 1997, NOU 1998, KanEnergi 2003, 2007). Also, the assessments by Langerud et al. (2007), Hobbelstad (2007a, 2007b), and Gjølsjø & Hobbelstad (2009) were

relatively simple, and few attempts were made to make the restrictions spatially explicit or to distinguish between different types of restrictions.

Regarding assessments of available timber resources, comprehensive analyses of environmentally oriented restrictions at national and regional levels as well as at property level have been done (Hoen et al. 1998, Eid et al. 2001, 2002). This work was done as a part of the Living Forest project (see section 3.2.2.), and since the standards of the certification regime (Living Forest 1998, 2001) had not yet been agreed, assumptions regarding the details of the standards had to be made. The analyses were done using Gaya-SGIS and included maintaining minimum proportions of old-growth forest, prolonged rotation cycles, treatments in buffer zones related to key biotopes, water bodies (rivers, lakes, etc.) and mires. The analyses at national and regional levels were based on NFI sample plots. The assumptions made for the treatments related to the environmentally oriented restrictions (Hoen et al. 1998), however, were mostly imposed according to a general description of the forest contitions, and not based on spatially explicit prescriptions from observations in the field. For the analyses made at the property level (Eid et al. 2001), the analyses were based on observations of, for example, border zones and key habitats derived from maps or observed in field. However, the assumptions were still based on the expected standards and not on those finally agreed upon.

Later, Ask et al. (2005) and Bergseng et al. (2009) performed analyses using Gaya-SGIS comprising data from Ski Municipality forest based on the assumptions and prescriptions of the silvicultural treatments from current Living Forest standards (Living Forest 2010). To date, however, the new standards have not been operationalized for NFI sample plots. The following sections provide descriptions and discussions regarding the most important environmentally oriented restrictions, and the impact these restrictions may have on the utilization of timber and biomass resources in Norway.

3.2.2. Environmentally oriented instruments and their impact on forest production
Environmentally oriented instruments in Norway range from 'hard' instruments related to legislation and regulations to certification regimes and standards, and to 'soft' instruments such as preservation administered by individual forest owners. Important Acts influencing forest production in Norway are the Act relating to the management of biological, geological and landscape diversity (Nature Diversity Act, Act No. 100 of 19 June 2009), the Act relating to forestry (Forestry Act, Act No. 31 of 27 May 2005), the Act relating to outdoor recreation

(Outdoor Recreation Act, Act No. 16 of 28 June 1957), the Act relating to planning and building (The Planning and Building Act, Act No. 77 of 14 June 1985), and the Act relating to river systems and groundwater (Water Resources Act, Act No. 82 of 24 November 2000).

The Living Forests standard has been implemented as basis for forest certification in Norway. Living Forests is a collaborative project between various stakeholders (forest owners, forest industry, trade unions, outdoor recreation organizations, and environmental organizations) to develop a framework for sustainable forest management. The main aim of the project is to achieve a balance between the three aspects forest production, environment, and social interests. The outcome was the published standard 'Living Forests: Standard for sustainable forest management in Norway'. The current standard is documented by Living Forest (2010). Most of the Norwegian forests are now certified according to the standard, either as individual properties or by group certification. The criteria applied as Living Forest standards fulfil the requirements of certification according to PEFC (Programme for the Endorsement of Forest Certification). A working group is currently preparing a Norwegian Forest Stewardship Council (FSC) standard. Until this is ready it is possible to certify forests through a 'generic' standard. However, the FSC is not widespread in Norway to date.

Nature Diversity Act (see Table 3, first four columns)
The most important legislation restricting forest production in Norway is the Nature Diversity Act (Act No. 100 of 19 June 2009). There are four relevant categories of site protection under this act: Nature Reserve (§ 37), National Park (§ 35), Protected Landscape Area (§ 36), and Habitat Management Area (§ 38). There is also a fifth category of protection, Nature types (§ 52), which not yet has been put into practice. This category may influence forest production in future.

In general, protection is established by the King in Council by means of management regulations specific for each site. Nature Reserves and National Parks provide a strong protection regime. Normal timber production activities are not allowed, and these two categories are therefore considered as fully protected. Protected Landscape Areas and Habitat Management Areas both imply restrictions on the utilization of the forest resources. The regulations, however, vary between sites and the prescriptions of treatments are partly formulated as 'recommendations' and partly as 'requirements'. The prescriptions may be connected to continuous cover forestry (i.e. selective cutting required) and regeneration method and size of the clear-cut area (e.g. 0.2 ha). In addition, road construction is normally prohibited. If clear cutting is not allowed for such areas,

the immediately available harvest quantities are obviously reduced. Applying selective cuttings, however, does not necessarily reduce the production and harvests in the long run (Lexerød 2007, Andreassen 1994). This depends on local forest conditions and suitability for applying selective cutting (Lexerød & Eid 2006). The impact of the regulations also varies according to how strongly they are formulated. If, for example, natural regeneration is a total requirement, the impact may be high, while it may be lower if natural regeneration in the regulations is stated as 'the preferred method when suitable'. To what extent prohibition of road construction reduces harvests is an economic issue that depends on terrain conditions and distance to presently existing roads.

Living Forest Standard and legislation (see Table 4, first four columns)
The Forestry Act (Act No. 31 of 27 May 2005) imposes several restrictions on forest management. Most restrictions are materialized in the Living Forest Standard (Living Forest 2010). Also other Acts are closely related to and partly work parallel with the Living Forest standard. The most important requirements in the standard, namely buffer zones, protection of key habitats, retention of living trees and dead wood, management adaptations for outdoor recreation activities, management adaptations in mountainous areas, forest structure, game habitats, and cultural monuments, are described in the following:

- The Water Resources Act (Act No. 82 of 24 November 2000) requires a natural belt of vegetation to be maintained along the banks of river systems with perennial flow (§ 11). The Living Forest Standard, section 12, states that buffer zones are required to be maintained or developed not only along river systems, but also along smaller streams, bogs, lakes, and cultural landscapes. The background for this standard is the high number of vital ecological functions related to biodiversity, water quality, landscape, and outdoor recreation served by the buffer zones.

  The basic buffer zones' width given in the Living Forest Standard is 10–15 m. However, the width should be adapted to local conditions and may vary within individual buffer zones, i.e. it may be narrowed down to 5 m or widened up to 30 m. Maintenance of existing zones or development of new zones implies that harvesting is allowed to a certain extent, i.e. maintenance by selective cutting in existing buffer zones or a more intensive harvesting in a one-storied forest where suitable trees are left to develop a new buffer zone. There are a few exceptions where the requirement of a buffer zone may be ignored, e.g. for the purposes of outdoor recreation (Living Forest Standard) and constructions connected to river systems (Water Resources Act). Thus,

there are three aspects related to buffer zones that are challenging when estimating the impact on forestry activities: 1) varying buffer zone widths, 2) different extents of harvesting allowed within the buffer zones, and 3) exceptions where the requirements may be ignored.

- Key habitats are defined as especially valuable sites from a conservation point of view, normally based on the presence of rare forest types or unusual structural elements, or the presence of rare species (Sverdrup-Thygeson 2002). According to the Living Forest Standard, key habitats '*shall be inventoried, selected, documented and specified on maps*'. There is no fixed general level for how much of a productive forest area that should be specified as a key habitat. The inventory instructions and the selection among the key habitats identified in the field vary according to local conditions at municipality level and the abundance of certain habitats at national level. For habitats that are rare at national level, but which frequently appear locally, only a small part may be finally specified as a key habitat, whereas all of them may be finally specified if the frequency is very low locally.

Two methods for identifying the key habitats in field are officially approved: Miljøregistrering i Skog (MiS) (Hotspot Inventory in Forests) and the Siste Sjanse-metoden (SiS) (Last Chance Method). The approaches of the two methods for identifying key habitats differ. While MiS focuses on habitats, i.e. certain forest types and structural elements, SiS focuses on the presence of indicator species. The Norwegian NFI has applied the MiS method for its sample plot inventory.

In general, the impact of key habitats on immediate harvest as well as long-term production is high. The key habitats may be totally preserved or some restriction may be imposed (i.e. some harvesting may take place). If harvesting is allowed, this has to be done in a way that does not weaken the conditions for biodiversity or that improves the conditions for biodiversity. In practice, this implies selective cutting. Thus, there are at least three aspects related to key habitats that are challenging when assessing the impact on forestry activities: 1) two different approaches to fieldwork, 2) the selection process for final specification of key habitats, and 3) varying levels of harvesting.

- According to the Living Forest Standard, section 8, an average of 10 living wind-resistant trees ha^{-1} must be left after harvesting. These retention trees should normally be selected among the oldest, and thus often the largest trees. The retention trees can also be part of buffer zones. Thus,

the actual effect of this requirement may be less than the effect of leaving 10 large trees ha^{-1} after harvesting.

- Also dead wood, such as standing dead deciduous trees, large dead pines, natural high stumps, and dead wood older than five years lying on the ground, should normally not be harvested (Living Forest Standard, section 8). Some of this wood could potentially be used for pulpwood or energy purposes. The general impact of this requirement, however, is low.

- In Norway the rights of every person to unimpeded access to the forests are strong. This is regulated through the Outdoor Recreation Act (Act No. 16 of 28 June 1957), section 2, which state that '*any person is entitled to access to and passage through uncultivated land at all times of year, provided that consideration and due care is shown*' (§ 2). The same applies to passage on horseback or with a packhorse, sledge, and bicycle on roads and paths. The Act also includes the right to pick berries and mushrooms. Some areas will naturally be more used for outdoor recreation than others, e.g. some coastal and mountainous areas. In such cases, the recreation areas can be secured by the State through compensation of the forest owner, or by means of a municipal zoning plan (The Planning and Building Act, Act No. 77 of 14 June 1985). In addition to forest areas set aside especially for outdoor recreation, general considerations should be taken regarding harvesting activities to secure outdoor recreation (section 7 in the Living Forest Standard).

All of the above-mentioned situations imply restrictions on forestry activities. The practical impact will most likely differ between the type of restriction (forest areas set aside especially for outdoor recreation as opposed to smaller adjustments of forest management for outdoor recreation).

- Two kinds of restrictions exist related to forest areas adjacent to mountains: those stipulated under the Forestry Act and those by the Living Forest Standard. The Forestry Act defines 'protective forests' as areas where the forest serves as protection zone for other forest or provides protection against natural damage (§ 12). This applies to areas near mountains or on the coast, where forests are vulnerable. According to the Forestry Act, the County Agricultural Committees have the authority to issue regulations governing 'protective forests'. Rules are normally provided concerning the obligation to report to the authorities before any harvesting is done.

Also, the Living Forest Standard, section 6 – Mountain forest, regulates forest management in mountain areas. The intention is to secure the biodiversity and recreational values of mountain forests. According to section 6, the lower border of mountain forests is identical to the border of protective forests in mountain areas, as defined in the Forestry Act. Thus, these areas will overlap.

In general, harvesting in mountainous areas should be done in a way that promotes or maintains a mature forest character. The harvesting method for spruce should as far as possible follow the 'mountain forest selection system', which requires that after harvesting the forest is still classified as development class IV or V. Small clear-cutting areas regenerated with seed trees are allowed in pine forests. There are at least two aspects related to mountainous forests that are challenging when assessing the impact on forestry activities: 1) protective forest borders are not available at a national scale, and 2) varying levels of removals in the harvesting.

- The Living Forest Standard, section 19 – Forest structure, requires that at any given time at least 30% of Norwegian forests should have a forest structure that is beneficial to species living in mature forests. This requirement does not apply to the property level, and measures can only be taken if the data from NFI show that the proportion of development class IV and V at county level is less than 30%. The practical impacts on the activities are therefore rather low.

- Section 14 – Landscape plan, in the Living Forest standard is intended to secure that forest management takes care of interests across stand and holding boundaries. Included here are considerations regarding game habitats and mating areas for capercaillie (wood grouse, *Tetrao urogallus*). The considerations are the same for all forestry activities, but there is no requirement for developing a landscape plan for small properties (Sverdrup-Thygeson et al. 2002). However, smaller forest properties known game habitats will, in most cases, be included in the forest management plan. A specific requirement may, for example, be a 50 m buffer zone around nests belonging to goshawks (*Accipiter gentilis*), where no harvesting is allowed.

- All monuments and sites originating from before 1537 and all Sami monuments and sites more than 100 years old are automatically protected (Act Concerning the Cultural Heritage, Act No.50 of 9 June 1978). The Living Forest standard, section 13, concerns the protection of cultural monuments and aims to secure all protected and other valuable monuments and sites in Norwegian forests. Planting, soil scarification or other measures that might pose a threat to a

monument or site is prohibited. Identification of cultural monuments in field may be a challenge because not all of them are surveyed and mapped. Cultural remains are not recorded by the Norwegian NFI.

Other regulations (see Table 5, first four columns)

- The Ministry of Environment apply INON-areas as a tool for preserving existing wild areas in Norway (Parliamentary bill 1 S (2009-2010)). INON-areas are described as areas without major infrastructure development and defined as being 1 km or longer in distance from technical installations such as roads, railways and power lines. The general aim is to protect such areas from new technical installations. Regular harvesting is not regarded as a 'new technical installation', but forest roads are. The forest management of such areas will therefore be indirectly influenced because road construction is not allowed. The impact of these regulations will vary according to whether it is profitable or not to carry out regular harvesting activities within the present road system. The profitability depends on local conditions, such as distance from harvesting site to nearest road, and terrain factors such as steepness, soil conditions, cliffs, etc. (see also Eriksen et al. 2004).

- In forest areas close to densely populated areas special restrictions may be imposed. Such restrictions may vary from being legislative to being administrative. The area surrounding Oslo, for example, is regulated under the Act relating to nature areas in Oslo and nearby municipalities (Act No. 35 of 5 June 2009). Also, in other forested areas owned by the municipalities, management is often adjusted to meet the demands of the public (e.g. Ski Municipality forests, Trondheim Municipality forests). These adjustments may be anchored both administratively and politically, and thus strongly binding. The impact of these restrictions may vary considerably. The practical silvicultural prescriptions, however, are usually connected to limitations on clear-cutting or recommendations for selective cutting.

- Also other restrictions and regulations not previously described may have an impact on forestry activities. Some examples are restrictions related to forest areas that recently have been burned, general adjustments of forest management for wildlife and landscape reasons, administratively protected private areas, and restrictions related to some nature types based on registrations at municipal level.

According to the Living Forest Standard, section 4, '*at least 5% of productive forest areas shall be managed as areas of ecological importance*'. Such areas include key habitats (provided by Living Forests Standard) and nature reserves and national parks (provide for under the Nature Diversity Act). If these elements do not fulfil the 5% requirement, a forest owner may make up the deficit by selecting areas from different forest types (e.g. calcareous forests, swamp forests, broadleaved temperate forests, pasture woodland, and other types). Also buffer zones in development classes IV and V may be included. Non-productive forest land may constitute up to 25% of the 5% area requirement. Thus, requirement stipulated by section 4 of the Living Forest Standard will most likely not influence the forest activities directly.

3.2.3. Challenges in operationalizing impacts

In addition to the actual management prescriptions related to the environmentally oriented restrictions and the impact they may have on immediate harvests and long-term production, many challenges need be faced to ensure that the prescriptions are operational when assessing available biomass resources. In the following, some challenges related to large-scale assessments based on Norwegian NFI sample plot data are discussed (see Tables 3, 4, and 5, last two columns).

The basic requirement for operationalizing is available spatially explicit information on the type of restriction. For some of the restrictions this is straightforward because the information is directly recorded by the NFI in the field or recorded by means of digital map data. This applies to restrictions related to the Nature Diversity Act and for most restrictions related to the Living Forest Standard. However, an exception regarding the Living Forest Standard is 'Mountain Forests', for which national digital maps do not exist. Similar problems apply also to forests near densely populated areas, game habitats, cultural remains, and a number of other restrictions. In general, where spatial information is not available, restrictions need to be handled in a 'pool' where the impacts are imposed subjectively and are spatially inexplicit, subsequent to all other restrictions which have been implemented.

Depending on whether the aim is to assess the present total biomass resources only, without including temporal aspects, or whether the aim also is to include temporal aspects by means of long-term analyses applying a decision support system, the approach to assessments will differ. In the former case, the impact on the immediate harvest and long-term production has to be assessed jointly by means of subjective judgements. For restrictions that impose a full protection regime (e.g. Nature Reserves or National Parks) this is straightforward because the present biomass will

be reduced by 100%. For all other restrictions, where some activities actually are allowed, the reduction should vary according to the type of activities allowed and the joint impact on immediate harvests and long-term production.

For long-term assessments it is necessary to apply a decision support system comprising a forest simulator describing growth and different silvicultural treatments over time. Gaya-SGIS has previously been used as tool for such assessments and most restrictions described in Tables 3, 4 and 5 (last column) can be applied as long as spatial information at plot level is available (Hoen et al. 1998, Ask et al. 2005). Since Gaya-SGIS is non-spatial in the sense that it does not allow adjacency restrictions, e.g. for reducing forest fragmentation using the core area concept (e.g. Øhman & Eriksson 1998), limitations on the clear-cutting area cannot be appropriately handled. Most remaining restrictions can be handled appropriately with the present version of Gaya-SGIS, although some 'fine tuning' according to the present regulations and standards may be necessary.

Table 3. Environmentally oriented restrictions according to the Nature Diversity Act.

Formal background	Function	Description	Impact		Spatially explicit information at NFI plot level	Applicable at plot level for Gaya-SGIS
			Immediate harvest	Long-term production		
Nature Diversity Act	Nature Reserve	Very few or no activities allowed	Full	Full	Yes	Yes
Nature Diversity Act	National Park	Very few or no activities allowed	Full	Full	Yes	Yes
Nature Diversity Act	Protected Landscapes Area	No road construction	Some	Some	Yes	Yes
		Limitation on clear-cutting area	High	Some	Yes	No
		Required or recommended selective cutting	High	Some	Yes	Yes
		Required or recommended natural regeneration	Some	Some	Yes	Yes
Nature Diversity Act	Habitat Management Area	No road construction	Some	Some	Yes	Yes
		Limitation on clear-cutting area	High	Some	Yes	No
		Required or recommended selective cutting	High	Some	Yes	Yes
		Required or recommended natural regeneration	Some	Some	Yes	Yes

Table 4. Environmentally oriented restrictions according to Living Forest standards and legislation.

Formal background	Function	Description	Impact		Spatially explicit information at NFI plot level	Applicable at plot level for Gaya-SGIS
			Immediate harvest	Long-term production		
Living Forest Standard Water Resources Act	Border zones	No clear-cutting, selective cutting allowed	High	Some	Yes	Yes
Living Forest Standard	Key habitats	No harvest, selective cutting sometimes allowed	High	High	Yes	Yes
Living Forest Standard	Retention of living trees	At least 10 trees ha^{-1} left after harvesting	Some	Some	Yes	Yes
Living Forest Standard	Dead wood	Certain qualities left after harvesting	Low	Low	Yes	Yes
Living Forest Standard Outdoor Recreation Act Planning and Building Act	Outdoor recreation	General considerations for all activities	Some	Some	Yes (Maps required)	Possibly
Living Forest Standard Forestry Act	Mountain forest	Mountain forest selection of spruce / Limitation on clear-cutting area pine	High / High	Some / Some	Yes (Maps required) / Yes (Maps required)	Yes / No
Living Forest Standard	Forest structure	Minimum 30% at any time in development classes IV–V at county level	Low	Low	Yes	Yes
Living Forest Standard	Game habitats	No harvest	High	High	Yes (Maps required)	Yes
Living Forest Standard Cultural Heritage Act	Cultural monuments and sites	Harvest or other measures disfiguring any monument or site is prohibited	Low	Low	Maps required	Yes

Table 5. Environmentally oriented restrictions according to other regulations.

Formal background	Function	Description	Impact		Spatially explicit information at NFI plot level	Applicable at plot level for Gaya-SGIS
			Immediate harvest	Long-term production		
Wild areas (INON)	Specific consideration	No road construction	Some	Some	Yes	Yes
Act relating to nature areas in Oslo and nearby municipalities Decision by municipality authorities	Specific considerations	Recommended selective cutting	Some	Some	Yes	Yes
		Limitation on clear-cutting area	Some	Some	Yes	No
Administrative protected areas	Protection of forest areas	Varying. Normally no harvesting.	High	High	Maps required	Possibly

3.3. Economic considerations

3.3.1. Background

The supply chain of biomass for energy purposes comprises a number of operations starting in the forest stand and ending at the power plant. The qualities and quantities required by the end-users to a large extent determine what kind of operations that are needed to be done. There are a lot of challenges related to logistics, technical solutions and production regarding storing and woodchip cutting at roadside and transport from roadside to end-user (see e.g. Junginger et al. 2005, 2006, Laitila 2006, Gjølsjø & Belbo 2008). This part of the biomass supply chain will not be considered in the present review.

Assessments of available timber quantities in Norway have been based on traditional considerations regaring gross timber value and harvesting costs. The timber quantities for a certain area have been regarded as non-available ('0-areas') if the difference between gross timber value and harvesting cost is negative, while they have been regarded as available if the difference is positive. Previous assessments of large areas have been based on this concept (see e.g. Hoen et al. 1998, 2001, NIJOS & NORSKOG 1999). Although there are many questions and uncertain factors related to such assessments (Bollandsås et al. 2004a, 2004b), estimations are quite straightforward regarding timber production due to the availability of models reflecting timber values in the market (Blingsmo & Veidahl 1992, Lexerød & Gobakken 2002) and models describing productivity and costs according to different forest conditions and harvesting methods (e.g. Dale et al. 1993, Dale & Stamm 1994, Eid 1998). However, many of these models are rather old and some updating is needed.

A similar approach, based on biomass values in the market and models for productivity regarding harvesting methods, could also be applied when considering biomass production. The biomass market for energy in Norway is rather 'immature', and a structured and well-documented price system similar to what we see for timber (saw timber, pulpwood) does not exist. One may, for example, expect different prices according to different fractions (harvesting residues, i.e. branches and tops, whole tree, stumps), tree species, and possibly treatment (e.g. storing in forests for drying purposes). Until a price system is established in Norway the only option is probably to assume a certain standardized price per ton at roadside independent of fraction, tree species or treatment. Harvesting methods related to bioenergy production, i.e. the operations in the supply chain comprising harvesting and transport of biomass to roadside, are discussed in the following.

3.3.2. Biomass harvesting methods

The supply of most biomass for energy production in Norway today and in the near future relies heavily on forest residues (branches and tops) from traditional timber production based on clear-cutting. Theoretically, however, there are a number of methods that could be applied to harvest the biomass, either where timber production is the main aim of the operations and biomass quantities is a result of this, or where biomass is the main production aim and all quantities are used for energy purposes. Table 6 gives an overview of these possibilities according to different silvicultural treatments.

Table 6. Timber and biomass production possibilities according to silvicultural treatments.

Silvicultural treatment	Aim of production	Timber fraction	Biomass fraction
Clear-cutting	Timber	Stem	Harvest residues, stumps
	Energy	-	Whole tree, stumps
Seed tree establishment and cutting	Timber	Stem	Harvest residues
	Energy	-	Whole tree
Shelterwood establishment and cutting	Timber	Stem	Harvest residues
	Energy	-	Whole tree
Thinning	Timber	Stem	Harvest residues
	Energy	-	Whole tree
Selective cutting	Timber	Stem	Harvest residues
	Energy	-	Whole tree
Young growth tending	Timber	None	-
	Energy	-	Whole tree

For clear-cutting, where the main aim is timber production, biomass for energy may come from harvest residues and stumps, while it may come from whole tree and stumps if the main production aim is energy. The same options exist, with the exception of stump harvesting, for seed tree and shelterwood establishment and cutting, conventional thinning, and selective cutting. Harvesting stumps for these silvicultural treatments would not be possible due to existing trees or newly recruited seedlings. For all the silvicultural treatments, except young growth tending, there is, at least theoretically, a competition between producing timber and biomass for energy. For young growth tending, this competition does not exist: either the felled trees remain in the forest or they may be used for bioenergy purposes.

Since there is competition between timber production and biomass production for energy, all silvicultural options and the corresponding harvesting and forwarding methods should be

compared with respect to productivity and profitability (to compare profitability, also the prices of biomass and timber need to be considered). Models describing production for harvesting and forwarding according to different forest conditions (e.g. volume ha^{-1} harvested, size of trees harvested, number of trees ha^{-1} prior to harvest, distance to roadside) and harvesting methods exist for all silvicultural treatments regarding timber production as described in Table 6 (Dale et al. 1993, Dale & Stamm 1994, Eid 1998). Currently, no corresponding models for harvesting of biomass exist in Norway. In the following, research on production related to the most important biomass harvesting options, mainly from Sweden and Finland, are discussed.

- Clear cutting, seed tree and shelterwood establishment and cutting

Few studies exist for estimating productivity or the costs of collecting harvest residues after conventional clear-cutting for timber production. The most relevant study for Norwegian conditions is probably of the harvesting of loose residues from Norway spruce dominated stands in Finland (Nurmi 2007). Productivity studies were carried out to study the effect of a single-grip harvester work method on the forwarder productivity when collecting the residues. The study comprised 65 effective machine hours (E_0) and the operations were divided into loading, forwarding, unloading, and driving unloaded. The results were presented partly as average values for production according to different sub-operations and partly as functions describing how the production varied according to different conditions. Rørstad et al. (2010) applied these results and developed a set of models where time consumption (h/ton) was estimated for the following operations:

- transport (average for forwarding and driving back unloaded) based on a function with hauling distance (km), driving speed (km/h) and load size (ton) as independent variables
- loading based on a given average productivity (ton/ h) calibrated according to residue density (ton/ha)
- unloading according to average productivity (ton/h) (Nurmi 2007)

The cost (NOK/ton) was finally calculated by multiplying time consumption (h/ton) by machine cost (NOK/h).

The bundling system, as an alternative to the above-described harvest method for loose residues, has been studied by Kärhä & Vartiamäki (2006). In the bundling system, the logging residues left by a harvester are collected and fed into a bundler to produce compact bundles which are then

forwarded to roadside. The study revealed that the cost of the bundling chain was higher than the cost of the loose residue chain when reviewing the total costs from harvest to roadside.

A few relevant studies on stump harvesting also exist. Karlsson (2007) in Sweden presented interesting results for lifting as well as forwarding of stumps based on time consumption studies. Average values and models for predicting production and cost were presented. The study was based on one spruce-dominated stand. Stump harvesting has also been studied by Lazdiņš et al. (2009) in Latvia, and results for production and costs based on three plots presented. Laitila (2006) have developed a Microsoft Excel program for calculating the production and cost of different harvesting methods. Stump harvesting is included in this program, where basic productivity calculations are based on a study by Laitila & Asikainen (2004).

Although clear-cutting in old mature stands, where the main aim is energy production (Table 6), i.e. harvesting of whole trees, probably is of marginal practical importance for most forested areas, the method might be of interest for forested areas such as old pasture and border zones surrounding agricultural land. No productivity studies have been found regarding old mature forests. For smaller trees, however, several studies exist (see below).

For seed tree establishment and cutting (Table 6) similar consideration as those for clear cutting apply. Final cutting of the seed trees, where biomass from residues or whole trees is collected for energy purposes, however, is probably not relevant because the biomass density ha^{-1} will be too low. Low biomass density is probably also a problem when considering energy production for the establishment as well as final cutting of shelterwood. No productivity studies have been found regarding seed trees or shelterwood.

- Thinning and selective cutting
A lot of research has been done previously in Finland on production and costs related to thinning. However, no research on the collection of loose forest residues from conventional thinning has been found. Instead, the research has focused on different methods related to whole tree harvesting (see e.g. Kärhä et al. 2005, Kärhä 2006, Ovaskainen et al. 2008) and whole tree bundle harvesting (Jylhä & Laitila 2007, Laitila et al. 2009) regarding thinning in young stands. Kärhä (2006), for example, studied two different harvesting systems, one with a separate harvester and forwarder and the other with a harwarder, i.e. one machine combining harvesting and forwarding. Results

were presented on productivity and cost variation according to, for example, distance to roadside and average tree size. No productivity models were presented.

Possibly the most interesting study regarding models for estimating productivity has been provided by Laitila et al. (2009). Models were developed for all sub-operations related to the transport of whole tree bundles to roadside. Laitila et al. also found that the productivity of the bundle system was almost twice as high compared to conventional individual whole tree forwarding.

- Young growth tending (and early thinning)

Laitila et al. (2007) studied the forwarding of whole trees after manual and mechanized felling in pre-commercial thinning (the majority of the trees were smaller than 12 cm at breast height). Forwarding after mechanized felling gave the highest productivity and lowest costs of the two methods. Productivity models with grapple log size and density (m^3 per 100 metres strip road) as independent variables were developed. No results for the productivity and costs of the felling operation were presented.

Laitila (2008) compared three systems for early thinning (i.e. the average size of trees was 0.030 m^3): manual cutting and forwarding of whole trees, mechanized cutting and forwarding of whole trees, and a system using a combined harvester and forwarder. The results for productivity and costs according to different sub-operations were presented.

A study of biomass harvesting of small trees, where a certain amount of trees were left for further growth, was provided by Björheden et al. (2003). A total of 10 different stands were included in the study and the average diameter in the removals was between 3 cm and 10 cm. Productivity and the costs of a number of different harvesting methods, from motor manual felling to fully mechanized methods, were presented. The study focused on the removal of small trees in urban areas, but may also be relevant for harvesting of biomass from 'energy forest production', i.e. pioneer tree species in short-rotation intensive silviculture regimes (see also section 4.2).

3.3.3. Research challenges

As previously stated, there are many challenges related to logistics, technical solutions and production regarding storing at roadside and transport from roadside to end-user. Quite often the harvesting methods bringing biomass to roadside are also dependent on the technical solutions

selected for the remaining chain. It is therefore important to develop 'a map' describing the supply chain of biomass from the forest stand to the power plant covering all options for operations and technical solutions. Such a map should form the basis for future research on the harvesting and logistical issues of the supply chain for biomass.

Ideally, productivity models covering all possibilities according to the different silvicultural treatments listed in Table 6 should be developed. However, it is particularly important to study the possibilities that combine the recovery of biomass residues from conventional clear-cutting for timber production. Today, the biomass quantities harvested in this way are low. To be able to reach the ambitious targets for future bioenergy production in Norway, it is quite obvious that most quantities will need to be based on such residues. However, also whole tree harvesting, from conventional thinning and from clear-cutting in areas not normally considered for timber production (pasture, power lines, roadsides, border zones around agricultural land), and possibly stump harvesting after conventional clear-cutting, needs to be considered in order to reach the targets. For all these harvesting systems it is therefore necessary to develop productivity models that capture variations related to terrain and location (e.g. slope and distance to roadside) and variation related to forests (density measures such as volume, basal area or number of trees ha^{-1}, and dimensions, i.e. diameter, height and volume of individual trees).

There are currently few models developed for Norwegian conditions that can be applied to estimate the productivity and costs of the harvesting systems. However, as demonstrated by Rørstad et al. (2010), it is possible to approach this based on productivity data from the literature. The large number of previous studies in Sweden and Finland constitute an excellent basis for further development along these lines. However, it is also important to conduct research in Norway regarding the time consumption and productivity of the harvesting systems, especially in order to capture the terrain conditions (slope) present in Norway, but not in Sweden and Finland. It also important to note that only a few production studies in Sweden and Finland focus on the harvesting of residues after conventional clear-cutting. The only research found relevant for Norwegian conditions is that provided by Nurmi (2007).

3.4. Decision support systems

Norway has long traditions in development and use of forest management decision support systems. Such systems have regularly been applied for the purposes of research, teaching, practical management planning for private and public properties, and by public authorities in

consequence analyses as a foundation for policy making. An extensive review of Norwegian decision support systems and challenges related to applications and further development has previously been done by Eid (2007). The existing decision support systems and their present and future potential for applications related to assessments of biomass for energy purposes in Norway are discussed in the following.

3.4.1. Existing decision support systems

Gaya-SGIS, AVVIRK-2000, and T (ree) are three software systems that over the past few years have been frequently used and/or developed. The systems apply different methodological approaches and serve different purposes for decision support. All three systems also currently have functionality that may be useful for decision support directed towards biomass production for energy purposes.

- Gaya-SGIS is a dynamic forest management system comprising a forest simulator and a linear programming module integrated into a GIS environment. The system combines the forest simulator, Gaya (Hoen & Eid 1990, Hoen 1996, Hoen & Gobakken 1997, Gobakken 2003), which generate a range of realistic treatment schedules for each stand in the forest and their corresponding net present values (NPV), and the linear programming (LP) model J (Lappi 2005), which optimizes forest management given a set goal and restrictions. Gaya and J are integrated in the ArcView GIS system. The system is non-spatial in the sense that it does not allow adjacency restrictions. However, the GIS linking of Gaya-SGIS (Næsset 1997, Gobakken 2003) enables the use of GIS to modify the data set for the simulator or to set restrictions for the input/output matrix that transfers data from the forest simulator to the LP solver.

  The forest simulator is developed from area-based empirical-statistical biological sub-models for growth (Tveite 1977, 1978, Blingsmo 1984), mortality (Eid & Øyen 2003), and regeneration and recruitment describing even-aged treatment alternatives (clear-cutting, seed tree and shelter wood cutting). Some rough adjustments of the area-based biological models have also been applied to facilitate selective cutting alternatives. The simulator describes the development over time for all variables related to traditional timber production (e.g. basal area mean diameter, mean height by basal, number of trees ha^{-1}), and the corresponding timber assortments, timber values (Blingsmo & Veidahl 1992, Lexerød & Gobakken 2002), harvesting costs, and net cash flow. The simulator also estimates total biomass and biomass fractions applying equations developed by Marklund (1987, 1988) and Petersson & Ståhl (2006). Since the simulator is area-

based, no information is available at individual tree level, and biomass is therefore estimated by means of basal area mean diameter and number of trees ha^{-1} (see also section 2.1.2.).

Gaya was at an early stage developed to study carbon flows (Hoen & Solberg 1994, 1999), and has since been substantially revised and currently comprises: (1) fixation of carbon in living trees, (2) release of carbon from dead trees, litter, harvest residues and soil, (3) release of carbon from wood products, and (4) saved greenhouse gas emissions (CO_2, CH_4, and N_2O) from the use of wood products instead of more energy intensive materials or fossil fuels (Raymer et al. 2009). New elements also include annual production and mortality of needles, leaves, branches, and fine roots and a process-based soil model. The latest improvement was the addition of cost functions describing cost variations according to forest conditions and geographic dispersion when harvesting residues from conventional timber harvesting (Rørstad et al. 2010).

- Avvirk-2000 is a forest management system comprising a forest simulator and a module scheduling potential harvests paths at forest level (Eid & Hobbelstad 1999, 2000, 2005). There is no optimization built in. The system should be operated heuristically, i.e. the user should compute different alternatives through 'intelligent' manipulation of the assumptions and search for a few, but satisfactory, solutions. No GIS functionality is currently linked to the system.

The forest simulator in Avvirk-2000 is similar to the one developed for Gaya, i.e. area-based empirical-statistical biological sub-models for growth, mortality and regeneration/recruitment describing even-aged treatment alternatives are applied. Also in this system adjustments of the area-based models have been done to facilitate selective cutting (Eid & Hobbelstad 2005). The basic biological performance of the system has been tested empirically based on historical inventory and harvest-level records (Eid 2004, Eid & Hobbelstad 2006). This simulator also provides quantities, timber values, harvesting costs, and NPV for traditional timber production. Total biomass and biomass fractions are estimated in the same way as described for Gaya. However, a comprehensive module for estimating harvest production and costs, including felling and forwarding related to clear-cutting, seed tree cutting, thinning, and selective cutting has been developed based on production studies and subsequent evaluations (Dale et al. 1993, Dale & Stamm 1994, Eid 1998). No production models for estimating harvesting costs related to bio-mass production are incorporated.

- T(ree) is a newly developed forest simulator based on sub-models for individual trees (Gobakken 2007, Gobakken et al. 2008). Currently, the simulator can only be applied for stand-level analyses, but may in the future form part of a decision support system that can be applied for large forest areas. The biological sub-models, i.e. distance-independent individual tree growth (Bollandsås 2007) and mortality models (Eid & Tuhus 2001), and area-based regeneration and recruitment models (Lexerød 2005, Lexerød & Eid 2005), are based on permanent sample plots from the Norwegian NFI. The economical sub-models estimate timber values (Blingsmo & Veidahl 1992, Lexerød & Gobakken 2002) and harvesting costs (Dale et al. 1993, Dale & Stamm 1994) based on individual trees. For each management unit (i.e. stand), the simulator produces treatment schedules with all feasible combinations of user-defined treatment and regeneration options (pre-commercial thinning, thinning, different kinds of regeneration cutting with different kinds of regeneration options, and selective cutting). A NPV is calculated for all treatment schedules.

No functionality related to carbon flows or biomass estimation has been implemented to date. The timber value estimation module in T has recently been rebuilt (see Lexerød et al. 2009). Instead of, as previously, using functions to estimate timber value, T now applies species-specific tree value matrices directly to estimate the timber value of harvested trees. The generation of tree value matrices is based on log values for different combinations of log diameter and length specified by the saw log industry and current pulpwood prices.

3.4.2. Research and development challenges

Gaya-SGIS and Avvirk-2000 are well suited for large-scale scenarios, for example related to available biomass resources and carbon sequestration. The main strength of these tools is to provide robust and appropriate results for larger areas (property level and higher). Gaya-SGIS and Avvirk-2000 are less suitable for detailed analyses and descriptions of a wide range of silvicultural options, especially those related to thinning and selective cutting. For this purpose T(ree), comprising sub-models for individual trees, is potentially more suitable, for example regarding density management, fertilization and energy forest issues (see sections 4.1 and 4.2). However, more testing and evaluation of the basic biological models, and probably also development of new models, are necessary before the program can be applied in analyses of biomass production aiming especially for energy production.

Gaya-SGIS will probably be the main tool for large-scale and long-term assessments of biomass resources in Norway in the future. The ultimate goal should be to develop Gaya-SGIS into a tool that comprises a fully integrated approach to harvesting systems and associated costs as well as prices for different timber assortments and biomass fractions, considering both traditional timber production and production of biomass for energy purposes. This requires work regarding testing of present functionality, the implementation of existing methods and models, the development of new methods and models, and analyses with different purposes and at different scales. A few challenges related to this are briefly described in the following.

- the present biomass estimation module is based on stand-level variables, i.e. basal area mean diameter and mean height by basal area, while the applied biomass equations require tree-level information. This procedure may cause biased estimates. Systematic testing of this problem to quantify and evaluate the impact should be done. Alternatively, stand-level biomass expansion factors could be developed (see section 2.1.2) and implemented in Gaya-SGIS.

- the present biomass estimation module is developed for analyses regarding carbon sequestration. In carbon estimations the aim is to determine the total biomass while quantification of different biomass fractions is less important. In estimations related to bioenergy it is important to quantify the biomass that actually can be used for energy purposes. It is also important to distinguish between different fractions since they have different potential in the production of energy.

- Gaya-SGIS quantifies biomass production in terms of kilograms of dry weight. The biomass, however, also needs to be converted into heating value (kWh/ton). The heating value of biomass depends on the composition of the biomass which may be different for different trees species and different fractions of the trees. Usually, a fixed average heating value is applied. The heating value also depends on the moisture content of the biomass, and the effective heating value varies according to this content, which in turn varies according to the harvesting systems and requirements of the end-users. A systematic review of these questions should therefore be carried out in order to standardize the assumptions which need to be made for such analyses.

- the present forest simulator does not include cost productivity and calculations according to mechanized timber harvesting methods (Dale et al. 1993, Dale & Stamm 1994, Eid 1998). A module for such calculations should be developed. In addition, the work should start on in-corporating productivity and cost models for bioenergy harvesting systems. As a first step,

Rørstad's et al. (2010) 'engineering' approach to harvesting of residues, i.e. developing a set of equations quantifying harvesting costs based on available productivity data, should be assessed and possibly revised. A similar concept could also be applied to, for example, whole tree harvesting and stump harvesting. As soon as Norwegian studies on productivity become available, the results should be implemented in Gaya-SGIS by means of appropriate equations.

- the present forest simulator is able to quantify the gross value of the timber in a forest stand based on models where the value varies according to the species and size of trees and the prevailing price system. A similar price system for biomass does not exist in Norway, and currently certain standardized prices per ton at roadside need to be implemented. However, as soon as the market for biomass becomes more 'mature', i.e. as soon as price differentiation appears according to, for example, different tree fraction, tree species or treatments, this should somehow be included in the forest simulator.

- the forest simulator comprises sub-models for recruitment and regeneration, diameter growth and height development, and mortality. Such models can always be calibrated or developed further depending on new data that becomes available. The models describing regeneration, recruitment and young growth phases are currently probably those with the highest potential for improvements. An improved module describing the impact of fertilization on growth should probably also be considered since such a treatment may be important in order to compensate for nutrient losses associated with biomass harvesting.

4. Biomass production

4.1. Silvicultural methods in forestry

Traditional forest management is currently optimizing other values than the volume of biomass production. Under current economic conditions in Norway it is most profitable to grow individual trees to a minimum dimension for industrial use. The preference given to individual tree dimension is always at the expense of reduced total stand volume and biomass production (Long et al. 2004). Traditional forest management and biomass production are therefore in conflict. In addition, the paper industry and bioenergy supply chains are competing over the same resources. Even though in conflict, the production of wood for energy and industrial use will also in the future be combined in the same stands and it is therefore important to design silvicultural systems that optimize all goals simultaneously (Heikkilä et al. 2009). The main objective of silvicultural methods adapted to management objectives that include bioenergy harvesting is to increase the total biomass production (Egnell 2009). Many of the silvicultural methods used in forestry to maximize the yield of biomass for fibre also apply if the same biomass or other biomass components are used for energy rather than fibre (Ståhl 2009). Harvesting other biomass components, such as branches, tops and stumps that have not been used previously, is another option. It is not rationale to increase the proportion of such biomass components at the expense of the more valuable stem biomass. Silvicultural methods have to increase the production of all biomass components simultaneously in order to maximize the total biomass production.

A number of silvicultural methods to increase biomass production in the context of combined production of wood for energy and industrial use are already well known because they apply in a similar way matter if volume production is maximized for industrial wood production only. Few modifications are necessary in order to adapt them to the combined production of the future. Due to the fact that the maximization of total volume production has been neglected at the expense of value production during recent decades, many of the research results are either outdated today or qualitative rather than quantitative, or are based on experiences outside Norway. The silvicultural methods that are known to significantly increase biomass production are density management, use of fast growing pioneer species, and fertilization. We will therefore concentrate our review on these three methods. Other methods discussed in less detail here are species selection (differences in productivity on different sites, adaption to environmental changes, exotic species), genetic improvement, intensive stand establishment (soil preparation, vegetation control, use of natural

regeneration in combination with planted seedlings, shelter, pine weevil control, reduced elk browsing, use of stump sprouts), avoidance of root rot damage, and ditching (Ståhl 2009).

All silvicultural methods that are used to intensify management in order to increase biomass production need to be carefully evaluated for their economic consequences. Due to the low prize for bioenergy not all investments in intensified silviculture are profitable. Some methods might give benefits in terms of increased biomass production for bioenergy and increased value of the wood produced for industrial use. In order to evaluate the consequences of different management options better growth models which predict not only the stem volume but also the biomass of all tree components and different wood properties are needed. This is currently the largest research challenge and needs long-term effort to be realized.

4.1.1. Density management

Density management is a simple method to increase biomass production because density has a large effect on total wood production per area. Management affects density during establishment, either by planting at a certain density or by preparing for natural regeneration, or during thinning operations. For either of these methods, no quantitative decision support tools are available in Norway that describe the effect of density on growth and that could help managers to decide on optimal density. Practical density management during thinning operations is today mostly accomplished by harvester drivers, who have little guidance on density targets and actual density.

The consequences of different thinning intensities on growth and yield are best projected using individual-tree based growth models that are calibrated based on data representing a range of different thinning intensities. Models of this type have been developed in Norway (Bollandsås et al. 2008) but are not operational yet. Stand-level growth models for Norway have been shown to underpredict growth after thinnings (Braastad & Tveite 2000). Thinning guidelines currently used in Norway (Myklestad et al. 2006) are therefore not based on quantitative predictions of growth and yield. In the absence of Norwegian guidelines, Swedish guidelines are applied in the south-eastern part of the country (Glommen Skogeierforening 2005).

Basal area is most frequently used in the international literature and management practice to measure and control stand density. The Norwegian tradition of using stem number has been revised and replaced by basal area (Myklestad et al. 2006). Results from many thinning experiments worldwide have demonstrated that the relationship between stand density, expressed

as basal area, and volume production follows an optimum curve. Volume increment can be reduced at maximum basal area, but certainly decreases with decreasing basal area (Pretzsch 2001, Zeide 2001, Skovsgaard & Vanclay 2008). The relationship varies according to species, site index and age. Results from Finnish and Swedish thinning experiments on Norway spruce and Scots pine confirm this relationship for the Fennoscandian boreal forest types (Eriksson 1990, Mäkinen & Isomäki 2004a, 2004b, Agestam 2009). Most striking is the difference between spruce and pine: spruce has a much larger flexibility to tolerate heavy thinnings without significant losses in growth, whereas pine has already responded to moderate thinning intensities with significant losses in growth as compared to growth at maximum stand density. Norwegian thinning experiments have not been analysed in a similar way, but published results (Braastad & Tveite 2000, 2001) show similar trends.

Quantification of the relationship between basal area and growth at stand level and its variation according to species, site and age for forests in Norway will be a valuable decision support tool for forest management and will be available as the result of a current PhD project at the Norwegian University of Life Sciences (Optimizing silviculture for bioenergy production in Norway, NFR 189098/I10). The shortcoming of the aforementioned tools is that they only produce predictions about effects of thinning on total volume production, which is most relevant in a bioenergy context, but not on diameter distribution. On the other hand, they are easier to establish and are expected to be operational before individual-tree based growth models for Norway are available. Thinning guidelines are much more urgently needed for Scots pine due to the current practice whereby Scots pine stands are thinned much more often than Norway spruce stands, and due to the fact that Scots pine reduces volume production significantly in response to heavy thinnings.

Thinning is currently carried out using harvesting machines. According to the most recent guidelines (Glommen Skogeierforening 2005, Myklestad et al. 2006), basal area targets are set for density after thinning. Stand density during operations is controlled by the subjective judgment of the operator. Only rarely do operators leave their machines and check the resulting stand density after thinning with relascope samples in order to adjust their activities. It can therefore be assumed that stand density targets are frequently only met with low precision. As a consequence, a part of the total yield might be lost if stands are thinned too heavily, or individual trees might not reach the diameter targets if stands are thinned too moderately.

Ground-based laser scanning has been developed into a tool for forest inventorying (Hopkinson et al. 2004, Parker et al. 2004, Thies et al. 2004, Watt & Donoghue 2005, Van der Zande et al. 2006). Laser scanners can detect the position and diameter of individual trees in sample areas around the scanner. Using a laser scanner mounted on a harvester would enable additional information to be gained on stand density (number of trees, basal area) and the diameter distribution for the part of the stand where the harvester operates. Such a tool will be available as a result of a current PhD project at the Norwegian University of Life Sciences (Optimizing silviculture for bioenergy production in Norway, NFR 189098/I10). The implementation of such a density management tool will combine density and diameter distribution calculated from scanner data with density management targets in order to indicate to the operator the number of trees to be removed and their diameter.

Results from a series of spacing trials established in Norway spruce stands in Norway clearly show the large effect that planting density has on growth and yield (Braastad 1970, 1979, Haveraaen 1981, Handler 1988, 1990, Øyen et al. 2001). Niemistö (1995) reports similar trends for birch in Finland. Gamborg (1997) reports on the effect of establishment density on woodchip harvesting from Norway spruce stands in Denmark. Significant parts of the total yield can be lost if stands are established with low stem numbers, either due to low planting density or due to sparse natural regeneration. During the last 50 years the focus of forest management has shifted from maximum volume production to high quality timber production. The latter also requires a minimum density at establishment in order to control branch growth, but this density is much lower than the minimum density required for maximum volume production. As a consequence, experiments on establishment density have not been followed up in recent decades and results have not been analysed or compiled. The increased focus on maximum volume production in the context of bioenergy production means that those experiments again can be used as a valuable data source. Compilation of published results, analysis of existing data, and remeasurement of some of the experiments will allow the generation of decision support tools that will be available as a result of a current PhD project at the Norwegian University of Life Sciences (Optimizing silviculture for bioenergy production in Norway, NFR 189098/I10).

Pre-commercial thinning is the first opportunity to harvest wood for bioenergy and has significant consequences for the total biomass production. Heikkilä et al. (2009) used a growth simulator to analyse the effects of stand density after pre-commercial thinning and the time of the first thinning for Norway spruce and Scots pine stands in Finland based on the assumption that biomass for

energy is harvested at the first thinning while industrial wood production is the main goal for the remainder of the rotation. The stand density after pre-commercial thinning used in their scenarios varied very little and consequently yield differences were minor, while the time of thinning resulted in slightly larger differences in total yield. On the other hand, it is well known from detailed analyses of extensive Swedish (Pettersson 1993) and Norwegian (Vestjordet 1977) pre-commercial thinning experiments that density after pre-commercial thinning has a significant effect on volume production up to the time of the first thinnings, i.e. trees removed during pre-commercial thinnings cannot be harvested later for bioenergy purposes and consequently a major proportion of the yield is lost. In their economic analysis, Heikkilä et al. (2009) also clearly demonstrate that wood for bioenergy should be harvested during later thinnings. Despite differences in management options it should be remembered that bioenergy harvesting under energy prices is only profitable for the forest owner and the complete product chain, if subsidized (Heikkilä et al. 2009).

In order to reduce the harvesting costs of bioenergy, geometric thinning has been proposed and the operational consequences of this approach evaluated (Bergström et al. 2007, Spinelli et al. 2009). It remains to analyse the consequences of this new type of geometric thinning for the growth and quality of the remaining stand.

The main challenge for future research with regard to stand density management is the development of growth models as decision support tools for forest managers. These new growth models also have to include other biomass components than stem wood in order to be useful in a bioenergy harvest context. It remains to be tested whether biomass expansion factors can be used to dynamically predict the biomass components based on stem wood growth models under a variety of different stand management options.

4.1.2. Use of pioneer species

Pioneer species are characterized by a rapid establishment after disturbances and fast growth in their youth in order to occupy a given site and compete with other species. These traits are sometimes used in forestry in order to maximize production. The two dominating tree species in forestry in Norway today, Norway spruce and Scots pine, lack some typical pioneer traits, especially rapid growth in their youth. Typical pioneers in the boreal forest types in Norway are birch and other broadleaved species. They are often not used by the industry in Norway and are therefore regarded as weeds and removed in early pre-commercial thinnings. Pioneer species can

be used in pure stands, often in short rotations in order to maximize volume production for fibre or energy use. A review of the current knowledge about these systems is given in section 4.2. Another method to take advantage of the rapid growth of pioneer species in traditional forestry is to grow them in stratified mixtures in young stands.

Birch in stratified mixtures with Norway spruce in young forests is a resource that is currently not used for bioenergy in Norway. By modifying current silvicultural practice and delaying pre-commercial thinning until birch can be harvested for bioenergy it is not only possible to use this resource but also to increase the total production of the stand.

In the boreal zone, Norway spruce forests established after clear-cutting are during the first years dominated by spontaneous regeneration of pioneer tree species, mostly birch (Frivold 1986, Hynynen et al. 2009). In order to concentrate production on the desired individuals, pre-commercial thinnings largely remove birch. However, pre-commercial thinning is an expensive intervention because no merchantable products are harvested. Even though a number of different methods have been tested in recent decades, it has not been possible to further mechanize early thinnings and therefore brush cutter is still the standard equipment. Due to their high costs, pre-commercial thinnings are often dropped and only public subsidies guarantee a sufficient level of pre-commercial thinning in Norway today. Trees removed during early thinning could be used for bioenergy and we anticipate that this feedstock for bioenergy could be available at a price as low as the harvesting costs. Forest owners might be willing to sell birch from early thinnings at very low prices if stand tending is free of charge. Even though biomass harvesting costs in young stands are currently much higher than for logging residues from final harvests (Hakkila 2005), biomass from young stands contributes significantly to the woodchip harvest in Finland (Laitila 2008) and technical innovation might reduce the costs in the near future. Similar concepts for energy wood thinnings have been presented for Finland (Hakkila 2005, Heikkilä et al. 2007, 2009) and in Sweden (Johansson 2003).

By delaying early thinning until birch has reached larger dimensions, harvesting costs for biomass can be reduced. Birch can, for example, reach 10 m in height in 20 years on typical Norway spruce sites (Strand & Braastad 1967). Harvesting methods for trees of these dimensions are under development (Jylhä & Laitila 2007, Spinelli et al. 2007, Laitila 2008) and we expect them to be further developed in the near future due to the current demand for bioenergy in other Nordic countries. By delaying the removal of birch shelters, the gowth of spruce can be reduced. It is

therefore important to quantify the growth dynamics of these two species when mixed in young stands in order to optimize total production.

Precommercial thinning in the period 2004–2007 was reported to approximately 30,000 ha per year and to 40,000 ha per year in 1996–1999 (http://www.ssb.no/emner/10/04/20/skogkultur/). For the period 1995–2005, between 40,000 and 50,000 ha per year were finally cut, indicating that not all of the young stands were thinned, even though due to the dominating clear cutting system it is likely that almost the total area of final cuts needed some kind of pre-commercial thinning. The numbers for harvestable birch biomass in young spruce and pine stands in Norway are lacking, but assuming 50 m^3/ha (Tham 1987, Tham 1994) and an area of 40,000 ha/year, a total of 2 million m^3/year might in theory be available for bioenergy purposes. For Finland, early thinning for bioenergy has been estimated to have a potential of 4 million m^3/year (Heikkilä et al. 2007).

To establish spruce stands, often only 1500–2000 trees ha^{-1} are planted in Norway today. This low number of spruce seedlings does not utilize the biomass production potential of the site, mostly because the species is characterized by slow growth in the early stage, as indicated by the differing times for spruce and birch to reach breast height (Frivold 1982, Mielikäinen 1985). Planted spruce on clear-cuts is mostly supplemented by spontaneous regeneration of spruce and pioneer trees, mostly birch. Pioneer species establish and grow much faster in their youth than spruce and therefore enable the site on which they grow to be put into full production after a much shorter period than a pure spruce stand. When harvesting this extra production of biomass from pioneers before they start retarding the growth of spruce, a spruce and birch mixture can produce more biomass than a pure spruce stand (Tham 1994). Frivold & Frank (2002) investigated a number of mixed stands of Norway spruce and birch in Norway and found that this mixture produces more than pure spruce stands only up to a birch top height of 17 m, suggesting that only the different growth dynamics of the two species is responsible for the additional production and that no 'mixture effect' (Kelty 1992, Frivold & Groven 1996, Frivold & Kolström 1999) is to be expected. It is also important to notice that downy birch (*Betula pubescens* Ehrh.) is slower growing than silver birch (*Betula pendula* Roth.) and therefore closer to Norway spruce in its dynamics. Additional yield from a mixture of downy birch and Norway spruce can therefore be less than the additional yield from silver birch, but this effect might be hidden by the fact that downy birch is generally found on poorer sites than silver birch.

Braathe (1988) reported results from an experiment in Norway where the birch shelter had been regulated to different densities. Norway spruce under the birch shelter was clearly affected by the density of the shelter. An individual-tree based competition index could be used to explain the reduction in height growth of spruce in response to competition. Based on the same experiment, Gobakken & Næsset (2002) calibrated a growth model that predicts stand mean diameter growth for Norway spruce based on, among other variables, a variable that describes competition between spruce and birch. Brække & Granhus (2004) presented preliminary results from a number of pre-commercial thinning experiments in mixed spruce and birch forests and modified the model describing spruce height growth in response to birch density (Braathe 1988).

Based on a number of experiments in young mixed stands of spruce and birch in Sweden, an individual-tree based growth model for this stand type was developed and scenarios were presented for energy wood thinnings in Central Sweden (Tham 1988, 1989, 1994). The thinning schedule included a pre-commercial thinning before age 15 to a density of 1200–3000 birches/ha, an energy wood thinning at age 20, and final harvest of the remaining birches at age 30. At age 20 the standing volume of birch was 40–80 m^3/ha, increasing with increasing birch density. For a stand density of 1200 birches ha^{-1}, birch produced 80 m^3/ha to the age of 30 years, while production of spruce was not reduced as compared to spruce without birch. Higher birch densities reduced spruce production slightly, but the total yield was at the same level as that of the sparsest birch shelter. The results also clearly indicate that individual tree dimensions of birch at the time of the energy wood thinning will depend on the density of the birch shelter. The increasing yield of birch in early stand phases with increasing initial stand density has also been reported for pure birch stands in Finland (Niemistö 1995).

More recently, an individual-tree based growth model for young mixed stands in Southern Sweden has been calibrated based on data from an extensive national survey of young stands (Fahlvik & Nyström 2006). The model overpredicted birch height growth and underpredicted spruce diameter growth when tested against data from experimental plots. Using this growth model, the effect of different species mixtures and height stratifications was simulated and results indicated that only if birches are higher than spruce will the total production of the mixed young stand be similar or greater than that of a pure spruce stand (Fahlvik et al. 2005).

Gamborg (1997) showed how increasing stand density and mixture with pioneer species can increase the woodchip harvest for Norway spruce stands in Denmark using growth models and

experimental data. Valkonen & Valsta (2001) demonstrated the economic benefits of growing a birch and spruce mixture for Finnish conditions. Despite the fact that birch prices are much higher in Finland and birches are in their simulations grown to timber dimensions, the sensitivity analysis presented in this study indicates that even an earlier harvest of birch for energy might overcompensate for the economic losses of reduced spruce production. Whole-tree harvesting of birch in young mixed birch and spruce stands did not reduce growth in the following five-year period when compared with a thinning without removal of birches in an experimental series in Sweden (Mård 1998).

Birch shelters have also often been kept beyond the time indicated above for an energy wood thinning. Even though birch admixtures have reduced the growth of spruce in a number of experiments in Sweden (Mård 1996, Bergqvist 1999, Klang & Ekö 1999, Lindén 2003) and Norway (Frivold 1982), the production of the birch shelter is often greater than the growth losses incurred by the spruce understory. A birch shelter over spruce also increases the height differentiation of spruce trees in the understory (Mård 1996). Growth models have been calibrated for older mixed stands in Sweden (Agestam 1985, Ekö 1985), Estonia (Jogiste 1998, 2000), and Finland (Mielikäinen 1980, 1985), and have been used to show the production of different mixtures of spruce and birch.

Spruce trees released from a birch shelter have been studied in Sweden (Mård 1997a, 1997b), where mechanical damage due to snow and wind affected up to 25% of the basal area, but no differences in damages were recorded based on the season of release. It has also been reported from Sweden that released spruce trees have faster height growth than previously unsuppressed spruce trees (Tham 1988).

A birch shelter over young spruce saplings can also have a number of positive effects, such as protecting againt microclimatic extremes, competing vegetation and voles (Bergan 1987) or reducing waterlogging (Brække & Granhus 2004). Slower growth of spruce in the understorey might also change wood quality, e.g. by reducing ring width and juvenile wood, improving wood density, reducing stem taper, and reducing branch number and sizes. When studying spruce planted at low density under birch in Sweden, smaller branches and ring width, lower numbers of branches per whorl, fewer defects but equal wood density, stem taper, and total number of branches per meter were found for sheltered than for open-grown spruce trees (Klang & Ekö 1999). In another experiment in northern Sweden, naturally regenerated spruce was grown under

a dense birch shelter up to a birch height of 13 m (spruce 2–4 m), and then the shelter was thinned to a number of different densities (Bergqvist 1998, Bergqvist et al. 2000). Juvenile wood was absent in the spruce trees that had been grown under the dense birch shelter up to a breast height age of 10 years, but it is uncertain whether this was due to the suppressed growth or harsh climatic conditions. The late modification of shelter density had little effects on wood density and fibre properties. In a Finnish study of young stands consisting of pine planted at low density and naturally regenerated birch (Valkonen & Ruuska 2003), the birch admixture significantly reduced the branch diameter of pines, despite the fact that both tree species grow at similar height growth rates in young stands.

Stratified mixtures of Norway spruce and birch in boreal Fennoscandinavia have been subject to a lot of research. This stand type dominates after clear-cutting and potentially causes problems for the main crop, which is considered to be Norway spruce, but offers a possibility to produce more than a pure stand of Norway spruce. Even though this mixture has been considered under the management objective to produce bioenergy from birch in Sweden and Finland earlier, quantitative knowledge is lacking for Norwegian conditions. Conditions in Sweden, Finland and Norway are similar, but application of Swedish and Finnish growth models and decision support tools needs testing against data from Norway. An important part of the decision support for forest managers is to quantify the competition between the birch shelter and the growth of Norway spruce in order to optimize the time of the removal of the birch shelter. A master's thesis at the Norwegian University of Life Sciences is currently examining this topic.

4.1.3. Fertilization

Fertilization might be necessary to compensate for nutrient losses in the context of whole-tree harvesting for bioenergy that might reduce site productivity (Egnell & Leijon 1997, 1999, Mård 1998, Jacobson et al. 2000, Egnell & Valinger 2003, Röser et al. 2008). The research project 'Ecological consequences of increased biomass removal from forests in Norway' includes an investigation of the need for compensation of nutrient losses during whole-tree harvesting. Wood ash recycling has frequently been tested as one measure to avoid nutrient export with whole-tree harvesting (Röser et al. 2008). Nitrogen not only limits the growth of most forests in Norway but is also missing in wood ash. High concentrations of toxic substances in wood ash pose a further problem. Wood ash recycling is therefore currently of limited use in order to sustain or increase production of biomass in forests.

On the other hand, fertilization is a well-known method to increase biomass production that has been used in forestry (Ståhl 2009). Results from Scandinavian fertilization experiments (Andersson et al. 1998, Ingerslev et al. 2001, Nilsen 2001, Nohrstedt 2001, Saarsalmi & Malkonen 2001, Högbom & Jacobson 2002) show that nitrogen fertilization is the most promising method due to the fact that most of the forest ecosystems in central and northern Scandinavia are lacking nitrogen. On the other hand, increasing nitrogen deposition will increase forest growth (Solberg et al. 2004) and regionally saturate forest ecosystems with nitrogen, thereby reducing the effects of nitrogen fertilization. Bergh et al. (2005), using a model-based analysis, demonstrated the effect of fertilization on the growth of Norway spruce in Sweden when nutrient limitations are removed completely. Biomass production can be drastically increased. Fertilization is therefore an important silvicultural method to increase biomass production.

Soil compaction and other effects of machine traffic as a consequence of intensified silviculture might be a threat to sustainability. Fertilization and wood ash recycling are other operations that can require additional machinery to be driven around in stands (Röser et al. 2008). It is therefore of extreme importance to restrict the traffic of the machinery to strip roads, in addition to other measures such as the use of specialized equipment and to restrict the use to periods with high carrying capacity of the soil.

Fertilization of forests in Norway has only been practised on an insignificant amount of land and almost ceased during the last few years (Nilsen 2001, Rognstad & Steinset 2008). Even though there is ample evidence that nitrogen fertilization can increase production substantially, we are missing decision support tools for forest managers who are predicting fertilization response based on simple variables describing the sites in which they work. In practical forest management it is unrealistic to base a decision about fertilization on analyses of the current nutritional status which in turn is based on analyses of foliage and soil samples. Simpler tools need to be developed for Norwegian conditions. For Sweden, similar decision support tools are available (http://www.skogforsk.se/). Finally, it would be desirable to include fertilization responses into growth models.

4.2. Energy forests
Pioneer tree species in short-rotation intensive silviculture are known to produce large amounts of biomass, often much larger than those from traditional forestry. Energy forests have therefore received much attention both in practice and research in many European countries after energy

supply problems came onto the international political agenda in the 1970s, but also in reaction to agricultural overproduction. Sweden and Austria had large programmes to subsidize energy forestry before they joined the European Union, because they had to solve agricultural overproduction problems nationally. Consequently, a large number of research results are available from Sweden, some of which might be applicable under Norwegian conditions. In contrast to Sweden and Finland, energy forestry has never received much attention in Norway. Apart from a single experiment (Hole 2001), no further research or practice is known to us. Differences in growth conditions and ownership structure might explain some of the differences between Norway and other Scandinavian countries when it comes to the practical application of energy forestry, but the lack of public subsidies is definitely an important factor. Even if agricultural land is unlikely to be available for energy in the near future, marginal lands (e.g. power lines, roadsides, and borders to agricultural land) have already become a source of biomass for energy and might be managed more intensively in the future. Energy forestry is currently in focus in Denmark, both as a topic for large research programmes and practical applications.

A typical energy forest is established on agricultural land after soil preparation. Willows, aspen, and poplars, often from selected individuals or genetically improved material, are the preferred species. Rapid establishment by vegetative regeneration from stump sprouts is an essential factor for the high productivity of such systems. In this respect, fertilization, vegetation control, pest and disease control, and in some cases irrigation are essential for success. The net energy gain is substantially reduced due to the high energy input of such intensive management compared to traditional forestry.

Birch is not a species that is typically used for energy purposes because other pioneer species have proven to be more productive if managed intensively. Nevertheless, with less intensive management, birch in short rotation might be a viable option under Norwegian conditions, where birch is the dominating pioneer in the natural forest type and often dominating in poorly managed young stands. Therefore, research results related to birch in short rotation from other countries (Ferm 1993, Johansson 1996, 1999b, 2007, Paukkonen & Kauppi 1998, Kaunisto 1999, Telenius 1999, Rydberg 2000, Hytonen & Luostarinen & Kauppi 2005, Walle et al. 2007a, 2007b) are of great interest and should be tested under Norwegian conditions.

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