Seppo Kellomäki · Antti Kilpeläinen
Ashraful Alam *Editors*

Forest BioEnergy Production

Management, Carbon sequestration and Adaptation

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ISBN 978-1-4614-8390-8 ISBN 978-1-4614-8391-5 (eBook)
DOI 10.1007/978-1-4614-8391-5
Springer New York Heidelberg Dordrecht London

Library of Congress Control Number: 2013947602

Printed on acid-free paper

Springer is part of Springer Science+Business Media (www.springer.com)

Preface

Throughout the world, forests and forest ecosystems provide timber, other raw materials, non-timber benefits, and protection against natural and human-induced threats. Forests are also an important energy source, providing fuel wood and energy biomass. In industrialized countries, fossil fuels have, however, replaced wood and become the dominant source of energy. Currently, coal, oil and natural gas provide cheap options for most human energy needs. Use of fossil fuels is increasing atmospheric concentrations of greenhouse gases (GHGs), especially carbon dioxide (CO_2), with the consequent warming of global climate and changes in precipitation. Global efforts are needed to mitigate the climate change and minimize the impacts of climate change. In this respect, the substitution of fossil fuels with renewable energy sources like forest biomass is among the ways to mitigate climate change. This option is attractive, because it has a direct effect on the global carbon cycle and allows it to be controlled through proper management of forest resources and forest ecosystems. Mitigating climate change through substituting fossil fuels is a new dimension of sustainable forestry and forest management.

This book summarizes recent experiences on how to manage forest land to produce woody biomass for energy use and what are the potentials to mitigate climate change by substituting fossil fuels in energy production. A key question is whether the energy based on forest biomass is carbon-neutral or not and what the possibilities are to reduce CO_2 emissions through proper management integrating timber and energy biomass in forestry. The book outlines the close interaction between the ecological systems and industrial systems, which controls the carbon cycle between the atmosphere and biosphere. In this respect, sustainable forest management is a key to understand and control carbon emissions due to the utilization of forest biomass (e.g. from management, harvesting and logistics, and ecosystem processes), which are often omitted from assessments of the carbon neutrality of energy systems based on forest biomass.

The focus in this book is on forests and forestry in the boreal and temperate zones, particularly in Northern Europe, where the use of woody biomass in the energy industry has increased rapidly in recent years. However, the global dimensions of forests and forestry place local findings in larger perspectives. This concerns especially the questions of the role of forest-based bioenergy in controlling the warming of global climate. Among many things, the book addresses how management can affect the supply of energy biomass using short-rotation forestry and the conventional forestry applying long rotations. In the latter case, there are many links between timber production and the supply of energy biomass, which require careful consideration in the management of forest resources.

We are grateful to all the persons who contributed to this book. Their role was most crucial to offer a wide and deep insight into some current issues which are affecting the use and acceptance of forest-based biomass in energy production. We also want to acknowledge Mr. Harri Strandman, University of Eastern Finland, for his help in preparing and editing the figures of this book. We are also grateful for the support from the "Motive" research program (EU Grant Agreement 226544) of the European Union, the ENERWOODS project of Nordic Energy Research, Kone Foundation and strategic funding from the University of Eastern Finland (SUBI project). The authors are supported by various organizations and/or funding agencies as specified in separate chapters. We gratefully acknowledge this support.

Joensuu, Finland
May 2013

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Chapter 1
Introduction

Seppo Kellomäki, Antti Kilpeläinen and Ashraful Alam

Abstract This textbook deals with the management of forest land for producing and harvesting energy biomass. Energy biomass refers to woody biomass originating from special plantations or forest biomass harvested in forestry primarily aiming at producing timber. The focus is on northern Europe, where there is now great interest in the use of woody biomass as a substitute for fossil fuels in producing energy, and thus in mitigating climate change. The chapters of the book address the potential of the main domestic and exotic tree species in producing energy biomass and the main principles of management to produce energy biomass in forestry in ecologically sustainable and cost-efficient ways. This provides the background for the discussions, which assess the potentials of using forest biomass in reducing carbon dioxide (CO_2) emissions by substituting it for fossil fuels. In this respect, the main focus is on how much CO_2 is taken up in growth and emitted in ecosystem processes, and in the management, harvesting and logistics of energy biomass and in combustion. The impacts of biomass production (forest growth) and energy biomass utilization are indicated by radiative forcing, which may be affected by proper management of forest ecosystems and substituting fossil fuels with energy biomass from forests. The environmental impacts of intensive management and harvesting of energy biomass are addressed in several chapters.

Keywords Climate change mitigation · Energy biomass · Forest biomass · Management · Nordic countries · Substitution · Thinning · Timber

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S. Kellomäki et al. (eds.), *Forest BioEnergy Production*,
DOI 10.1007/978-1-4614-8391-5_1,

1.1 Background

For thousands of years, forest biomass or wood has been among the main energy sources of humans around the world. Since the industrial revolution, fossil fuels have replaced wood and become the dominant source of energy around the globe. Currently, coal, oil and natural gas dominate the energy sector, providing cheap and flexible options for most energy needs. The unrestricted use of fossil fuels is increasing the atmospheric concentrations of greenhouse gases (GHGs) at an alarming rate, especially those of carbon dioxide (CO_2) and dinitrogen oxide (N_2O). This increase traps more heat in the lower atmosphere, with the consequent warming of global climate and changes in precipitation in all parts of the world. Global efforts are needed to mitigate climate change and to minimize the impact of climate change. The substitution of fossil fuels with renewable energy sources like forest biomass is among the ways to mitigate climate change.

Currently, biomass (including forest biomass) accounts for over 10 % of the global primary energy supply. Wood-based fuels may comprise the woody biomass originating from special plantations established for producing energy biomass by using fast-growing species (e.g. willows) and intensive management (Fig. 1.1). Wood-based fuels may also comprise forest biomass harvested in forestry primarily aimed at producing timber. Forest biomass may include residues harvested in the tending of seedling stands and in thinning (precommercial and commercial thinning) and residues harvested from clear cut areas. In the latter case, stumps and coarse roots may also be harvested for energy biomass. Forest biomass is also used in the form of industrial residues including bark, saw dust etc. as such or in the form of other energy products, e.g. pellets. Furthermore, recycled wood used in construction and packages may finally be used in energy production.

On the European scale, the current potential to produce woody biomass is about 1,000 million $m^3\ a^{-1}$, of which about 700 million $m^3\ a^{-1}$ is forest biomass. At the same time, the demand for woody biomass is about 700 million $m^3\ a^{-1}$, of which slightly more than half is used in forest industry and the rest for producing energy. In the foreseeable future, the demand for forest biomass will substantially exceed the availability; i.e. in 2030 the demand is estimated to be slightly less than 1,400 million $m^3\ a^{-1}$, but the potential supply is 1,100 million $m^3\ a^{-1}$. The main part of the increase in demand represents the use of forest biomass for producing energy (Mantau et al. 2010; Röser et al. 2008).

In the Nordic countries, especially Finland and Sweden, the use of forest biomass has increased rapidly. In fact, energy biomass is a new variety of forest production, which is modifying the management and harvesting regimes used in forestry. This process is driven to a great extent by the commitment of the European Union (EU) to reduce CO_2 emissions in response to the Kyoto Protocol, thus mitigating climate change. Until now, the main part of energy biomass is that produced as a side product of timber production, which refers to the management of a forest ecosystem to produce saw logs and pulp wood. In this context, the energy biomass represents biomass originating from the tending of seedling stands and thinning of young stands

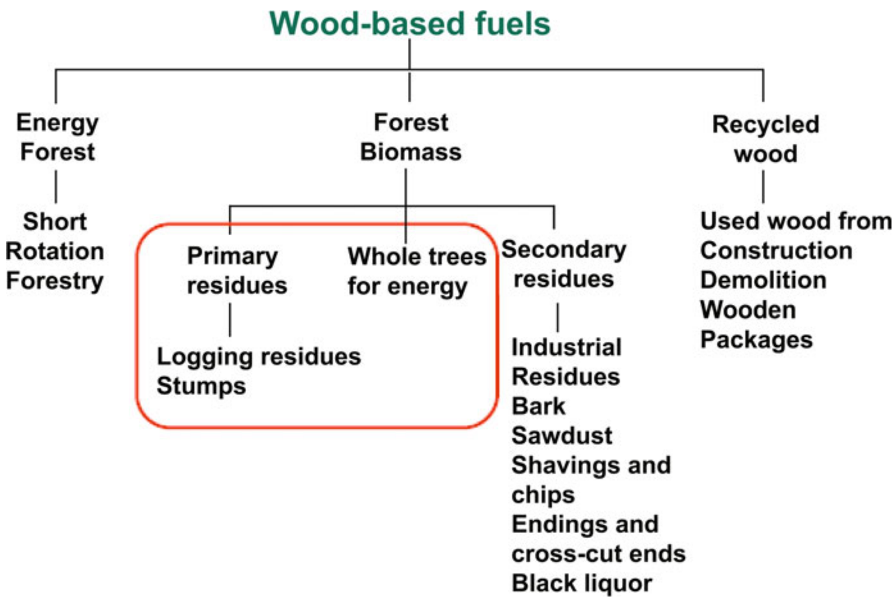

Fig. 1.1 Wood-based fuels and use of forest biomass in energy production in different phases of the life cycle of forest biomass. (Redrawn based on Röser et al. 2008)

not yet providing pulp wood. The growing need to use biomass in energy production has, however, enhanced interest in shortening the production cycle by utilizing fast-growing tree species and intensive management regimes, namely short-rotation forestry. In Sweden, in particular, fast-growing willows are cultivated intensively on agricultural land for energy purposes. This is an attractive option for using agricultural land to produce energy biomass, but it provides methodologies to enhance the production of biomass also in conventional forestry.

Today, the main part of energy biomass is produced in forestry by harvesting logging residues and biomass in precommercial thinnings and the tending of young stand. Appropriate choice of tree species, soil management, and control of spacing and rotation may substantially increase the potential to produce biomass on forest land. Sustainable and cost-efficient production of energy biomass on forest land is possible through integrated management, where the production of timber and energy biomass is balanced in an optimal way.

1.2 Objective and structure of the book

The general objective of this book is to summarize recent experiences on how to manage forest land to produce woody biomass for energy use and the potential to mitigate climate change by substituting forest biomass for fossil fuels in energy production. A key question is whether the energy generated from forest biomass is carbon neutral or not, and, in this respect, what are the possibilities to reduce CO_2 emissions through proper management by integrating the production of timber and energy biomass in forestry. The atmospheric impacts of energy biomass production and utilization are linked to the forest management which controls the sink/source dynamics in forest ecosystems. The concept of integration enables us to approach management strategies, including energy biomass, from the viewpoint of climate change mitigation. The focus is on northern Europe and the Nordic and Baltic countries, where woody biomass is widely used in generating energy.

The book is divided into four Parts.

Part I focuses on the main tree species available for biomass production and their management in biomass plantations (short-rotation forestry) and in forestry aimed at producing timber. In both cases, the impacts of management tools such as spacing in plantation and thinnings are addressed. Furthermore, nutrient management is discussed with the focus on how to avoid the detrimental effects of biomass removal on nutrient resources. On this basis, *Part II* focuses on the sequestration of carbon in the forest ecosystem and the mitigation of climate change by substituting fossil fuels with forest biomass. Uptake and emission of carbon in different phases of the production cycle are addressed in order to identify how the substitution of fossil fuels by biomass may have an effect on the atmospheric carbon and what are the potentials to mitigate the climate change in an efficient way by using forest biomass in generating energy. The importance of the overall analysis of carbon dynamics through the whole production chain of energy biomass "from cradle to grave" is emphasized, with the focus on life cycle assessment (LCA) in identifying direct and indirect emissions of carbon in order to assess the carbon neutrality of energy biomass and the role of energy biomass in mitigating climate change. These issues are further addressed in *Part III*, which focuses on adaptation in climate change and the role of energy biomass in adaptation. In this context, the impacts of climate change on the production potentials of energy biomass are addressed. Furthermore, the risks and uncertainties of future developments and their effects on decision-making are discussed, including the competitiveness of bioenergy in relation to fossil-fuel energy. Finally, *Part IV* summarizes some of the major issues affecting the role of forest energy biomass in mitigating climate change.

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Part I
Forest Management for Bioenergy Production

Chapter 2
Tree Species, Genetics and Regeneration for Bioenergy Feedstock in Northern Europe

Lars Rytter, Karin Johansson, Bo Karlsson and Lars-Göran Stener

Abstract In this chapter we discuss tree species that exhibit rapid growth in northern Europe, i.e. the Nordic and Baltic countries. These species include both common indigenous species and introduced species. We continue with an evaluation of current breeding work and the genetic potential of species that may be suitable for biomass production in this region. Because short rotation times are commonly desired in biomass production, fast, safe and cost-efficient establishment of stands is important. By carefully considering the conditions of the regeneration sites, selecting the most improved plant material from the tree species best suited to each site, and using the best available techniques for stand establishment, we offer guidance to successful growth and cultivation of various tree species to provide society with a renewable biomass supply for energy use.

Keywords Adaptation · Biomass production · Breeding · Clone · Management · Native and non-native species · Nordic and Baltic countries · Planting · Regeneration · Rotation time · Seedlings · Silviculture

2.1 Role of Forests in Supplying Energy Biomass

Large amounts of tree-derived biomass can be produced in regions where the environmental conditions are favourable for forest growth, and where large land areas are available for the cultivation of fast-growing tree species. In the European context, the Nordic (Denmark, Finland, Sweden and Norway) and Baltic countries

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S. Kellomäki et al. (eds.), *Forest BioEnergy Production*,
DOI 10.1007/978-1-4614-8391-5_2, © Springer Science+Business Media New York 2013

(Estonia, Latvia and Lithuania) are extensively covered by forest land, which represents a potentially valuable source of energy biomass. At present, the supply of energy biomass from forests includes mainly small trees, stem tops and branches, and stumps, whereas stem wood is mainly used in the pulp and sawmill industries. However, there are several ways to enhance the supply of energy biomass available from forests: (1) to allocate more land for cultivating trees and other woody plants for energy biomass, (2) to utilize more efficiently existing forest stocks for energy biomass by exploiting assortments that are currently under-utilized and/or of small value in forest industry, and (3) to increase productivity through choice of tree species, tree breeding and proper management.

In this chapter, we discuss methods to increase forest growth for the supply of energy biomass, including the selection of appropriate tree species, the application of genetic knowledge and breeding improvements, and the efficient regeneration for given combinations of species and site conditions. The focus is on rapid initial growth and the use of short rotation times in biomass production in northern Europe, including the Nordic and the Baltic countries.

2.2 Forest Resources in Northern Europe

In the Nordic and Baltic countries, the total forest area is 69 million ha, of which around 54 million ha are in commercial use (Forest Europe 2011) (Fig. 2.1). The total growing stock of stem wood in this region is 8100 million m^3, of which almost 7000 million m^3 is available for commercial use. The available annual net increment of stem wood is over 237 million m^3 including bark.

Norway spruce (*Picea abies* (L.) Karst), Scots pine (*Pinus sylvestris* L.), birches (*Betula* spp.) and alders (*Alnus* spp.) are the most common tree species in the Nordic and Baltic countries, where they grow in both pure and mixed stands. Altogether, these species account for a growing stock of 7700 million m^3, representing almost 95 % of the total growing stock in the region (Forest Europe 2011) (Table 2.1). This huge volume emphasizes the dominance of these species in producing bioenergy in this region. In the southern parts of the region, oak and beech are also potential sources of energy biomass. Oak and beech currently account for a growing stock of slightly over 110 million m^3. These species are important in Denmark, Latvia, Lithuania and southern Sweden.

2.3 Tree Species Available for Biomass Supply in Northern Europe

2.3.1 Tree Species Available in the Nordic and Baltic countries

The main part of the forest resource in northern Europe is composed of native (or domestic) species, which are well adapted to the prevailing climatic and edaphic conditions (Table 2.1). Furthermore, there are several exotic (or non-native) species

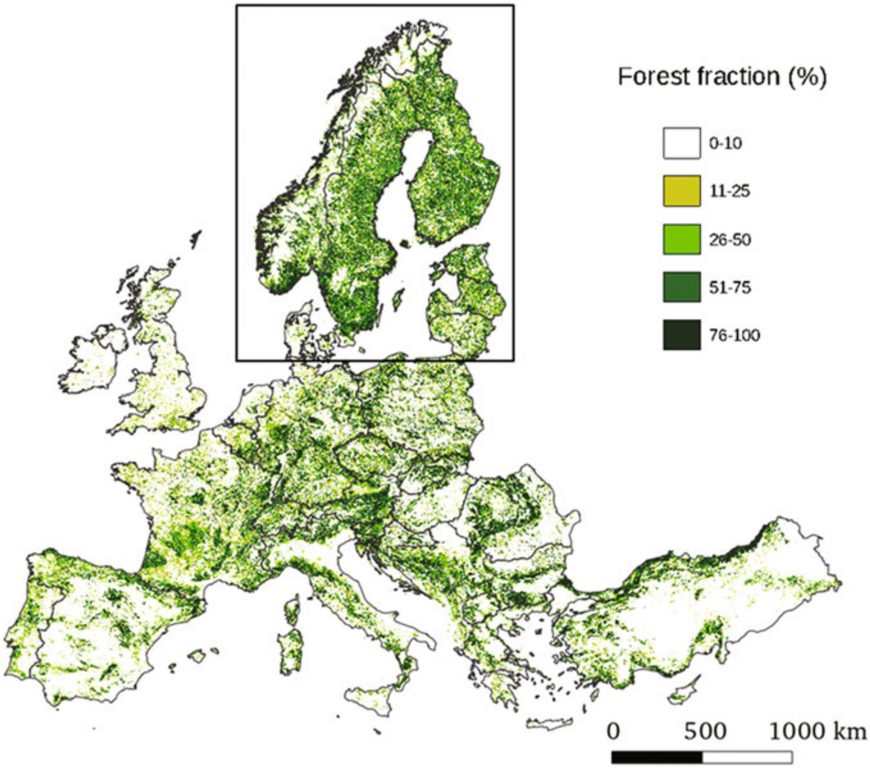

Fig. 2.1 Map showing the forest coverage of Western Europe and Turkey. The map was made for this book using methods presented in Kempeneers et al. (2011)

which grow successfully in these conditions as found in long-term experiments with tree species. Table 2.2 provides information on the regions in which the tree species can be grown, together with appropriate management regimes, while Table 2.3 gives information on productivity and wood density for the different tree species.

Native species include Norway spruce (*Picea abies* (L.) Karst), Scots pine (*Pinus sylvestris* L.), and silver and downy birch (*Betula pendula* Roth and *B. pubescens* Ehrh.), which grow in pure and/or mixed stands. Furthermore, aspen (*Populus tremula* L.) is common, but this species seldom grows in pure stands and even then in small patches, restricting the use of aspen biomass in energy use. Grey alder (*Alnus incana* L. (Moench)) is common in the Baltic countries, while the hardwoods common in Central Europe (e.g. oak, *Quercus robur* L. and beech, *Fagus sylvatica* L.) are abundant only in southern part of the region.

Exotic (or non-native) deciduous and coniferous species may have high growth potentials but their role in supplying energy biomass is still small in the Nordic and Baltic countries (cf. Table 2.1). The exotic deciduous species include, for example, several poplars (*Populus* spp.) and hybrid aspen (*P. tremula* L. × *P. tremuloides* Michx.). The exotic conifers include Sitka spruce (*Picea sitchensis* (Bong) Carrière),

Table 2.1 Growing stocks of native and exotic tree species in the Nordic and Baltic countries

Tree species	Growing stock, (million m^3)	Area as dominant tree species, (ha)
Native species		
Norway spruce (*Picea abies*)	> 2,700	c. 18 million
Scots pine (*Pinus sylvestris*)	c. 3,300	> 30 million
Birch (*Betula pendula*, *B. pubescens*)	c. 1,450	c. 8 million
Alder (*Alnus incana*, *A. glutinosa*)	> 290	–
Aspen (*Populus tremula*)	> 150	–
Oak (*Quercus robur*)	> 70	–
Beech (*Fagus sylvatica*)	> 40	–
Exotic species		
Lodgepole pine (*Pinus contorta*)	c. 30	c. 600,000
Sitka spruce (*Picea sitchensis*)	–	c. 85,000
Douglas fir (*Pseudotsuga menziesii*)	–	> 6000
Grand fir (*Abies grandis*)	–	c. 3000
Hybrid larch (*Larix × eurolepis*)	c. 1.4	–
Siberian larch (*Larix sibirica*)	–	c. 30,000
Populus (excl. *P. tremula*)	–	c. 5000

Douglas fir (*Pseudotsuga menziesii* (Mirb.) Franco), Grand fir (*Abies grandis* (Douglas ex D. Don)) and hybrid larch (*Larix × eurolepis* Henry), which are successful in the southern parts of northern Europe along with the lodgepole pine (*Pinus contorta* Douglas ex Loudon). Furthermore, the Siberian larch (*Larix sibirica* Ledeb.) is successful even at the Arctic timber line in the north, but its importance in biomass supply is still unexplored. The deciduous species also include fast-growing willows (*Salix* spp.). These are mainly grown in biomass plantations on agricultural land, thus they are classed as agricultural biomass rather than forest biomass.

2.3.2 Common Native Species

2.3.2.1 Norway Spruce

In northern Europe, Norway spruce is a dominant species, occupying 18 million ha of forest land, with a total growing stock of 2700 million m^3 (Keskkonnateabe Keskus 2010; Bekeris 2011; Finnish Forest Research Institute 2011; Statistics Norway 2011; Danmarks Statistik 2012; Directorate General of State Forests 2012; Swedish Forest Agency 2012). Norway spruce is also the most planted tree species in the region, with more than 350 million plants being produced annually (Finnish Forest Research Institute 2011; Swedish Forest Agency 2012).

Norway spruce is native throughout the Nordic and Baltic countries except Denmark (Hultén 1950) and is found here (Seppä et al. 2009). It is a shade-tolerant species with comparatively low initial growth but high growth during the later phases of the rotation period, and it can grow in stands of high density without losing vigour.

Table 2.2 Regions and sites suitable for different tree species used for the production of energy biomass in the Nordic and Baltic countries. The planting density, number of thinnings and rotation time included in this table are suitable for intensive management in conventional forestry

Tree species	Suitable region, sites	Planting density (plants ha^{-1})	Thinnings (number)	Rotation time (years)
Coniferous species				
Norway spruce	Whole region, preferably mesic and reasonably fertile soils	2,000–2,500	2–3	55+
Scots pine	Whole region, preferably mesic and dry sites, not the most fertile soils	2,000–2,500	2–3	70–100
Lodgepole pine	Above 60 °N on most sites except moist and very fertile	c. 2,300	2	60–100
Hybrid larch	Below 59 °N on medium fertile soils	2,000–2,500	up to 5	c. 40
Siberian larch	Above 59 °N on fertile soils	2,000–2,500	up to 5	80–100
Sitka spruce	Maritime climate, along the coasts in the southern part	c. 2,500	0–5	35–80
Douglas fir	Mainly below 59 °N on mild mesic to somewhat dry sites	750–1,500	3–4	80–100
Grand fir	Limited knowledge, probably like beech	2,500+	2–6	50–80
Deciduous species				
Birch	Whole region, silver birch on mesic sites, downy birch on moist sites	1,500–2,000	2–3	c. 40
Grey alder	Above 59 °N in the Nordic countries, in the Baltic area, mesic to moist soils	2,000–3,000	2–3	25–40
Aspen	Whole region, preferably mesic and fertile soils	c. 2,000[a]	2	c. 50
Oak	Below 60 °N on deep, fertile, mesic soils, also clay soils	400–800 grouped	5–10	100–150
Beech	Below 57 °N on deep, mild, fertile soils, preferably slopes	> 4,000, seeding	4–7	90–120
Poplar	Below 59 °N on mild, fertile sites, pref. agric. land. Future expansion	1,000–1,500	0–2	c. 20
Hybrid aspen	Below 59 °N on mild, fertile sites. Expanded in the future	c. 1,100	0–2	20–25

[a]Aspen is usually regenerated via root suckers rather than planted

Table 2.3 Productivity of stem wood of selected trees species representing natural populations and the genetic gain representing populations originating from genetically improved trees. The values represent the populations in recommended regions (Table 2.2)

Tree species	MAI for "natural" stands ($m^3\ ha^{-1}\ a^{-1}$)	Genetic gain (%)	MAI for improved plant material[g] ($Mg\ ha^{-1}\ a^{-1}$)	Basic wood density ($kg\ m^{-3}$)
Norway spruce	10–14	10–30	4–6	350
Scots pine	7–9	10–20	3–5	440
Birch[a]	7–10	10–30[e]	4–6	480
Grey alder	10–15	n.a.	4–5	360
Aspen	7–10	n.a.	3–4	380
Oak	4–6	n.a.	2–3	575
Beech	5–8	n.a.	3–5	580
Poplar	20–25[c]	n.a.	7–9	345
Hybrid aspen	15–20[d]	c. 25[f]	c. 9	360
Lodgepole pine[b]	9–13	10–20	4–7	430
Hybrid larch	10–14	n.a.	4–6	450[h]
Siberian larch	7–10	n.a.	4–6	600[h]
Sitka spruce	11–20	15–20	6–9	360
Douglas fir	15–20	n.a.	7–9	450
Grand fir	25–30	n.a.	9–10	350

MAI is the mean annual increment; *n.a.* not available. [a] Refers to Silver birch; [b] In the northern part of the region; [c] Result obtained with the OP42 clone; [d] Initial selection of clones; [e] With the Ekebo3 material; [f] Current commercial material for southern Sweden; [g] Where improved material was not available, the figures were based on the productivity in natural stands; [h] Density based on volume with 5 % moisture content, and thus resulting in an overestimation of the productivity in terms of mass

The productivity of Norway spruce on fertile sites (Table 2.3) is 10–14 $m^3\ ha^{-1}\ a^{-1}$ for stands generated from unimproved plant material (Eriksson 1976). The rotation used in managing Norway spruce is generally over 55 years (Table 2.2). The wood of Norway spruce is fairly light, with a basic density of 310–400 $kg\ m^{-3}$ (Hakkila 1966; Brolin et al. 1995). Harvest residues from Norway spruce, consisting of branches and top parts of stem, are an important source of energy biomass in Finland and Sweden (Brunberg 2011; Parviainen and Västilä 2011).

2.3.2.2 Scots Pine

Scots pine is widely distributed in the Nordic and Baltic countries, and Scots pine forests cover more than 30 million ha in this region. Scots pine grows even on poor sites, where its ability to tolerate water shortages is of utmost importance. The total growing stock in the region is almost 3300 million m^3.

Scots pine is native to all of the Nordic and Baltic countries except Denmark (Hultén 1950). Its growth on fertile sites is 7–9 $m^3\ ha^{-1}\ a^{-1}$ (Persson 1992), and on sites of medium fertility 3–5 $m^3\ ha^{-1}\ a^{-1}$. Rotation periods are usually 70–90 years on fertile and medium-fertile sites and more than 100 years on poor sites (e.g. Persson 1992) (Table 2.2). The wood density of Scots pine is higher than that of

Norway spruce; i.e. 410–475 kg m^{-3} (Hakkila 1966; Peltola et al. 2007). Scots pine yields less harvest residues (branches, top parts of stem) than Norway spruce per unit area (Marklund 1988). This is due to the lower production and shorter life span of branches and foliage relative to stem in Scots pine compared with Norway spruce.

2.3.2.3 Silver and Downy Birches

Silver and downy birches are the dominant deciduous tree species in the Nordic and Baltic countries. The combined growing stock of both species is about 1450 million m^3. They often grow mixed with Scots pine and Norway spruce, but birch-dominated stands cover almost 8 million ha. The productivity of both species is the highest on nutrient-rich sites with sufficient availability of water, but silver birch is more successful on drier sites than downy birch (Rytter et al. 2008). Both birch species tolerate pH levels below 4 (Cameron 1996), making them usable on most forest and agricultural sites. Downy birch also grows well on nutrient rich peatlands drained for forestry.

Both birch species are native in all the Nordic and Baltic countries. They are pioneer species that prefer non-shaded conditions, and each tree needs a relatively large space to grow fast (Rytter et al. 2008). In the southern parts of the Nordic countries, the average growth of silver birch is 9–10 m^3 ha^{-1} a^{-1} (Niemistö 1996; Rytter 2004) over the 40–50 year rotation (Table 2.2), whereas in more northerly areas, the growth is 5–8 m^3 ha^{-1} a^{-1}. Birch wood is heavier than that of most conifers, with a basic density of 430–520 kg m^{-3} (Rytter 2004). Until now, birches have seldom been planted for energy biomass alone due to their high establishment costs. In general, energy biomass based on birch trees is a side-product from naturally regenerated young stands, which are thinned in conventional forestry operations.

2.3.2.4 Black and Grey Alder

Black alder is common in Denmark, the southern parts of Finland and Sweden and along the southern coast of Norway, whereas grey alder is not native to Denmark. Both alders are common in the Baltic countries, where they account for a growing stock of 170 million m^3 (Latvia Forest Industry Federation 2008; Keskkonateabe Keskus 2010; Directorate General of State Forests 2012). Their combined growing stock in Sweden and Finland is 120 million m^3 (Finnish Forest Institute 2011; Swedish Forest Agency 2012).

Black alder grows best on nutrient-rich soils with a generous water supply, and it withstands periodic flooding. Grey alder prefers similar sites, but it is more tolerant of shortage of nutrients and water (e.g. Rytter 2004). Both alders have the unique ability to fix atmospheric nitrogen in symbiosis with the actinomycete *Frankia*. They can fix up to 100 kg N ha^{-1} a^{-1} (Binkley 1981; Rytter 1996), which facilitates the maintenance of site productivity when harvesting nutrient-rich tree residues.

In dense young stands used in short-rotation forestry, the annual mean growth of black and grey alders can be over 15 m^3 ha^{-1} a^{-1}, but remains around 10 m^3 ha^{-1} a^{-1} when applying conventional management (Rytter 2004). In biomass-oriented cultivation, a rotation less than 30 years is feasible (Table 2.2), whereas a rotation of 40–50 years is used for black alder in conventional forestry. The basic density of alder wood is 350–370 kg m^{-3} (Rytter 2004). The red colour of alder wood makes it less attractive for pulping (Rytter 1998), and therefore logs of small diameter may be used for energy. While black alder mainly regenerates from stump sprouts, grey alder effectively produces root suckers (Rytter et al. 2000). This could potentially be exploited in cultivating of grey alder for biomass production.

2.3.2.5 Aspen

Aspen is common throughout the Nordic and the Baltic countries (Hultén 1950). It grows mainly mixed with other species, which makes it difficult to estimate the total coverage of aspen. For example, Stener (1998) found that almost 60 % of the aspen volume in Sweden was in mixed stands with Norway spruce and Scots pine. This is also why aspen cannot be regarded as an important species for biomass harvest from existing forests. The total growing stock of aspen in the Nordic and Baltic countries is over 150 million m^3. The growth of aspen is generally in the range of 7–10 m^3 ha^{-1} a^{-1} on suitable high fertility sites. The basic density of aspen wood is 350–400 kg m^{-3} (Rytter 2004).

2.3.2.6 Oak and Beech

Oak grows in Denmark, southern Sweden, along the southwest coast of Norway, in the Baltic countries and in southern Finland, where it is a rare and endangered species (Hultén 1950). Beech is of economic importance only in Denmark and in the southernmost parts of Sweden. The total growing stock of oak is 70 million m^3 and of beech 40 million m^3. The growth of oak on fertile sites is commonly 4–6 m^3 ha^{-1} a^{-1}, while the growth of beech is 5–8 m^3 ha^{-1} a^{-1} (e.g. Rytter 1998). The basic density of wood of both species is 575–580 kg m^{-3}. Oak and beech are not normally planted specifically to produce energy biomass, but the branches and top part of stems of both species are used for energy.

2.3.3 Non-Native Species

2.3.3.1 Lodgepole Pine

Lodgepole pine is the most widely used non-native tree species in the Nordic countries. It has primarily been used in northern Sweden. The species is native to the north-western parts of North America. The variety of lodgepole pine (variety *latifolia*) used in the Nordic countries comes from the northern inland areas of this region. In Sweden, lodgepole pine was introduced on a large scale in the 1970s, and plantations cover almost 600,000 ha (Elfving et al. 2001). In other Nordic countries, lodgepole pine has not been this popular, and in Finland, for example, the plantations cover only 9000 ha (Finnish Forest Research Institute 2012). Currently, the total stocking of lodgepole pine in Sweden is 30 million m^3 (Swedish Forest Agency 2012). Its growth is 36–50 % larger than that of Scots pine regardless of site fertility, while its wood density is about 3 % lower (Elfving et al. 2001).

Lodgepole pine grows successfully over a wide range of sites, but less so on moist and highly fertile sites. The survival rate of lodgepole pine is higher than that of Scots pine in the establishment phase. This is because lodgepole pine is less sensitive to low temperatures, and is browsed less by moose than Scots pine. Furthermore, lodgepole pine suffers less from snow blight (*Phacidium infestans*) and twist rust (*Melampsora pinitorqua*) than Scots pine. However, lodgepole pine is more sensitive to wind and snow damage, and to attacks by Scleroderris canker (*Gremmeniella abietina*) (Elfving et al. 2001).

2.3.3.2 Larch Species

Hybrid larch is probably the most useful larch in the Nordic and Baltic areas. It is a cross between the European (*L. decidua*) and Japanese (*L. kaempferi*) larches. Currently, this hybrid accounts for the majority of the 1.4 million m^3 of stem wood stocking of larches in Sweden (Swedish Forest Agency 2012). The annual mean growth of hybrid larch is about 13 $m^3\ ha^{-1}\ a^{-1}$ on fertile sites over a 35–40 year rotation (Ekö et al. 2004). Thus, the productivity of hybrid larch is similar to that of Norway spruce, but the rotation is shorter. Wood density of hybrid larch is 410–490 $kg\ m^{-3}$ (Karlman et al. 2005; volume determined at 5 % moisture). Hybrid larch is sensitive to root rot (Rönnberg and Vollbrecht 1999), and it is vulnerable to browsing animals (Frisk 2011).

Siberian larch is used only marginally in forestry in the Nordic and Baltic countries. In Finland, for example, there are about 30,000 ha of Siberian larch plantations (Lukkarinen et al. 2010). Growth of Siberian larch on fertile sites is 7–10 $m^3\ ha^{-1}\ a^{-1}$ during a fairly long rotation (Karlman 2010). The wood density of Siberian larch is 535–670 $kg\ m^{-3}$ (Karlman et al. 2005; see the hybrid above), and larch wood is commonly used outdoors due to its high resistance to rot and decay. Neither hybrid larch nor Siberian larch is species primarily grown to produce biomass for energy use.

2.3.3.3 Sitka Spruce

Sitka spruce is native to western North America, from Alaska in the north to California in the south. This species is likely best used in the maritime parts of the Nordic and Baltic countries. Sitka spruce is most common in Denmark and Norway, where it has been planted on about 50,000 ha (Øyen 2005; Vadla 2007). In Denmark, the plantations of Sitka spruce cover around 34,000 ha (Danmarks Statistik 2012), which represents about 7 % of the total forested area in the country. Sitka spruce grows more rapidly than Norway spruce, and its total growth is up to 40 % higher than that of Norway spruce. Growth of Sitka spruce in western Norway will peak at an age of 70–115 years at a level of 20–33 $m^3\ ha^{-1}\ a^{-1}$ (Øyen 2005), while the growth of Norway spruce under similar conditions is 12–24 $m^3\ ha^{-1}\ a^{-1}$. The basic density of Sitka spruce wood falls in the range 325–390 $kg\ m^{-3}$, which is somewhat lower than that for Norway spruce (Vadla 2007). Sitka spruce resembles Norway spruce in many respects. Its wood could be used for the same purposes and it will most probably be treated like spruce in terms of biomass production for energy.

2.3.3.4 Douglas Fir

There are two major subspecies of Douglas fir; i.e. the costal and interior ones. The coastal Douglas fir is found in northern British Columbia and along the Rocky Mountains in California. The interior Douglas fir is native to the eastern Rocky Mountains through Montana down to Mexico. The interior Douglas fir is preferable in the southern parts of the Nordic and Baltic region, where it is used in forest cultivations due its resistance to a harsh climate. However, the coastal Douglas fir is so far the more widely used subspecies in the Nordic and Baltic countries (Svensson 2011), even though frost damage is common. At present, Douglas fir plantations cover only 500 ha in Finland (Metla 2011), and they account for around 1 % ($\sim$ 5,000 ha) of the forested area in Denmark (Nord-Larsen et al. 2009). Growth of Douglas fir is probably superior to that of Norway spruce, and in Denmark its average annual growth is expected to be 20 $m^3\ ha^{-1} a^{-1}$ (Henriksen 1988). Douglas fir is usually cultivated for the production of high quality timber, but tops and branches could be used for energy generation.

2.3.3.5 Grand Fir

Grand fir is only sparsely used in northern Europe, and its growth in these conditions is poorly known. Grand fir is most widely planted in Denmark, where it covers approximately 3,000 ha of forest land (Bergstedt and Jørgensen 1992). Under these conditions, its annual mean growth is 25–30 $m^3\ ha^{-1}\ a^{-1}$ (Bergstedt 2005) over a rotation of 50 years; i.e. the yields are 65–70 % higher than those achieved by Norway spruce. Furthermore, Grand fir seems to be less sensitive to root rot (*Heterobasidion* spp.) than Norway spruce (Swedjemark and Stenlid 1995). Grand fir can grow on a fairly wide range of site conditions. It is a secondary species with relatively high light demands capable of growing in multi-layered stands. Establishment can be tricky because the plants are sensitive to handling, low temperatures and browsing.

2.3.3.6 Poplars and Hybrid Aspen

Use of poplars (*Populus* species) in forestry is relatively new in the Nordic and Baltic countries, although poplars have been used in landscaping and shelter belts for a long time. Poplars belonging to the section balsam poplars (Tacamaha) seem best suited to the Nordic conditions. At present, about 5,000 ha of land has been planted with poplars, including hybrid aspen (Rytter et al. 2011a; Tullus et al. 2012). All poplars are highly productive and should be used on fertile sites. For example, the growth of hybrid aspen is over 20 m^3 ha^{-1} a^{-1} in 20–25 year rotations (Rytter and Stener 2005; Tullus et al. 2012). Regarding other poplars, there is less information available, but in the Nordic and Baltic countries the growth of some other poplars will probably be somewhat higher than that of hybrid aspen (e.g. Stener 2010; Rytter et al. 2011a). The wood of poplars is relatively light; i.e. the basic density is 300–420 kg m^{-3} for hybrid aspen and 300–390 kg m^{-3} for balsam poplars depending on species, clone and age (Rytter 2004; Stener 2010).

Currently, hybrid aspen is a most promising candidate for the effective supply of energy biomass. Hybrid aspen is the hybrid of European aspen and trembling aspen from North America. It is well adapted to the Nordic and Baltic conditions, because both parent species have boreal distributions. Hybrid aspen produces root suckers after the final felling, whereas other poplars mainly regenerate via stump sprouts. The root sucker stands of hybrid aspen quickly produce large amounts of biomass. In a few years, the average growth may reach 10 Mg ha^{-1} a^{-1} (about 30 m^3 ha^{-1} a^{-1}) (Rytter 2006; Tullus et al. 2012). Regarding the use of stump sprouts in poplar regeneration, some clones sprout vigorously while others are less inclined to sprout (McCarthy and Rytter 2012). Therefore, the natural regeneration of poplars is still an unreliable way to establish new poplar plantations, until the clonal performance of sprouting is better understood.

2.4 Potential to Enhance Biomass Supply Through Tree Breeding

2.4.1 Breeding Practices

2.4.1.1 Objectives of Breeding

Tree breeding refers to the genetic improvement of tree populations in order to enhance their survival, growth and wood properties by making use of the genetic variability (diversity) of trees and their ability to inherit specific traits. Breeding can be divided into long- and short-term breeding.

Long-term breeding combines intensive breeding, gene conservation and preparedness for future climatic changes (Danell 1993). Within species, the material is divided into multiple breeding populations (MPBS), where crossings, testing and