SILVA FENNICA

Silva Fennica 40(4) research articles

www.metla.fi/silvafennica · ISSN 0037-5330
The Finnish Society of Forest Science · The Finnish Forest Research Institute

Effects of Rotation Period on Biomass Production and Atmospheric CO_2 Emissions from Broadleaved Stands Growing on Abandoned Farmland

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Eriksson, E. & Johansson, T. 2006. Effects of rotation period on biomass production and atmospheric CO_2 emissions from broadleaved stands growing on abandoned farmland. Silva Fennica 40(4): 603–613.

The growth rates and carbon stocks of unthinned young and mature stands of broadleaved trees growing on abandoned farmland were determined to assess whether their management regimes should involve short (15-year) or long (45-year) rotations to maximize biomass production and reductions of CO_2 emissions. Dry mass production and mean annual increment (MAI) were calculated for 28 young stands and 65 mature stands of European aspen (*Populus tremula* L.), common alder (*Alnus glutinosa* (L.) Gaertn.), grey alder (*Alnus incana* (L.) Moench.), silver birch (*Betula pendula* Roth) and downy birch (*Betula pubescens* Ehrh.) ranging in latitude from 57° to 63° N in Sweden. The potential for using biomass from the stands to replace coal as a fuel and to store carbon was then evaluated both in short and long rotation scenarios. The results indicate that long rotations are beneficial if the objective is to maximize the average carbon stock in biomass. If, on the other hand, the intention is to optimize reductions in atmospheric CO_2 emissions, rotations should be short for aspen, silver birch and grey alder stands. For downy birch and common alder, the MAI was higher for the mature stands than the young stands, indicating that in these species the mature stands are superior for both storing carbon and replacing fossil fuel. Stands of broadleaved trees grown to produce biofuel on abandoned farmland should be established on fertile soils to promote high MAI. If the MAI is low, the rotation period should be long to maximize the average carbon stock.

Keywords abandoned farmland, atmospheric CO_2, biofuel, biomass, broadleaved trees, carbon stock, MAI
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Received 11 January 2006 **Revised** 20 June 2006 **Accepted** 9 August 2006
Available at http://www.metla.fi/silvafennica/full/sf40/sf404603.pdf

1 Introduction

In recent decades there has been increased interest in biomass and biofuel in Sweden, for two main reasons. Firstly, the government decided at the beginning of the 1990's to support biofuel by imposing a carbon dioxide tax on fossil fuel in order to reduce dependence on fossil fuel and promote the use of biofuel in heating and power plants. Secondly, biofuel plays an important role in reducing the levels of greenhouse gases. Schlamadinger and Marland (1996) and Ericsson (2003) argued that forestry can help reduce CO_2 levels in several ways, including: accumulation and storage of carbon in biomass, soil, and wood products; substituting fossil fuel by biofuel; and substituting energy-intensive materials like cement, steel, and plastics with wood products. Thus, the production of biomass in trees could be useful in many ways to reduce atmospheric CO_2 levels. The impact of forestry is considered in several strategic documents. Under the Kyoto Protocol, forestry and forest management can be taken into account in attempts to reduce greenhouse gases (Kyoto Protocol…1997). For instance, participating countries may choose to apply changes in carbon stocks due to afforestation, deforestation and reforestation according to Article 3.3 of the Protocol, and changes due to forest management activities according to Article 3.4. However, in the Swedish climate strategy, it has been decided that changes in carbon stocks will not be taken into account during the first commitment period (The Swedish climate …2001).

Most anthropogenic CO_2 emissions originate from the combustion of fossil fuels, but land-use changes may also have a considerable impact on the amount of greenhouse gases in the atmosphere. During the 1990s, about 20% of the total anthropogenic emissions to the atmosphere were ascribable to land-use changes (IPCC Special report…2000). Emissions due to land-use changes could be decreased by increasing afforestation or decreasing deforestation. Afforestation has to be conducted on lands that do not already sustain large amounts of biomass. Pasture land and abandoned farmland are examples of land that could be used for establishing new forest stands. According to Johansson (1999a), 348 000 ha of farmland was abandoned in Sweden between 1974 and 1999, and 231 100 ha of this land has not been used for any purposes such as planting trees or other forestry activities. Establishing trees on this area could make a considerable contribution to reductions in CO_2 levels. Afforesting abandoned farmland would result in carbon removal from the atmosphere until the stand was fully mature, and saturated with carbon. At this point, the afforested stand could not contribute further to reductions in CO_2 levels in the atmosphere, but it could act as a carbon reservoir since it would still keep the carbon locked in its biomass out of the atmosphere. Thus, to postpone increases in CO_2 levels in the atmosphere by afforestation, new plantations have to be established annually. In the long term, a managed forest stand does not sequester carbon since all of the biomass that is built up during the rotation period is harvested. Thus, to increase the amount of carbon in biomass at a regional or national level the amount of forest land has to be increased or the forest management has to be improved, which is what the Kyoto Protocol suggests (Kyoto Protocol…1997). Adjusting the rotation period could be an important forest management strategy to reduce atmospheric CO_2 levels since this variable affects the carbon storage capacity of both the biomass and soil (Kaipainen et al. 2004). Species with long rotations generally have larger average carbon stocks than species with shorter rotations, and can therefore store more carbon in their biomass (Maclaren 2000). Thus, if the abandoned farmland is afforested in order to increase the amount of carbon in biomass it is important to consider the rotation period.

Another strategy that could significantly increase the production of biofuel that could replace fossil fuels is afforestation of former arable land with broadleaved tree stands. Today, most of the biofuel harvested in Sweden consists of logging residues from final cuttings in coniferous stands, and the annual amount of residues harvested is estimated to be 2×10^6 tonnes dry weight (d.w.) (Nilsson 1999). Residues from final cuttings will probably be the main sources of biofuel from the forest for a long time, but to further increase biofuel usage, other possibilities for producing biofuel must be explored. Using residues from thinning operations could be one option, and could yield about 2×10^6 tonnes d.w. year^{-1}

(Nilsson 1999), but removing logging residues from thinning operations could reduce subsequent growth in tree volumes (Jacobson et al. 2000). Using trees grown on abandoned farmland for biofuel could be a valid strategy since it could yield considerable amounts of biofuel (Johansson 2000a) and the distances between such stands and the power plants are often short (Johansson 1999b). The amount of biofuel that could be produced and used to substitute fossil fuel is affected by the rotation period (Ericsson 2003), so it is important to estimate the amount of broadleaved tree stands of various species on abandoned farmland that could be used for this purpose, and to identify optimal rotation periods for stands of each species. However, managing stands in order to optimise biofuel production affects the carbon stocks in the biomass and soil (Wihersaari 2005), and it is not possible to manage forest stands in such a way that both carbon storage and biofuel production are maximized (Kirschbaum 2003).

It is important to evaluate the biomass yields that could be obtained in different forest management scenarios since the management strategy may affect both the carbon stock in biomass and the production of biofuel. As discussed by Paul et al. (2002), management regimes with short rotations (10–15 years) could be applied to stands established on abandoned farmland for biofuel or pulpwood production, or regimes with long (20–50 years) rotations for timber or veneer production. An advantage of the former is that no intermediate thinning is required, whereas the latter requires several thinning operations as well as longer rotation periods. Another alternative would be to apply regimes with long rotations, but no thinning operations, and to use the wood produced in the resulting dense stands for energy. Increasing the length of the rotation period could also increase the carbon stock in the biomass (Kaipainen et al. 2004).

The aim of this study was to assess whether management regimes with short (15-year) or long (45-year) rotations would be best for stands of broadleaved trees on abandoned farmland in order to maximize biomass production and reductions in atmospheric CO_2 levels. To do this, we estimated the average carbon stock and the amount of potential biofuel that could replace fossil fuel in a wide range of such stands of various species. The rotation period can also affect soil carbon levels, but they were not determined in the present study.

2 Material and Methods

2.1 Standing Above Ground Biomass

We examined young and mature stands of broadleaved trees growing on abandoned farmland ranging in latitude from 57° to 63° N (Fig. 1). The 28 young stands ranged in age from 10 to 20 years and included seven stands of European aspen (*Populus tremula* L.), four of downy birch (*Betula pubescent* Ehrh.), five of silver birch (*Betula pendula* Roth), four of common alder (*Alnus glutinosa* (L.) Gaertn.) and eight of grey alder (*Alnus incana* (L.) Moench) (Table 1). These stands had been previously measured and described by Johansson (1999c, d and 2000b).

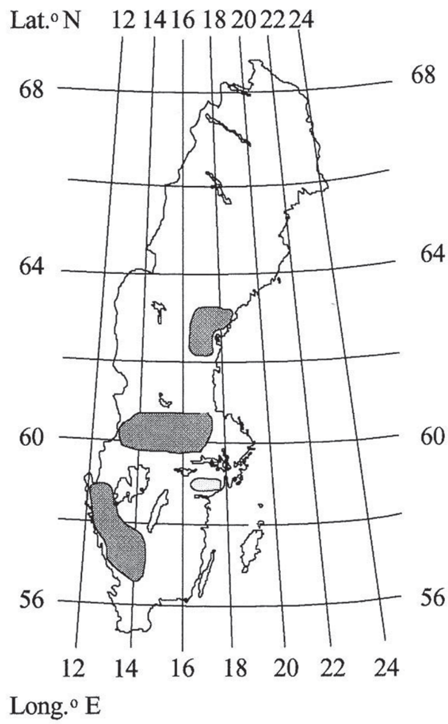

Fig. 1. Geographical locations of the stands.

Table 1. Characteristics of the young and old stands of European aspen (*Populus tremula* L.), silver birch (*Betula pendula* Roth), downy birch (*Betula pubescent* Ehrh.), common alder (*Alnus glutinosa* (L.) Gaertn.) and grey alder (*Alnus incana* (L.) Moench)

Tree species	No of stands	Age (years) Mean±SE	Range	Diameter (mm) Mean±SE	Range	Stems ha^{-1} Mean±SE	Range	Site index (H_{40} m) Mean±SE	Range	Moisture cont. (%)
European aspen	7	16±1	10–20	70±7	47–92	10123±1628	5964–16500	–	–	46
European aspen	19	42±2	32–64	188±9	123–282	1294±127	846–3242	21.5±0.8	16–26	59
Silver birch	5	13±1	10–17	43±14	11–92	25000±8243	3301–45500	–	–	40
Silver birch	8	36±3	26–50	140±14	77–213	2187±421	950–4061	23.3±0.8	21–28	41
Downy birch	4	14±2	11–20	45±14	14–80	18743±7384	2737–32400	–	–	40
Downy birch	9	43±4	30–57	162±12	128–232	1426±251	838–3253	23.1±1.0	19–27	41
Common alder	4	13±2	10–17	47±8	28–69	10380±3938	3861–21600	–	–	43
Common alder	14	45±3	31–61	185±9	122–238	1457±179	826–2994	19.9±0.7	15–23	53
Grey alder	8	15±1	10–17	57±8	24–89	18275±4423	7400–47600	–	–	45
Grey alder	15	43±3	30–66	166±9	95–219	2005±255	904–4031	20.0±0.5	17–24	54

The 65 mature stands (19 of European aspen, 14 of common alder, 15 of grey alder, eight of silver birch and nine of downy birch) ranged in age between 26 and 66 years. Stands which had obviously been thinned during the current rotation were not included in this study. The aspen and alder stands had previously been measured and described by Johansson (1999b, 2002), but the birch stands were evaluated for the first time in the present study. Mature birch stands often consist of a mixture of silver and downy birches and it is sometimes difficult to separate the species from each other in an older stand. The stands used in the present study were mostly mixtures of the two species, but we only used stands where one species comprised >75% of the total number of stems.

The areas of the stands varied from 0.02 to 2 ha, and the diameter, age and number of stems on each plot were measured. In stands growing on small areas, <0.1 ha, all trees were registered and the diameter at breast height was measured. However, for stands larger than 0.1 ha, 10 to 20 circular 100 m^2 plots were established and the number of stems and their diameter were recorded within each plot (Table 1). The number of stems per hectare was plotted against the mean diameter (dbh) in each stand to evaluate the development of the five species. Site indices (H_{40}) were estimated for the mature aspen and alder stands using equations presented by Johansson (1996, 1999e) and for the mature birch stands, site index (SI) equations by Eriksson et al. (1997) were used. Site indices for the young stands could not be estimated by these equations, but their soil types had already been analysed and described by Johansson (1999c, d and 2000b). The young aspen stands were established on fine sand, silt and medium clay soils, while the silver birch stands were growing on silt and light clay, and downy birch on fine sand and silt soils. Common alder stands were established on light clay soils and grey alder stands on fine sand and light clay soils. Fractions of the sample trees were weighed before and after drying to estimate their moisture contents (Johansson 1999c). The above ground biomass (stem and branches) of all the stands, except the mature birch stands, was calculated using the biomass equations of Johansson (1999b, c, d, 2000b and 2002). For the mature birch stands, Marklund's (1988) biomass equation was used. In his functions, silver birch and downy birch are not separated.

2.2 Substituting Fossil Fuel with Biofuel and the Average Carbon Stocks

The estimated outputs obtained with the long and short rotations should not be compared after a single cycle, due to the large differences in the rotation periods. Therefore, it was assumed that the young stands were harvested after 15 years, that a new stand was immediately established naturally and that the stands passed through three rotation periods. It was also assumed that the mature stands would be harvested after 45 years, and that the harvested biomass from the logging operations in both the short and long rotation scenarios would be used for biofuel. In addition, it was assumed that the same amount of standing biomass was produced in each rotation of the young stands. However, in practice, the MAI may vary both within and between the three rotations. Therefore, two further scenarios were considered, in which the MAI in the second and third rotations was assumed to be 25% higher and lower, respectively, than in the first rotation. The rough assumption that the yield would be the same during subsequent rotations has been made previously (Person et al. 1971). However, the rotation length for aspen must be at least 10 years otherwise the yield may decrease dramatically in subsequent rotations (Berry and Stiell 1978).

The amount of biofuel that could be produced and used to replace fossil fuel was calculated for all combinations of species and rotation periods considered. Data on the effective heating value (q_v(net)) (Nurmi 1993) and moisture content of each species (Table 1) were used to calculate heating values for wet biomass (q_v(moist)). The energy efficiency of generating power from biofuel was assumed to be 42% (Ekström et al. 2001). The energy content in the broadleaved tree stands and the amounts of carbon emitted as CO_2 when combusting coal with equivalent energy contents were then calculated. Combustion of biofuel was assumed to make no net contributions to atmospheric CO_2 since biofuel participates in the carbon cycle as long as the stands are managed sustainably. However, the production of biofuel from the forest results indirectly in CO_2 emissions during its harvesting, chipping and transportation to the power plant. According to Ekström et al. (2001), the indirect emissions when generating power amount to 0.01 tonnes CO_2 MWh^{-1} for biofuel from the forest and 0.03 tonnes CO_2 MWh^{-1} for coal. The indirect emissions from biofuel and coal were included in the calculations.

The present study was conducted at a stand level, so the biomass did not act as a carbon sink in the long term, since all of the biomass that built up was assumed to be clear-cut at the end of each rotation period. Therefore, the average carbon stock during the studied period was calculated to evaluate the differences in carbon storage between the short and long rotation scenarios. A large average carbon stock during the studied period results in more carbon storage in the biomass. Thus, the differences in average carbon stocks between the scenarios indicate the relative potential of the respective strategies for keeping carbon out of the atmosphere during the studied period. Estimates of the average carbon stock were derived from the amounts of carbon in biomass in the stands, assuming that the carbon content of all of the trees, which varies both within and between trees in reality, was 50% (Hakkila 1989).

3 Results

3.1 MAI of Above Ground Biomass

There is no practical way to obtain SI values as indicators of site conditions in young stands, however MAI values can provide indications of the conditions in fully stocked stands. The mean SI values for the mature broadleaved tree stands were mostly consistent with previously reported values for stands on forest land, but the MAI of several of the aspen stands was low to medium (Tables 1 and 3). Among the young stands, the aspen stands had the lowest number of stems per hectare and the largest breast height diameter (Table 1), the birch stands had the largest number of stems and the smallest mean diameter, but the ranges of numbers of stems and diameters were large in the young stands of all species. The MAI of above ground biomass was highest in the aspen and grey alder stands and lowest in the downy birch and common alder stands (Table 2). Among the mature stands, the aspen stands had the largest mean diameter and the lowest number of stems, while the silver birch stands had the lowest mean diameter and the largest number of stems (Table 1). The MAI of the mature stands showed a different pattern from that of the young stands, since it was highest in the common alder and silver birch stands and lowest in the aspen stands (Table 2). The mean number of stems per hectare and the mean diameter of the stems in young and mature stands of each of the species considered are shown in Fig. 2. The relationship between diameter and stem density was similar in young stands of both birch species (Fig. 2a),

Table 2. Standing above ground biomass (tonnes dry weight (d.w.) ha^{-1}) and mean annual increment, MAI, (tonnes d.w. ha^{-1} $year^{-1}$) of the young and old stands of European aspen (*Populus tremula* L.), silver birch (*Betula pendula* Roth), downy birch (*Betula pubescent* Ehrh.), common alder (*Alnus glutinosa* (L.) Gaertn.) and grey alder (*Alnus incana* (L.) Moench).

Tree species	No of stands	Age (years) Mean ± SE	Age (years) Range	Standing biomass (tonnes d.w. ha^{-1}) Mean ± SE	Standing biomass Range	MAI (tonnes d.w. ha^{-1} $year^{-1}$) Mean ± SE	MAI Range
European aspen	7	16 ± 1	10–20	85 ± 15	52–155	5.5 ± 0.8	2.9–8.6
European aspen	19	42 ± 2	32–64	118 ± 13	48–245	2.9 ± 0.3	1.4–6.9
Silver birch	5	13 ± 1	10–17	65 ± 16	9–99	4.8 ± 1.2	0.9–8.3
Silver birch	8	36 ± 3	26–50	128 ± 24	53–276	3.7 ± 0.7	1.6–6.7
Downy birch	4	14 ± 2	11–20	41 ± 12	6–65	2.9 ± 1.0	0.5–5.4
Downy birch	9	43 ± 4	30–57	139 ± 32	50–359	3.2 ± 0.7	1.7–7.3
Common alder	4	13 ± 2	10–17	45 ± 12	19–77	3.4 ± 0.6	1.7–4.5
Common alder	14	45 ± 3	31–61	155 ± 8	108–221	3.6 ± 0.2	2.4–5.3
Grey alder	8	15 ± 1	10–17	79 ± 14	31–133	5.4 ± 0.9	2.0–8.8
Grey alder	15	43 ± 3	30–66	133 ± 10	69–198	3.1 ± 0.2	1.9–4.5

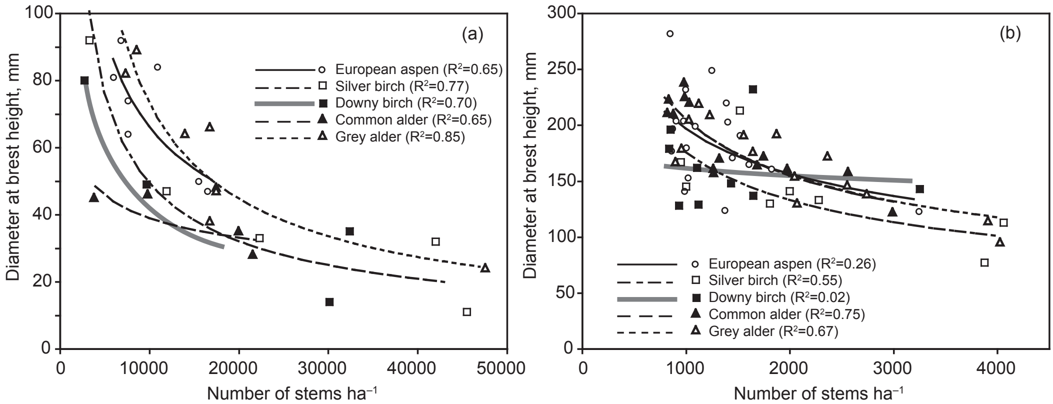

Fig. 2. The relationship between mean number of stems ha^{-1} and mean diameter at breast height (mm) for young stands (a) and mature stands (b).

and the relationship was also similar in mature stands of grey alder, common alder and aspen (Fig. 2b).

3.2 Biofuel Production and Average Carbon Stocks

The effects on net CO_2 emissions of replacing coal with biofuel produced from stands of each species in both short and long scenarios are presented in Fig. 3. After three rotation periods, the young stands of aspen, grey alder and silver birch substituted 32% to 112% more carbon than the mature stands of these species. The potential CO_2 emissions that could be avoided by growing downy birch were lower with short rotations than with long rotations. If the MAI was 25% lower in the second and third rotations than in the first rotation, 9% to 77% more carbon could be replaced by growing aspen, grey alder and silver birch with 15-year rotations than with the long rotation period. When the MAI was increased by 25% in the second and third rotations, biofuel from trees grown with the short rotations could replace more carbon than the mature stands for all species.

The average carbon stock varied from 32 to 41 tonnes C ha^{-1} for the mature stands and 11 to 21 tonnes C ha^{-1} for the young stands (Fig. 4). Aspen stored 52% more carbon in the long rota-

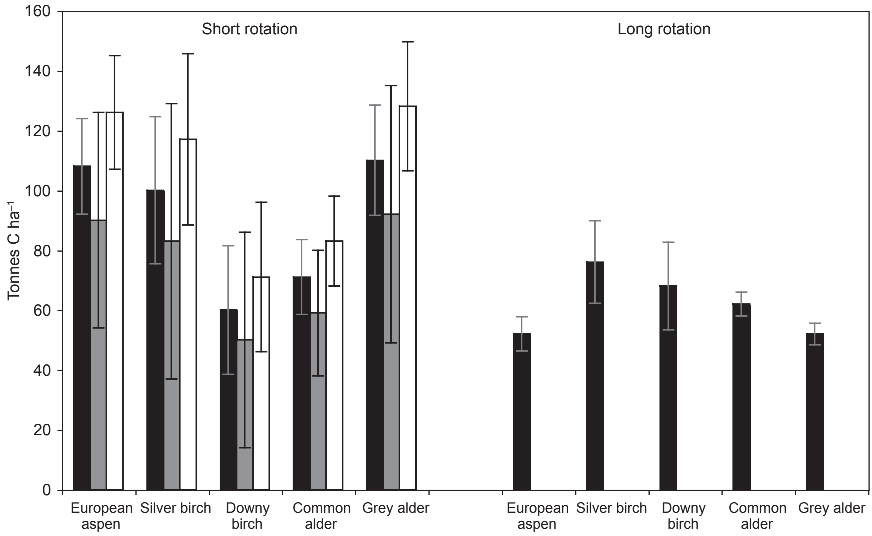

Fig. 3. Avoided emissions of CO_2 when replacing coal with biofuel (tonnes C ha^{-1}) after three rotation periods for the young stands and one rotation period for the mature stands (error bars indicate SE). MAI for the second and third rotation period was equal in all rotations (■), decreased by 25% (■) and increased by 25% (□), respectively, for the short rotation period.

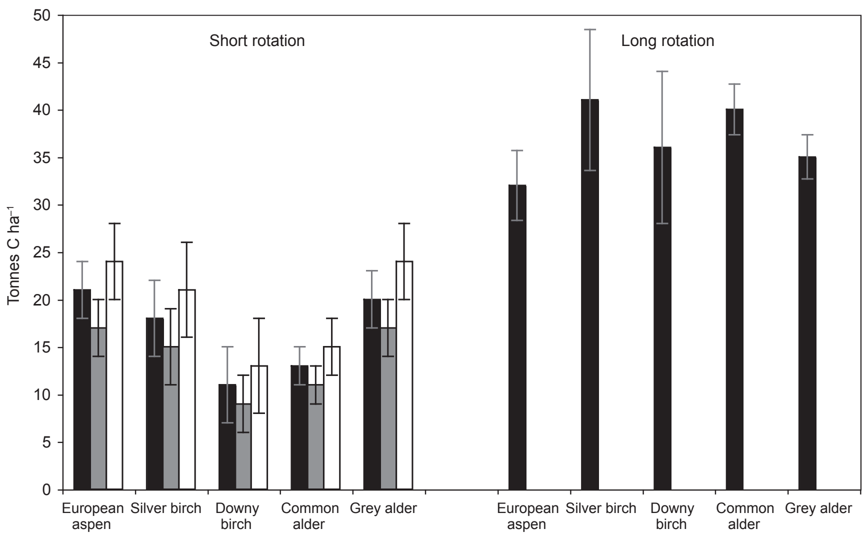

Fig. 4. Average carbon stock (tonnes C ha^{-1}) after three rotation periods for the young stands and one rotation period for the mature stands (error bars indicate SE). MAI for the second and third rotation period was equal in all rotations (■), decreased by 25% (■) and increased by 25% (□), respectively, for the short rotation period.

tion than in the short rotation scenarios during the studied period. The corresponding figures for the other species were 75%–227%. Reducing and increasing MAI by 25% for the second and third rotations in the 15-year rotation scenario resulted in the stands storing 15 to 29 tonnes and 8 to 25 tonnes more C ha^{-1}, respectively, in the long rotation scenario than they did in the short rotation scenario (Fig. 4).

Table 3. Reported above ground (stem and branches) MAI for European aspen (*Populus tremula* L.), silver birch (*Betula pendula* Roth), downy birch (*Betula pubescent* Ehrh.), common alder (*Alnus glutinosa* (L.) Gaertn.) and grey alder (*Alnus incana* (L.) Moench).

Species	Reference	Age (years)	MAI (tonnes ha^{-1} year^{-1})	Remarks
Aspen	Liesebach et al. (1999)	10	2.6–4.8	*Populus tremula*, Germany
Aspen	Cannell (1982)	25	5.9	*Populus tremula*, Russia
Aspen	Paavilainen (1981)	12	14.2 *	*Populus tremula*, Finland
Aspen	Wang et al. (1995)	15	2.1–4.1	*Populus tremuloides*, British Columbia
Aspen	Wang et al. (1995)	54	2.4–2.9	*Populus tremuloides*, British Columbia
Birch	Frivold & Borchgrevink (1981)	6	3.9	*Betula pendula*, Norway
Birch	Ferm & Kaunisto (1983).	14	4.7	*Betula pendula*, Finland
Birch	Cannell (1982)	42	4.8	*Betula pendula*, Russia
Birch	Ovington & Madgewick (1959)	38	1.8	*Betula pendula*, UK
Birch	Cannell (1982)	20	2.9	*Betula pubescens*, Russia
Birch	Mälkönen & Saarsalmi (1982)	20	1.8–2.2	*Betula pubescens*, Finland
Birch	Mälkönen (1977)	40	2.2	*Betula pubescens*, Finland
Birch	Mälkönen & Saarsalmi (1982)	40	2.5–2.9	*Betula pubescens*, Finland
Alder	Rytter (1995)	12	4.3	*Alnus incana*, Sweden
Alder	Saarsalmi & Mälkönen (1989)	35	0.9–1.9	*Alnus incana*, Finland
Alder	Cannell (1982)	13–18	3.3–4.6	*Alnus glutinosa*, Belgium
Alder	Meeuwissen & Rottier (1984)	30, 35	3.6, 3.4	*Alnus glutinosa*, The Netherlands

* Fresh weight

4 Discussion

4.1 MAI of Broadleaved Stands

Most of the young broadleaved tree stands were growing on soil types that are predicted to be the most favourable for the respective species. In some stands MAI was low, which might be due, *inter alia*, to the low number of stems, dry sites, or previous damage caused by frost or grazing animals. In the present study the mean SI for aspen was 21.5 m (H_{40}), which is lower than most previously reported figures, and considerably lower than the 25 m for managing mature aspen stands for timber production recommended by Johansson (1996). Common and grey alder sites were of medium SI level and the SI ranges for mature silver and downy birch (21–28 m and 19–27 m, respectively) indicate that the stands were growing on medium to rich sites. The MAI of young aspen stands in the present study was high compared to previously reported values for young stands, but the MAI of the mature stands was consistent with other studies (Table 3). For silver and downy birch the MAI values were in accordance with previous reports, although the variation in earlier studies is large (Table 3). In both the present study and other studies, tendencies were found for the MAI of young silver birch stands to be larger than that of young downy birch stands. However, the significance of these differences has not been tested statistically in the present study.

Relatively few young stands of downy birch and common alder were included in the present study, which could have an impact on the results. Johansson (1999c, 2000b) used more observations when studying young stands of common alder and downy birch, but the MAI values were lower in his reports than those found here. Langhammer and Opdahl (1990) reported that the MAI of dense, unmanaged stands of European aspen peaks at 18 to 20 years of age, while Perala (1973) showed that the MAI of trembling aspen (*Populus tremuloides* Michx.) generally peaks after about 20 years. For grey alder previously published reports are conflicting. Rytter (1995) found that MAI for grey alder peaks after about 15 years while Børset and Langhammer (1966) showed that MAI starts to decline after 30 to 35 years. The MAI curves by Børset and Langhammer (1966) were flat while Rytter (1995) found that MAI increased sharply until it reached its peak. However, it should be noted that the alder stands studied by Rytter (1995) were irrigated and fertilized.

4.2 Should Rotations of Broadleaves Be Long or Short?

If the objective is to maximize the average carbon stock, the rotation period should be long since the carbon stock was large with long rotations for all species. These results are consistent with reports by Alban and Perala (1992), Maclaren (2000) and Kaipainen et al. (2004). Even if the MAI for the second and third rotations was increased by 25% for the young stands, the long rotation period was preferable since more carbon could be stored as biomass during the studied period. The largest differences in storage capacity between the rotation periods were found for downy birch and common alder, since there were small differences in MAI between young and mature stands of these species. If, on the other hand, the purpose is to maximize the substitution of fossil fuel, and thus reductions in CO_2 emissions, a short rotation period should be used for aspen, grey alder and silver birch since more coal could then be replaced by biofuel than if long rotations are used for these species. However, since the MAI values for young stands of downy birch and common alder were low, more coal could be replaced if their management regimes included 45-year rotations rather than 15-year rotations.

Considering the differences between the rotation scenarios in terms of both average carbon stocks and the potential to replace coal, it was found that the aspen and grey alder stands could contribute more to reductions in atmospheric CO_2 if their management regimes involved 15-year rotations rather than 45-year rotations. This was mainly due to the large amount of coal that could potentially be replaced by biomass produced from short-rotation aspen and grey alder stands. For downy birch and common alder the 45-year rotation period was favourable, even if MAI was increased in the second and third rotations in the 15-year rotation scenario. When the difference in MAI between young and mature stands was low, the potential for replacing fossil fuel was similar for the two rotation scenarios, but the average carbon stock was larger for the 45-year rotation periods. To maximize the reduction of atmospheric CO_2 emissions, the rotation periods for broadleaved trees grown on fertile soils to produce biofuel should be short. If the MAI is low (i.e. < 4 tonnes d.w. ha^{-1}) in a young stand, the amount of fossil fuel that can be replaced will be low if the rotations are short. If the MAI is low, the average carbon stock will also be low under short rotation regimes compared with long rotation regimes. Therefore, the stands with low yield should be managed with long rotations to maximize the average carbon stock in the biomass.

5 Conclusions

Management of broadleaved trees growing on abandoned farmland can contribute to reductions in atmospheric CO_2 both by producing biofuel that could replace fossil fuel and by sequestering carbon in biomass. Practical implications of the present study include the following:

1) If the objective is to maximize the average carbon stock in the biomass, the rotation period should be long. If, on the other hand, the objective is to maximize the biofuel production the rotation period should be short (i.e. 15–20 years).
2) The management regimes of broadleaved stands on short rotations should be conducted on rich soils to promote high MAI, and thus high potential to substitute fossil fuel.
3) If the yield of young stands is low (i.e. < 4 tonnes d.w. ha^{-1}), their rotations should be long. Low MAI in combination with short rotation would give low average carbon stock in biomass and low potential to replace fossil fuel.

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