Chapter 3
Short-rotation Forestry for Supplying Biomass for Energy Production

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Abstract In this chapter, we discuss the opportunities that short-rotation forestry may provide to meet the increasing demand for energy based on renewable resources. We present information on suitable species for northern Europe, their productivity, establishment and management. In this region, grey alder, hybrid aspen, poplars and willows are the most promising species for short-rotation forestry. The productivity of these species is around 5–12 Mg ha^{-1} a^{-1} in fertile sites. All of these species regenerate vegetatively, and they can be managed in several consecutive rotations without needing to repeat the establishment between rotations. No major negative environmental impacts have been found with the cultivation of these species. This is especially the case when plantations are established on abandoned agricultural land or otherwise degraded land.

Keywords Agro-forestry · Alder · Aspen · Bioenergy · Coppice system · Energy forestry · Management · Northern Europe · Plantation forestry · Planted forests · Poplar · Short-rotation forestry · Willow

3.1 Short-rotation Forestry in Supplying Energy Biomass—Why?

Two contradictory trends characterize modern forestry: (1) to increase the area of forests protected for biological conservation, and (2) to increase the land area under intensively managed plantations for producing biomass. In the current chapter, we

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focus mainly on the Nordic and Baltic countries, where forestry is traditionally based on long rotation periods (commonly 60 to 120 years) and where short-rotation forestry (SRF) with rotation periods of less than 30 years is still emerging (Weih 2004; Aosaar et al. 2012; Tullus et al. 2012a). The rapid increase of short-rotation plantation forestry is an important trend throughout the world. Globally, 6–7 % of the forests are planted (FAO 2010) but they provide around a quarter of the world's annual roundwood production and this share is predicted to increase considerably in the future (Siry et al. 2005).

There are two main reasons why SRF has received increasing attention during the last three decades in northern Europe. The first reason is that the agricultural use of land has decreased in several countries due to political, economic and social changes (Astover et al. 2006; Alcantara et al. 2012). In this case, SRF is an attractive land use justified both by economic and environmental reasons. The second reason is that that we need to substitute fossil fuels with renewable energy sources, a commitment of the member states of the European Union (EU). According to the EU energy policy, the share of energy from renewable sources is to increase to 20 % by the year 2020 (Directive 2009/28/EC). Increasing production of woody biomass in SRF plantations is a promising means to reach this goal. In this chapter, we discuss the general outlines of SRF and its potential application in the Nordic and Baltic countries. The focus is mainly on the most promising tree species and their management.

3.2 Management Concepts Used in Intensive Production of Woody Biomass

3.2.1 Coppice Systems and Agro-forestry

To start, we need to clarify management (silvicultural) concepts to characterize SRF at northern latitudes. In this regard, *coppice system (low forest)* refers to forests originating from root or stump sprouts (suckers), which restricts this concept to broadleaved trees. Historically, the main aim of the coppice system has been to provide forage and fuel wood. The opposite to low forest, *high forest* is used to refer to seed-originating tree stands managed for timber. High forest may represent naturally or artificially (sown, planted) regenerated coniferous or deciduous stands.

In a coppice forest, trees are cut at the stump level or branches are cut leaving 2–3 m standing stems to protect new sprouts against browsing by cattle. Nowadays, this method is no longer important in producing fuel wood or forage. However, it is still used by farmers in the Mediterranean region, where sparsely spaced trees are grown in grassland grazed by livestock. Usually, some branches are cut from living crowns to stimulate the flowering and fertility of these trees (e.g. oaks, olives, chestnuts, stone pines) as is also done to enhance apple crops in northern Europe. A land use that is simultaneously for forestry and agriculture is also known as *agro-forestry*. Traditional rotation in coppicing is about 20 years.

In the coppice system, clear cut can be used in final felling or some trees may be left to grow to larger dimensions. This system is called *coppice selection* in order to distinguish it from *coppices with standards*. The latter means that vegetative and seed-originating trees are grown together and selectively cut by leaving some trees to grow older and provide large specimens. In general, the short-rotation stands and plantations of willow, grey alder and hybrid aspen can be regarded as modern examples of low forests, although grey alder and *Populus* species will grow to large dimensions.

3.2.2 Plantation Forestry and Forest Plantations

Plantation forestry (silviculture) is a term that refers to the intensive production of woody biomass in forest plantations. A forest plantation is an artificially established set of trees (as an act of plantation forestry) on previous agricultural land, on otherwise artificially degraded land, or on forest land after clear felling. The main aim of plantation forestry is to maximize the production of wood or some other products of trees (e.g. fruits, leaves, bark, resin, natural rubber), while less attention is paid to the creation of a system resembling a real forest ecosystem. In international forestry terminology (as recognized by the FAO), the term plantation forestry incorporates all man-made (primarily planted) forests and management of such forests (FAO 2006a). In 2010 the FAO introduced a broader term, *planted forests*, instead of *forest plantations*. Planted forests comprise productive and protective forest plantations and planted components of semi-natural forests. Globally, planted forests cover 264 million ha, which constitutes 6.6 % of the forest area, whereas in the last decade the planted forest area has increased by an average of almost 5 million ha every year (FAO 2010).

3.2.3 Short-rotation Forestry and Energy Forestry

Short-rotation forestry (SRF) utilizes much shorter harvesting intervals and rotations than traditional forestry (high forestry) and therefore uses species with high productivity and early growth culmination. In general, the final harvesting in SRF is done after the culmination of mean annual increment (MAI), which coincides with the financial maturity. In boreal conditions, the rotation in SRF is about 30 years, whereas in the tropics the rotation could be as short as 5–7 years (FAO 2006b). SRF may incorporate high initial stand densities, is often monocultural, and requires optimal or close-to-optimal site conditions for the used species for an economically successful outcome.

Energy plantations (energy forestry) became well-known in the 1980s, when the first willow plantations for energy use were established in Sweden (e.g. Christersson et al. 1993). Energy plantations are usually managed on a rotation of 3–5 years. The main advantage of producing energy from woody biomass compared with herbaceous biomass (e.g. combustion of seeds or whole above-ground part of the crops) is that woody biomass is mainly composed of carbon, oxygen and hydrogen. Furthermore, the ash content of woody biomass is 5–10 times lower than that of herbaceous biomass. Concentrations of nutrients (N, P, K and others) in wood and bark are also lower, which reduces the amount of nutrients removed in harvesting, thus reducing the need to compensate nutrient losses through fertilization. However, bark has higher ash content than wood and thus woody biomass with a higher share of wood and a lower share of bark is generally preferred. Furthermore, energy produced from woody biomass is considered to be carbon neutral; i.e. the amount of carbon released at combustion equals the amount of carbon fixed in trees during their life-time. This is probably true in the long run, if indirect carbon emissions (e.g. emissions from fossil fuels used in management and logistics, and emissions due to the change of land use) are excluded. The wood of potential energy tree species has comparatively low density and the fuel value per volume is low, but calculated on a weight basis differences between different tree species are small (Nurmi 1993). A more important factor to consider is the moisture content of the actual biomass fraction, which depends on the species as well as harvest occasion and storage time.

3.3 Species Suitable in Short-Rotation Forestry

3.3.1 General Characterization

A suitable tree species for SRF in the boreal climate should combine rapid growth with high frost hardiness. Regarding these requirements, *alders* (grey and black alder), *aspens* (common and hybrid aspen), *poplars* and *willows* have a high potential to be used in SRF in northern Europe (Karačić et al. 2003; Rytter 2004; Weih 2004; Rytter and Verwijst 2009; Aosaar et al. 2012; Tullus et al. 2012a, Table 3.1, Fig. 3.1).

Furthermore, there is evidence that deciduous tree plantations on agricultural or forest lands have no negative effect on the site fertility.

3.3.2 Poplars, Aspens, Alders and Willows for Short-rotation Forestry

3.3.2.1 Poplars

The *Populus* genus (family Salicaceae) is spread over most of the northern hemisphere, mainly within the temperate zone. However, for most parts of northern Europe, only European aspen (*P. tremula* L.) is an endemic species, hence aspens and their hybrids are presented hereinafter separately from other poplars, which are exotic to the region's forestry. Most *Populus* species are fast-growing, and they are dioecious and hybrids between species are common. Poplars are divided into six sections; among them black poplars (e.g. *P. deltoides, P. nigra*), aspens and white poplars

Table 3.1 Main characteristics of selected deciduous tree species for short-rotation forestry (SRF) in the Nordic and Baltic countries representing hemiboreal region with northern temperate climate. The item "mean annual growth" refers to stem wood excluding tops and branches except willows, the growth of which includes also stem tops and branches. Growth in terms of mass represents dry mass.

Item	Poplars	Hybrid aspen	Grey alder	Willows
Establishment	Cuttings or rooted cutting in the first generation; new cuttings or vegetatively from root suckers in the following generations	Micro-propagated clonal plants in the first generation; vegetatively from root suckers in the following generations	Seedlings in the first generation; vegetatively from root suckers in the following generations	Cuttings in the first generation; vegetatively from root suckers in the following generations
Rotation	20–25 years for energy wood, pulpwood and logs, < 20 years for energy wood only	20–25 years for energy wood, pulpwood and logs, < 20 years for energy wood only	15–20 years for energy wood, pulpwood and logs, < 15 years for energy wood only	3–5 years for energy wood only
Site requirements	Fertile, fresh to moderately moist	Fertile, fresh to moderately moist	Fertile, fresh to moderately moist	Fertile, fresh to moist
Mean annual growth at fertile sites	25 m^3 ha^{-1} a^{-1} 7.5–10 Mg ha^{-1} a^{-1}	20–25 m^3 ha^{-1} a^{-1} 7–9 Mg ha^{-1} a^{-1}	7–11 m^3 ha^{-1} a^{-1} 3–5 Mg ha^{-1} a^{-1}	8–12 Mg ha^{-1} a^{-1}
Main advantages	Highly productive (selected poplar clones are probably the most fast-growing trees in the region), easy to establish with cuttings	Highly productive with high quality wood fibres, cold-resistant	At young age, among the fastest growing domestic deciduous trees, not susceptible to damagers, improves soil N-content	Highly productive in very short rotations
Main concerns or constraints	Exotic for the region, cold-resistance in central and northern boreal areas is low	High establishment cost, half-exotic for the region, high risk of herbivore browsing	No market for other assortments than for energy wood	Requires fertilization for high productivity, pathogens reduce growth

(e.g. *P. alba*, *P. tremula*, *P. tremuloides*) and balsam poplars (e.g. *P. balsamifera*, *P. trichocarpa* and *P. maximowiczii*) are the most interesting for SRF.

Most experiences of poplars in the Nordic and Baltic countries come from southern Sweden and Denmark. In these conditions, balsam poplars (both pure clones and

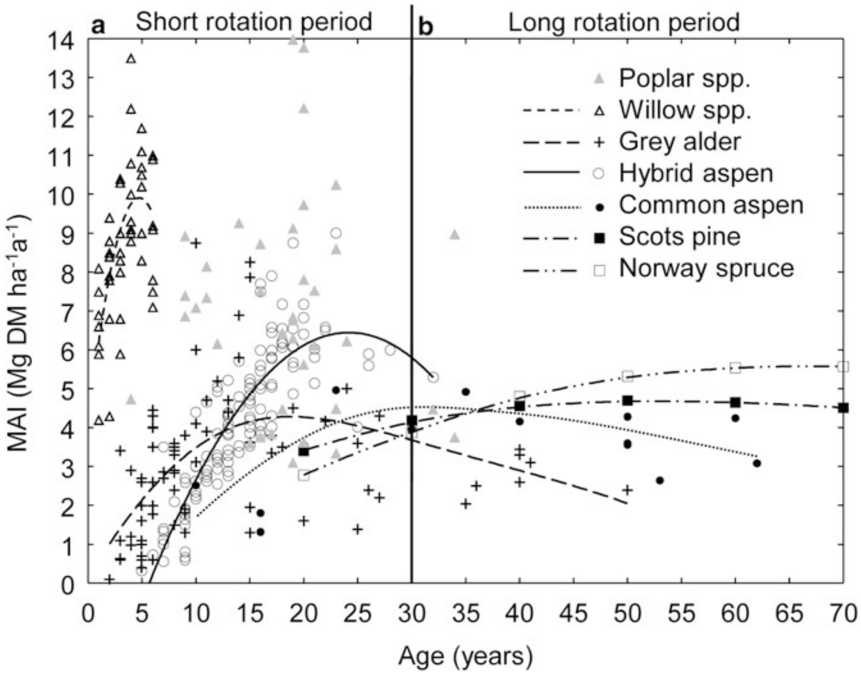

Fig. 3.1 Mean annual increment (MAI) of dry biomass of selected tree species potential for short- and long-rotation forestry in northern Europe. **a** total above-ground biomasses in planted and fertilized willow (Willebrand et al. 1993) and poplar stands (Johansson and Karačić 2011), stem biomasses in planted and natural grey alder (Aosaar et al. 2012) and planted hybrid aspen stands (Rytter and Stener 2005; Tullus et al. 2012a, unpublished data). **b** stem biomasses in planted and natural *P. tremula* stands (Krigul 1971; Tullus et al. 2012a), and natural Scots pine and Norway spruce stands in fertile sites (Krigul 1971)

hybrids) are very promising. Especially, the balsam hybrid clone OP42 (*P. maximowiczii* × *P. trichocarpa*) is a dominating clone, but today twelve other clones are available to be grown in mixtures. Furthermore, pure *P. trichocarpa* plantations are under evaluation (Christersson 2006). The balsam poplars (e.g. *Populus balsamifera, P. trichocarpa*) seem to have a higher potential to adapt to the Nordic conditions than the black poplars (e.g. *P. deltoides, P. nigra*) or the white poplar (*P. alba*).

In general, all poplars tested in northern Europe are nutrient-demanding species (Grosscurth 1972; Bergstedt 1981), which are most successful on well drained soils with continuous supply of water and low acidity (pH value of 5.5–7.5) (Bergstedt 1981; Boysen and Strobl 1991). This implies that poplars are sensitive to drought (Blake et al. 1996) due to their low efficiency of water use (Marron et al. 2008). However, breeding for increased drought tolerance is possible (Tyree et al. 1979) although the relationship between growth and drought tolerance seems to be low. In general, poplars are resistant to occasional flooding but such conditions seem to reduce their growth (Neuman et al. 1996). The high demand for light of black poplars makes them more sensitive to shading than is the case for other poplar groups including the balsam poplars (Bergstedt 1981).

3.3.2.2 Aspens, Hybrid Aspen

Aspens belong to the section *Populus* (formerly *Leuce*, aspens and white poplars) of the genus *Populus*. This section includes ten species (Eckenwalder 1996). Regarding SRF, the most promising species are *Populus tremula* L. (common, European or Eurasian aspen) and its hybrid with its North-American counterpart *P. tremuloides* Michx. (quaking or trembling aspen). *P. tremula* is among the most widely distributed tree species in the world (Worrell 1995), while *P. tremuloides* is among the most widely distributed tree species indigenous in North America (Dickmann and Kuzovkina 2008).

P. tremula is a common native deciduous tree in the Nordic and Baltic countries. It is a fast-growing species grown for energy biomass, pulp wood and logs. In the latter two cases, its economic value may be reduced by stem heart rot, which commonly damages mature trees. In this respect, the hybrid between *P. tremula* and *P. tremuloides*, known as hybrid aspen (*P.* × *wettsteinii* Hämet-Ahti = *P. tremula* L. × *P. tremuloides* Michx.) represents a high capacity to produce biomass with lower risks of damage by pathogens like stem heart rot (Tullus et al. 2012a). During recent decades about 4500 ha of hybrid aspen has been cultivated in the Nordic and Baltic countries both for experimental and practical purposes (Tullus et al. 2012a).

3.3.2.3 Alders, Grey Alder

Alders belong to the family Betulaceae, genus *Alnus*. Two species occur naturally in the Nordic and Baltic countries: grey alder (*A. incana* (L.) Moench.) and black alder (*A. glutinosa*). Grey alder grows throughout northern Europe, except in the very southern part of Sweden and Denmark (Hultén 1950). Black alder, on the other hand, has a more southern origin than grey alder. Black alder is absent from the very northern parts of the Nordic countries.

Grey alder is a fast-growing but relatively short-lived species. It has a rapid juvenile growth but is surpassed by black alder at the age of 25–30 years (Ljunger 1972). Alders are typically light-demanding species, which efficiently colonize bare land, e.g. abandoned agricultural land. Germ plants are small as are the nutrient reserves in seeds. Therefore, establishment from seed is hampered by thick humus and competition from other plants. Grey alder prefers moist and nutrient rich sites, and it can grow on somewhat drier and less fertile soils than black alder (Rytter 1996). Grey alder also tolerates acidity (low soil pH down to a pH value of 4) without negative effects on growth (Ericsson and Lindsjö 1981). A symbiotic nitrogen-fixing bacterium (*Frankia* spp.) in root-nodules makes alder species self-sufficient in nitrogen (N) supply. In grey alder, the fixation of atmospheric N_2 may exceed 100 kg N ha^{-1} a^{-1} (Rytter 1996), but the fixation rate is dependent on the age of the tree and soil and light conditions. Fertilization, leading to enhanced nutrient concentrations in the soil, may temporally reduce the N_2 fixation (Rytter et al. 1991).

3.3.2.4 Willows

Salix species represent a variable morphology spanning from trees (e.g. *S. caprea* L. and *S. fragilis* L.) through bushes (e.g. *S. viminalis* L. and *S. dasyclados* Wimmer) to small shrubs (e.g. *S. polaris* Wahlenb. and *S. repens* L.). In particular, the bush-formed species are used in biomass plantations and breeding. In this respect, an important attribute is the capacity for resprouting after harvest (cf. Sennerby-Forsse and Zsuffa 1995). *Salix* species are spread over the whole of northern Europe, but the species choice varies from region to region. In general, *Salix* species are well-adapted to the climate in northern Europe. *Salix* species consume large amounts of water per unit yield of biomass (Grip et al. 1989; Lindroth et al. 1994). Therefore, willow cultivation should be established only on sites where the availability of water is high enough in relation to needs for unlimited growth.

Most work in breeding *Salix* species is done in Sweden. Since the 1980s, more than twenty varieties have been produced. They all have the Community Plant Variety Right, and they are thus protected in the EU. The willow species mainly recommended for plantations include *S. dasyclados* Wimmer and crossings between *S. viminalis* L. and *S. schwerinii* E. L. Wolf. At the moment, research is being done to develop genetic markers for use in practical breeding (e.g. Berlin et al. 2011; Samils et al. 2011).

3.4 Productivity and Varieties of Poplar, Aspen, Alder and Willow

3.4.1 Poplars

Regarding poplar clones, the growth is up to 25 m^3 ha^{-1} a^{-1} of stem wood in the southern parts of the Nordic and Baltic countries (e.g. Rytter 2004), but future breeding work will most probably increase the growth (Telenius 1999; Karačić et al. 2003; Stener 2010). The basic wood density of the currently used poplars is 300–390 kg m^{-3} depending on the clone and the age of trees (Stener 2010). Consequently, the growth of dry matter of stem wood in poplars is 7.5–10 Mg ha^{-1} a^{-1}. Including branches without leaves, the biomass growth of poplars could increase by 7–20 % (cf. Rytter 2004) (Fig. 3.1). However, the growth of poplars is heavily dependent on the length of rotation and the degree of adaptation to the prevailing conditions. In the poplar experiments, rotations of only 8–12 years are used, but there are damages in the young trees (e.g. Stener 2010) indicating that the poplars used so far are not sufficiently adapted to the northern-European climate (Christersson 2006).

3.4.2 Aspen and Hybrid Aspen

Aspen plantations may supply raw material for pulp and paper mills, but their role in supplying biomass for energy use has increased rapidly (Christersson 1996; Beuker

2000; Rytter 2006). However, plantations of aspen are not as common in the Nordic and Baltic countries as is the case for hybrid aspen. Breeding programs have provided clones of hybrid aspen, whose annual mean growth is 20–25 m^3 ha^{-1} a^{-1} when applying a rotation of 20–30 years. In terms of biomass, this corresponds to 7–9 Mg ha^{-1} a^{-1} of dry mass (Fig. 3.1). Even if regenerated through root suckers, the productivity of hybrid aspen is high. In southern Sweden, the annual mean growth was 9.5 Mg ha^{-1} a^{-1} of dry mass already at the age of four years (Rytter 2006). Thus, young dense stands of hybrid aspen are as productive as willow stands. Due to high establishment costs, low planting densities are preferred in establishing hybrid aspen plantations and productivity figures can be quite low in young planted stands (Tullus et al. 2009).

The wood of hybrid aspen is high in carbohydrates and low in lignin, the average concentrations of cellulose and acid-insoluble lignin varying in the ranges of 50–60 % and 11–20 % (Zeps et al. 2008; Tullus et al. 2010). The cells of aspen wood are narrow in diameter, and the wood is composed of thin-walled fibres, which are ideal for producing a high-density paper with a smooth surface (Karl 1988; Dhak et al. 1997). Furthermore, the wood density of hybrid aspen is less than that of *P. tremula*; i.e. 350–370 kg m^{-3} for hybrid aspen and 370–380 kg m^{-3} for *P. tremula* (Kärki 2001; Rytter and Stener 2003; Rytter 2004; Heräjärvi and Junkkonen 2006; Stener 2010). However, the basic density is age-dependent, with lower values during the first ten years but increasing thereafter with age (Heräjärvi and Junkkonen 2006; Stener 2010). The energy value of hybrid aspen biomass is 19.3 kJ g^{-1} for stem wood and 20.3 kJ g^{-1} for current-year shoots (Tullus et al. 2009).

3.4.3 Grey Alder

The annual mean productivity of grey alder is usually 3–5 Mg ha^{-1} a^{-1} but may reach up to 8.8 Mg ha^{-1} a^{-1} of stem wood (Rytter 1996, 2004; Aosaar et al. 2012) (Fig. 3.1) depending on the stand age, site conditions, stand density, fertilization, and type of regeneration (natural, planted), the highest values representing dense stands. The current estimates exclude any contribution from breeding activities. However, Matthews (1987) regarded grey alder as a promising candidate for breeding, because it flowers at an early age and can be propagated vegetatively from cuttings or using tissue and cell cultures. The basic density of the wood of grey alder is 350–400 kg m^{-3} (Aosaar et al. 2012), which is close to that of *Populus* species and Norway spruce.

3.4.4 Willows

The productivity of *Salix* species varies substantially in commercial plantations (Fig. 3.1). In fertilized experiments, more than 10 Mg ha^{-1} a^{-1} of woody biomass is obtained (e.g. Willebrand et al. 1993; Alriksson 1997; Bullard et al. 2002; Heinsoo et al. 2002) (Fig. 3.1). In commercial willow plantations, the values are smaller depending on the management intensity and the choice of land for plantation (Dimitriou et al. 2011). The rotation for willow plantations is short ($\sim$ 3–5 years) with the consequence that the current annual increment is very different among years and cutting cycles, lower values representing the first or second year and higher values the years thereafter (e.g. Willebrand et al. 1993; Alriksson 1997).

3.5 Establishment, Management and Profitability of Short-Rotation Tree Plantations

3.5.1 Poplars

Poplars are planted either directly using stem cuttings or using nursery-rooted cuttings, whose survival is higher than cuttings with no roots used in direct planting. In direct planting, the optimal cutting is 25 cm long and 1–3 cm thick (Boysen and Strobl 1991). Planting density is between 3.6 × 3.6 m and 2.5 × 2.5 m; i.e. about 800 to 1,600 plants ha^{-1} (Boysen and Strobl 1991; Rytter et al. 2011a). Poplars are less expensive to establish than hybrid aspen, because a costly micro-propagation technique is used for hybrid aspen.

Management of poplars resembles that of hybrid aspen (Fig. 3.2). In general, pre-commercial thinning is not required due to the low initial stand density. The first thinning is recommended to be done after 10–15 years since planting depends on the initial stand density (Rytter et al. 2011a). No more than one thinning is needed before the final cut at 20–25 years from planting if the management aims only at producing energy biomass (Rytter et al. 2011b). After harvest, many clones regenerate from stump shoots, and these can be used for the next generation. Unfortunately, this is not always the case, sprouting of stumps may be small and/or sprouts will die (McCarthy and Rytter 2012). Regeneration of poplars from stump sprouts is still poorly known and further research about the sprouting ability among clones is needed for developing proper regeneration methods.

3.5.2 Aspen, Hybrid Aspen

In northern Europe, the aspen plantations represent mainly hybrid aspen, whose clones are propagated using micro-propagation or root cuttings (e.g. Stenvall et al. 2004). The planting density is generally 1,100–1,600 plants ha^{-1} (Tullus et al. 2012a). Usually site preparation is carried out, and chemical or mechanical weed control is needed during the first year(s), if the plantation is established on agricultural land. A higher planting density (>4000 plants ha^{-1}) could be used if the plantation is established for the production of energy biomass in very short rotations (5–10 years) as done in central Europe (Liesebach et al. 1999). Traditionally, high planting densities have not been used in northern Europe, where hybrid aspen is planted for producing merchantable timber. In such a case, the rotation is 20–25 years (Hynynen et al. 2004; Rytter and Stener 2005, Fig. 3.2), with the total yield of pulpwood and logs of 300–450 m^3 ha^{-1}. During the rotation, one to three thinnings

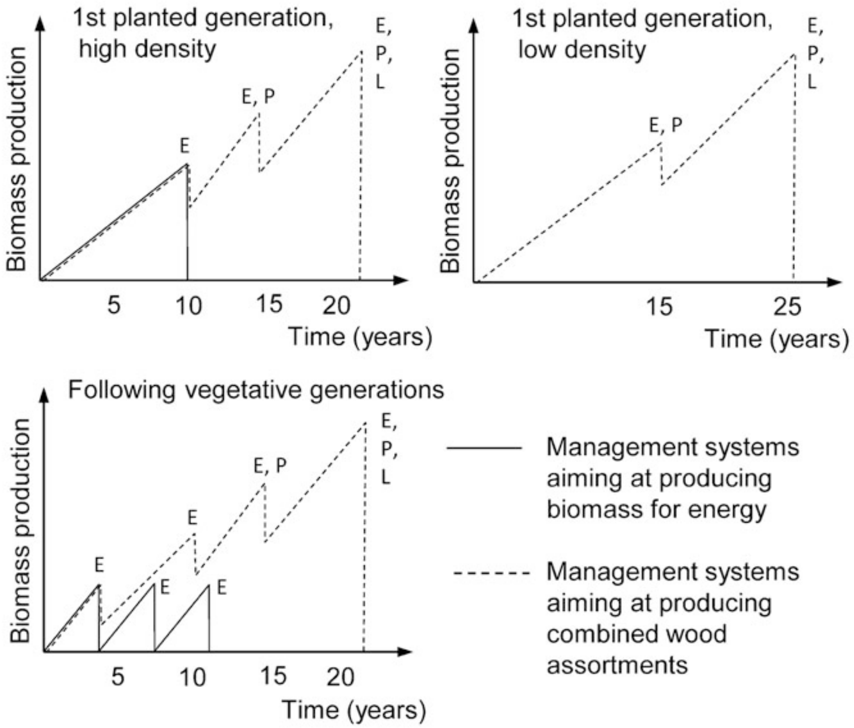

Fig. 3.2 Theoretical management (timing of thinnings and final fellings) schemes for *Populus* (poplar and hybrid aspen) plantations aimed at producing energy wood (E), pulpwood (P) and logs (L). The first thinning in the following vegetative generations corresponds to pre-commercial thinning in conventional forestry

are needed depending on the initial stand density, the growth rate and intensity of thinning.

When producing energy biomass in hybrid aspen plantations, management with shorter rotations and vegetative regeneration in establishing successive generations would probably be successful (Liesebach et al. 1999; Rytter 2006). High-quality energy biomass (i.e. higher wood content and lower bark content of the stems) may be obtained if the harvesting is done in the phase when the breast-height diameter of trees exceeds 4 cm (Tullus et al. 2009). Furthermore, management combining early harvest of root suckers in conventional forestry is proposed for hybrid aspen (Fig. 3.2). In this case, the biomass in root suckers could be exploited by using corridor cleaning, while the remaining trees could be managed by applying ordinary forestry practices to produce pulp wood and logs (Rytter 2006).

There are few economic assessments concerning the commercial plantation of hybrid aspen. Rytter et al. (2011b) and Tullus et al. (2012b) showed positive results with an internal rate of return (IRR) of around 8–10 % in Swedish and Estonian conditions, if the plantations were established on abandoned agricultural land. With current prices in Estonia, the IRR was 1 % higher than that for silver birch plantations

(Tullus et al. 2012b). Similarly, the economic calculations for the Swedish conditions show that hybrid aspen could be competitive with Norway spruce on forest land and with food production on agricultural land (Rytter et al. 2011b). However, the price relations between food, energy biomass, pulpwood and saw logs ultimately determine the economic ranking.

3.5.3 Grey Alder

In establishing grey alder plantations, seedlings should be inoculated with *Frankia* in order to enhance the early growth of seedlings (e.g. Hendrickson et al. 1993). Until now, there has been little experience on grey alder plantations, but the optimal planting density in biomass-oriented management is 2000–3000 plants ha^{-1} (cf. Matthews 1987; Almgren 1990). This implies that the canopy will close in a reasonable time after planting and no thinning will be needed during the rotation. Grey alder regenerates successfully also through seeds, root suckers and stump sprouts. In the latter two cases, regeneration through root suckers seems to dominate (Rytter et al. 2000). The initial density of natural grey alder stands is usually high, which may facilitate precommercial thinning combined with biomass removal. In such a case, the optimal density is probably $<$ 10,000 plants ha^{-1} in the early phase, whereas 3,000 to 6,000 plants ha^{-1} may be left to the final harvest (Aosaar et al. 2012). In producing energy biomass in dense stands, a rotation length of 15–20 years is recommended, while when combining energy biomass production and the production of small-sized timber the rotation length of 25–30 years is more optimal (Daugavietes et al. 2009; Aosaar et al. 2012). During the rotation, up to two thinnings may be needed in order to avoid mortality due to self-shading in growing and developing stands (Rytter 1995).

The costs of establishing grey alder stands are probably similar to that of birch since the production costs of plants and the planting techniques are similar. On the other hand, there are no regeneration costs, if root and stump shoots are used in regeneration (Rytter et al. 2000). The economy of SRF based on grey alder is still poorly known. Opdahl and Veidahl (1993) found that the production of energy biomass combined with the production of pulp wood and saw logs was an economically attractive way to manage grey alder. Regarding more biomass-oriented forestry, Mizaras et al. (2011) concluded that SRF based on grey alder may be profitable, especially if whole-tree techniques were used in harvesting.

3.5.4 Willows

Current plant material allows the establishment of willow plantations over most of northern Europe, except the very northern areas with the harshest climates. Willow plantations are established only on fertile agricultural land with an ample supply of water and low acidity (pH over 5.5) (Gustafsson et al. 2007; Hollsten et al. 2012). In general, cuttings of 18–20 cm are used in mechanized planting, which is the most common way to establish *Salix* plantations (Gustafsson et al. 2007; Hollsten et al. 2012). In general, the planting density is 13,500–15,000 cuttings ha^{-1} (Gustafsson et al. 2007) in double rows with the spacing of 75 and 150 cm in order to facilitate mechanized harvesting operations. The distance between cuttings in the row is 60–65 cm. Biomass yield in *Salix* plantations may be further increased by increasing the planting density and shortening rotation (Bullard et al. 2002; Szczukowski et al. 2005).

Weed control, both before and after planting, can improve regeneration and enhance the early growth of *Salix* saplings. The rotation length of 3–5 years is commonly used, but it depends on site conditions and management. After the harvest, the sprouting stools establish a new generation. In general, the same stools may be used for 25 years (Gustafsson et al. 2007); i.e. five to six harvest cycles are possible, before new planting is necessary. Nitrogen fertilization will substantially enhance the growth of willows, e.g. an addition of 220 kg N ha^{-1} during a three-year cycle may increase the biomass yield up to 60 % compared with no N addition (Aronsson and Rosenqvist 2011). In general, the economics shows positive net results (e.g. Ledin 1996; Ericsson et al. 2009; Rosenqvist 2010), but the production is currently subsidized.

3.6 Environmental Issues

An increased area of poplar plantations on forest and/or agricultural lands has both positive and negative environmental impacts. Above all, the biomass produced in poplar cultivations can be used to substitute for fossil fuels and/or enhance carbon sequestration in soil, especially on agricultural land. Furthermore, the energy balance of producing biomass in poplar plantations is positive compared with other crops (Börjeson 2006; Rytter et al. 2011b). On the other hand, poplar plantations may reduce the biodiversity, depending on where the plantations are located in the landscape and how they are managed. However, the biodiversity values of poplar plantations seem to be higher than Norway spruce plantations but lower than deciduous plantations or a mixture of deciduous and coniferous trees (Weih et al. 2003; Britt et al. 2007; Rytter et al. 2011b). Regarding the effects on recreational and amenity values of the landscape, the effects are probably more positive than those of Norway spruce plantations.

Grey alder is a common species in the Nordic and Baltic countries, and it has thus a natural value for nature conservation in raising the share of deciduous species in forests. Additionally, grey alder is a domestic species in northern Europe, with no complications with forest laws or certifications. The N_2-fixing ability of grey alder will provide the possibilities to produce energy biomass in a sustainable way, wherever grey alder dominates the tree communities used for biomass supply. Furthermore, grey alder is capable of growing on soils polluted by heavy metals (Hawrys 1987), and thus it can be used to ameliorate soil and enhance the afforestation of polluted land areas.

SRF with willows in its current form represents an intensive management with continuous supply of fertilizers. However, Weih (2009) concluded that willow plantations can improve the biodiversity at the landscape level, especially if they replace cereal cultivation or Norway spruce plantations in a homogenous agricultural landscape and make the landscape structure more variable. Willow species may also improve the properties of soils used for a long time for conventional agriculture, e.g. more carbon will be stored in the soil (Kahle et al. 2005; Rytter 2012). Furthermore, willow plantations may be used for the phyto-remediation of polluted soils (Aronsson and Perttu 2001; Bertholdsson 2001; Mleczek et al. 2010), e.g. to take up heavy metals from the soil (Sennerby-Forsse et al. 1993; Labrecque et al. 1995; Bertholdsson 2001).

3.7 Conclusions

Short-rotation forestry (SRF) is a promising and environmentally sound way to produce biomass for energy production in northern Europe. For establishing SRF plantations, there exist several domestic and exotic deciduous tree species whose productivity is high even in the northern climate. These include several poplar species and their hybrids, hybrid aspen, grey alder and several willow species and their hybrids. The annual mean biomass growth of these species can be as high as 5–12 Mg ha^{-1} a^{-1} during rotations of less than 20–30 years. However, the highest productivity is achieved only on fertile soils or if the cultivation is fertilized, as is the case of willows. These species provide flexible management opportunities in producing energy biomass alone or combined with the production of other materials (pulpwood, logs). Most of the environmental concerns regarding SRF are similar to those of traditional forestry.

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