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Review

Suitability of Fast Growing Tree Species (*Salix* spp., *Populus* spp., *Alnus* spp.) For Establishment of Economic Agroforestry Zones for Biomass Producing in Baltic Sea Region

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Abstract. The main goal of the review is to provide a summary and an assessment of the potential of fast-growing tree species for suitable transformation of agroforestry areas for biomass production in the Baltic Sea region. The article summarizes the research on the management process of agroforestry zones by establishing short rotation plantations with tree species *Salix* spp., *Populus* spp., *Alnus* spp. and looks at the perspectives of planning of these zones as biomass producers. Short rotation forestry (SRF) with a combination of species and a rotation time of 15 to 30 years, depending on the species used, is the most suitable approach for management of these agroforestry zones. Willows (*Salix* spp.) and poplars (*Populus* spp.) are suitable for short rotation coppice (SRC), as these tree species can be harvested at much shorter intervals, respectively, 1–5 and 4–10 years, facilitating their use in agricultural systems. In *Alnus* spp. short rotation plantation the life cycle for energy wood production is assumed to be 15-30 years. The black alder plantations in agroforestry zones are used for sawnwood and firewood production, with a rotation span of 20–40 years. Calculated economic agroforestry zone repayment period is about 10-15 years, if costs and prices as in 2021 are used.

Keywords: economic agroforestry zone; *Salix* spp.; *Populus* spp.; *Alnus* spp.; short rotation coppice (SRC); short rotation forestry (SRF); energy wood.

1. Introduction

Climate change, the increasing biomass demand for energy and the expectations to reduce greenhouse gas (GHG) emissions and provide carbon storage in soils and vegetation at the same time, are projected to add further pressure on managed economic agroforestry zones [1-5]. The European Green Deal foresees that sustainability and climate neutrality in several European Union (EU) countries will be achieved by 2050 [9]. Climate policies, such as the Paris agreement will increase the demand for biomass for bioeconomy needs, including energy, industry and agriculture sector. European Union (EU) aims to increase the share of renewable energy in the final energy consumption to 27% by 2030 [6-8]. EU planning documents state that the use of renewable energy sources in the energy sector must be increased to promote the reduction of fossil resources in energy production [10]. Each member state has set its own individual target, and the goal of EU countries is to reach around 42% (Estonia) - 65% (Sweden) of the share of renewable energy resources in the gross final energy consumption by 2030, which will be done by increasing the use of wood for energy production [11,12]. In addition, the strategy of the Baltic Sea countries for achieving climate neutrality by 2050 sets out to promote sustainable land management and a gradual transition from fossil to renewable energy sources [13-15].

The main goal of the review is to provide a summary and an assessment of the potential of fast-growing tree species for suitable transformation of agroforestry areas for biomass production in the Baltic Sea region. In Latvia and neighbouring countries, these agroforestry zones have a significant biofuel production, as well as climate change mitigation and nutrient retention potential [32].

The article summarizes the research on the management process of agroforestry zones by establishing short rotation plantations with tree species *Salix* spp., *Populus* spp., *Alnus* spp. and looks at the perspectives in the planning of these zones as biomass producers.

Scope of short rotation tree species in agroforestry

Agroforestry is an ancient agricultural practice that is widely implemented in the EU countries [16-18]. In the EU agroforestry research has begun in the 1980s, focusing on coastal buffer zones and other landscape features designed to reduce pollution in watercourses and to produce biomass for energy at the same time [19, 20]. Over the next 30 years, in-depth studies were conducted on the effects of agroforestry zones on nitrogen (N) [21, 22], phosphorus (P) [23, 24] and various other pollutants. About 30–99% of nitrate (NO_3^-) and 20–100% of phosphorus (P) from runoff and shallow groundwater are retained in coastal agroforestry zones [25], this regards also to production of biomass from there [1, 3, 5, 26-30].

Recent studies in the EU confirm that agroforestry zones on agricultural land protect surface water quality, as well as reduce soil erosion and diffuse pollution [1,3,5, 26, 27,29, 30,31,32]. Agroforestry zones also play a key role in nature protection and flood risk reduction, as well as in the design of climate-resilient bioenergy measures, the effects of intensive agricultural and policy pressures on the environment [31].

In the EU countries economic agroforestry zones are common, but the growing demand for bioenergy and agricultural products requires to establish even more of them[1, 3, 5, 26, 27, 29, 30, 31, 32].

Land use is much more important in determining hydrology of the catchment area than soil type: agroforestry protection zones have a significantly higher infiltration capacity than fields or pastures [3].

Agroforestry zones as shelter belts are also very effective in removing pesticides and preserving biodiversity of agricultural land and have a high potential for fuel, feed or fibre production [33, 3].

The EU Water Framework Directive (Directive 2000/60/EC) calls for good ecological status of waters and to reduce pollution by 2027 at the latest [35]. Along with rising energy prices, future fossil fuel shortages and impending climate change are also driving new measures that combine environmental protection with energy production and carbon sequestration to mitigate climate change [36, 37]. One way of tackling this problem is to re-evaluate agricultural systems in the combined food and bioenergy production process [35]. Specially planned and designed agroforestry zones reduce nutrient losses and retain pesticides from agricultural land, regulate water cycles, reduce the risk of floods, increase carbon sequestration and reduce greenhouse gas emissions, as well as secure energy production from agriculture [27].

Legislation of the Baltic Sea region countries allows that woody biomass can be grown on agricultural land as short rotation plantations , as agriculture or plantation forests [37, 38, 39, 40]. The maximum growing period for short rotation plantations as agriculture is 15 years, after which the plantations are restored or the land is used to grow other crops [38]. Natural forest grown on agricultural land can be registered as a plantation, if it does not exceed age of 20The term “fast-growing tree plantations” in practice is used for both land uses – agriculture as long term plantations of single-age fast-growing tree species (willow, aspen hybrids, Grey alder), grown as a short rotation tree plantation for 15 years, as well afforested land – plantation forest with a maximum single rotation period $\leq$ 20 years. When trees are grown together with grasses or other crops, it is considered an agroforestry system, but depending on the number of trees planted, it could correspond to both agriculture and forest land [38].

For economic agroforestry zones, fast-growing tree species are recommended as biomass producers, according to the terms of the Baltic Sea region countries, including Latvian regulatory enactments for tree plantations and short rotation coppice, which refers to cultivation of trees on agricultural land [38]. The EU Regulation refers to the term agroforestry system, defined as a land use system in which trees are grown on agricultural land [15, 28].

Tree , shrub and crop in short rotation agroforestry

Short rotation forestry (SRF) with a combination of species and a rotation time of 15 to 30 years, depending on the species used, is the most suitable way for management of economic agroforestry zones [26, 41, 42, 43]. Short rotation coppice(SRC) is suitable for willows (*Salix* spp.) and poplars (*Populus* spp.) as these tree species can be harvested at much shorter intervals - 1–5 or 4–10 years, facilitating their use in agricultural systems [40, 42, 43].

For tree species such as Grey alder (*Alnus incana*) and Black alder (*Alnus glutinosa* L.) the harvesting intervals of short rotation coppice is approx. 15-25 years [44, 45, 46, 47, 48, 49,]. Production studies on alder plantations indicate that the potential for biomass production is similar to poplar (*Populus* spp.) and willow (*Salix* spp.) [42, 43, 50, 51].

Suitable species such as *Salix* spp., *Populus* spp. can be renewed with coppice 2–3 times until the shoots run out or yields are significantly reduced [42, 52, 53, 54, 55]. Assuming that most of short rotation coppice (*Salix* spp., *Populus* spp.) will be planted on fertile soils with high nutrient potential as well as successful species combination and growth conditions, the calculated annual DM yield estimate on average per unit area is 5–8 t ha^{-1} (6–18 m^3 ha^{-1}) by SRF and up to 16 t ha^{-1} (39 m^3 ha^{-1}) in willow/poplar short rotation coppice [42].

Scientists have evaluated the maximum biomass production potential for short rotation plantations and short rotation coppice tree species in European countries [3, 56]. The highest yield in short-rotation plantations is expected from Poplar hybrids, which produce 16 t DM ha^{-1}, followed by *Salix* spp., which annually produces 14 DM t ha^{-1}, hybrid aspen with a yield of 10.3 t DM $ha^{-1}$and Grey alder - 9.7 t DM ha^{-1} [3, 56, 57]. This biomass production potential is also similar to area of economic agroforestry zones with similar soil conditions.

Model of economic agroforestry zone vis a vis shelter belt agroforestry

It is determined that in the economic agroforestry zones, which serve as shelter belts, willows can be planted alone as a low protection zone or on the ditch ramp in the protection zones of larger trees, to allow movement around the ditch area without cutting large trees, as well as rows of larger trees on the wind side, to lift wind flows over the tops of trees and prevent wind damages [3].

Within the scope of the study, Latvian scientists recommended the agroforestry zone as shelter belts marked on agricultural lands as 15 m wide strips along the ditch area on both sides of the ditch (Figure 1).

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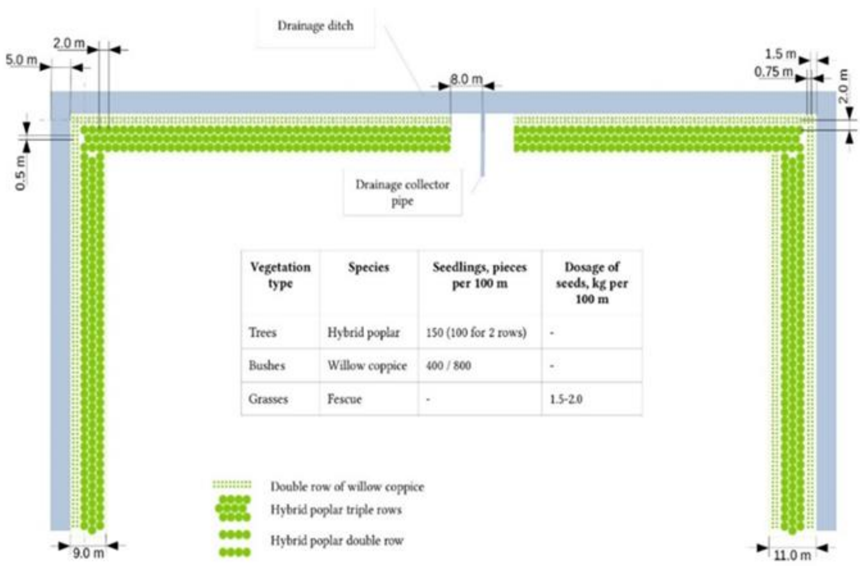

Figure 1. Principal scheme of a shelter belt.

Research shows, that in agroforestry zones as shelter belts with a width of 15 m, willows could be planted in a double row along the edge of the shelter belt, but Grey alder seedlings in rows of 1–1.5 × 2.5 m, but fast growing breeds of *Poplar* spp., *Alder* spp. – in rows of 1x2.5 m [58].

The length of a rotation cycle is 15–20 years. The rotation period of willow plantations is 2–5 years (5–7 production cycles) to produce wood chips and 6–15 years to produce firewood [42, 43, 59]. Willows can be used to make firewood, wood chips, pellets and charcoal [42, 43, 59].The life cycle of *Populus* spp., including aspen hybrids is 15–30 years, whereas in energy wood plantations the life cycle is 15 years [52, 53, 54, 55, 60, 61, 62, 63].The number of rotation cycles is 1–3. When the purpose of growing a hybrid aspen plantation is to produce energy wood, the first felling can be done earlier (in about 10 years) and then managed as a coppice [56,61, 62, 63]. Life cycle of *Alder spp*. is 15-30 years, in energy wood plantations the life cycle is 15 years [45, 46, 47, 48, 49, 64, 65].

During the first years, in plantations of *Populus* spp., *Alnus* spp. the line spacing can be used to grow other crops, including agricultural crops [66, 67, 68, 69], to make the most efficient use of land and additional profits. Barley, clover, oats, rye, wheat, corn, potatoes and other crops can be grown between the rows of poplars [67]. Cultivation of these crops reduces growth of vegetation and forms green manure. The poplar crowns later joins, limiting the availability of light, water and nutrients to these crops [69].

The task of sowing grass is to provide income in the first years after the establishment of a tree plantation. The design of the tree plantation provided that the area can be used as efficiently as possible until the tree crowns closed [68, 70].

The biomass productivity of woody plants in SRC and SRF for producing biomass is summarized in Table 1.

Table 1. Biomass extraction potential from tree species suitable for SRF and SRC in Latvia.

Species	Latin name	Duration of rotation, years	Average annual growth, DM t ha^{-1}	Stock produced per year	Stock produced in 5 years, willow, poplar; 10–25 years, aspen hybrids
Willow hybrids	*Salix viminalis* L. based and other hybrids	1–5	8–12	30–36 m^3 ha^{-1}; 75–90 bulk m^3 ha^{-1}	50–60 m^3 ha^{-1}; 125–150 bulk m^3 ha^{-1}
Aspen hybrids	*Populus tremula* L. based	10–25	23	15–20 m^3 ha^{-1}	200–400 m^3 ha^{-1}
Poplar hybrids	*Populus deltoides* L. based and other hybrids	3–5	7	5–9 t ha^{-1}; 9–16 m^3 ha^{-1}	20–45 t ha^{-1}; 36–80 m^3 ha^{-1}
Grey alder	*Alnus incana* L.	5–15	3.4–5.5	11.8 m^3 ha^{-1}	178 m^3 ha^{-1}
Black alder	*Alnus glutinosa* L.	15–20	15.5	19–26 m^3 ha^{-1}	249 m^3 ha^{-1}

Studies have shown that for the climate of the Baltic Sea region, the most suitable tree species as a biomass producers are *Salix* spp., *Populus* spp and *Alnus* spp, if they are established and managed as short-rotation plantations [28, 42, 43, 71, 72, 73, 74]. The average annual growth of willow biomass is 8 t DM ha^{-1} per year [42]. In Sweden, the average yield is 7–20 tons of dry matter per ha [29] and in Poland – 7–12 tons of dry matter per ha; in Germany: 6–14 t DM ha^{-1}; in Latvia 8–12 tons of dry matter per ha [43].

In order to produce as much biomass as possible in a short period of time, in economic agroforestry zones poplars are recommended to be grown in short rotation (3–5 years) plantations and plantations regenerated with coppice [42, 43]. The length of a rotation cycle is 20–30 years [29, 42, 43]. After 20–30 years, the plantations are replanted or the species is replaced. The recommended number of rotation cycles is 3–4. At the end of rotation period, the growing stock reaches 20–45 t ha^{-1} of naturally wet wood [29, 42]. The average annual increase in biomass in Europe for poplars varies from 2 to 13.5 t ha^{-1} [29, 42].

The growing stock of hybrid aspen plantation with the initial density of 1,100 trees per hectare at the age of 8 years reaches 50 m^3 ha^{-1}, but, if the initial density is 2,500 trees per hectare, at the age of 10 years growing stock reaches 200 m^3 ha^{-1}, whereas in 15 years it is 230 m^3 ha^{-1} and in 20–25 years – 300–400 m^3 ha^{-1} [63].

Research shows that in the climatic zone of the Baltic Sea countries - - Sweden, Estonia, Latvia, Lithuania etc. *Alnus* spp. trees are suitable for producing biomass by energy wood production [3, 44, 48, 49, 57, 64]. Scientists from Sweden and Finland demonstrated that Grey alder plantations have the highest biomass yields – 17 t DM ha^{-1} annually [74]. In Latvian climatic conditions the growing stock of Grey alder in 5-year-old stands, depending on soil fertility and stand density, is 8–32 m^3 ha^{-1} (20–97.5 m^3 of wood chips), in 10-year old stands it is 20–102 m^3 ha^{-1} (50–255 m^3 of wood chips) and in 15-year old stands - 34–178 m^3 ha^{-1} (85–445 m^3 of wood chips) [64, 75,76,].

In the Northern Europe, the Netherlands, Estonia and other countries black alder is considered a major producer of biomass [56, 57, 71]. Estonian scientists have found that the surface biomass produced by Black alder at 21 years of age can reach 88.8 t DM ha^{-1}, giving an annual biomass production of 17.1 t DM ha^{-1} [57, 74]. In Sweden Black alder is found to be able to produce 152.3 ± 7.7 t of dry matter ha^{-1} at the ages of 21 to 91 [44].

In Latvian climatic conditions the growing stock in **Black alder** plantations at the age of 15 years reaches up to 249 m^3 ha^{-1}, if 2–3 root offshoots have been left near the trunk during the early tending , but at the age of maturity growing stock reaches up to 400 m3 ha^{-1}[48, 76].

In order to maximize the use of the area of economic agroforestry zone, in many European countries herbaceous plants are grown in the rows of tree plantations for several purposes, e.g. on food and feed supply and nitrogen balance and were considered focusing on: a) landscape aesthetics and biodiversity b) groundwater protection, c) maintaining current food and feed production, or d) on site carbon sequestration [71, 73].

The study evaluated 3 different herb mixtures, including a community dominated by nectar plants, a community of fodder herbs and an industrial herb community. All herb communities evaluated in the study are universal and can be used in different types of agricultural soils [67,69].

It should be noted that the grass community can only be transplanted at the same time, when the economic agroforestry zone is replanted; therefore, it must be taken into account that in a few years a new community of undergrowth vegetation will replace the sown crop. The composition and productivity of the undergrowth vegetation is determined by growth conditions and the design of the economic agroforestry zone. The herb communities proposed according to an earlier study [69] are described in Table 2.

Table 2. Proposed grass mixtures in the shelter belts of hybrid aspen, poplar hybrids, Grey alder and Black alder.

No	Explanation	Community of nectar plants	Fodder grass community	Industrial grass community
1	Herbaceous species	*Trifolium pratense, T. repens, T. hybridum, Lotus corniculatus, Trifolium incarnatum, Melilotus albus, M. officinalis, Festuca ovina, F. pratensis*	*Lolium multiflorum, L. perenne; Festulolium, Festuca pratensis, Phleum pratense, Trifolium pratense, T. repens, Medicago sativa/ varia*	*Lolium multiflorum, Festuca arundinacea, F. pratensis, Festuca rubra; Phleum pratense; Alopecurus pratensis*
2	Rotation cycle length	5–6 years	4–5 years	5–7 years
3	Number of rotations recommended prior to change of species	1	1	Can be sown repeatedly
4	Above- and below-ground biomass	Increase of above-ground biomass 5–6 t DM ha^{-1}; below-ground biomass is about 50% of the total plant biomass	Increase in above-ground biomass 8–10 t DM ha^{-1}; below-ground biomass is about 50% of the total plant biomass	Increase in above-ground biomass is 5–12 t DM ha^{-1}, depending on growing conditions and lawn mowing regime

Perennial grasslands have a potential to produce bioenergy in temperate climate, given their growing conditions, productivity, biomass quality and productive longevity. To help to achieve these goals, a study was conducted on growth potential of the grass *Phalaris arundinacea* L., as well as hybrid grasses (× *Festulolium*)and trees, using biogas digestate and wood ash as fertilizers [67].

Economic viability of the economic agroforestry zones in the Countries of Baltic Sea region

A number of measures are affecting results of establishment and management of the economic agroforestry zone: site evaluation (soil properties, moisture regime), overgrowth removal, soil preparation before planting, use of fertilizers, quality and delivery of planting material, planting, early tending and following management activities, biomass extraction and regeneration of the agroforestry zone.

Soil preparation costs before planting are similar for all tree species. Data for the cost calculations are taken from Latvian Rural Advisory and Training Centre agriculture service costs database and represents the situation in 2021 [77]. Soil preparation costs are the following – ovegrowth removal (300 EUR ha^{-1}), herbicide costs (24 EUR ha^{-1}), fertilizers costs (173 EUR ha^{-1}), plowing (55 EUR ha^{-1}), herbicide transport (18 EUR ha^{-1}), herbicide spraying (23 EUR ha^{-1}), discing (40 EUR ha^{-1}), cultivation (33 EUR ha^{-1}), fertilizer transport (18 EUR ha^{-1}) and fertilizer spreading (19 EUR ha^{-1}), in total 701 EUR ha^{-1}.

Due to the increase in fuel prices by 26.6%, the average consumer price index increased by 8.7% leading to an increase of the total costs [78]. The cost of soil preparation is 762 EUR ha^{-1}. It should be noted that due to continuously rising fuel prices in 2022, soil preparation costs may be significantly higher at the end of 2022 and in 2023.

The area is marked according to a previously elaborated design and planted after soil preparation. Planting cost includes planting material and planting, as well as seeds and sowing. Assuming that an agroforestry zone consists of willows, on average 13,000 seedlings are necessary per hectare, which is the optimal number of seedlings in Latvia. The total cost of establishment of one hectare of willow plantations is 1,060 EUR, of which 845 EUR (75%) is the price for planting material and 215 EUR (25%) is the price for planting. Cuttings of selected willow varieties are used as planting material, while planting is carried out using a planting machine. Prices of cuttings and planting costs are provided by the by harvesting every 4th to 6th year and fertilizers are used only during the establishment of the agroforestry zone.

Willow in agroforestry zones should be managed intensively by harvesting every 3rd year and fertilizers should be used after every harvest, while it is not mandatory in agroforestry zones, which receive nutrients from surrounding cropland. The main objective of agroforestry zones is water protection by retaining nutrients and biomass production as added value, therefore the buffer zones should be managed extensively. In agroforestry zones surrounding agricultural lands additional fertilization is not crucial and even may be avoided to reduce nutrient leakage to water bodies.

The mechanized harvesting method of willow SRC uses self-propelled shredders, where mowing is carried out simultaneously with chipping, while biomass is loaded into the supply tractor. The supplied biomass is stored for some time in open piles at the edge of the field to dry before further transportation. Manual harvesting can be used to produce willow cuttings or firewood from larger shoots, while this method is very expensive considering the small dimensions of trees. Transportation of biomass to a roadside is performed by a middle- or compact-class forest forwarder or a suitable agricultural tractor with a trailer adapted to transport long shoots. In case of chip production stems are comminuted after a certain drying period with mobile chippers. Biomass can be delivered to customers using tractors or chip trucks (load size up to 90 m^3 in Latvia).

The cost of mechanized willow harvesting is around 3.00 EUR bulk m^3, while manual harvesting using chainsaw costs 4.19 EUR bulk m^3, which is by 43% more (Makovskis, 2021). The mechanized willow harvesting method is used in plantations with a total continuous area of at least 5 ha [43]. Therefore, in an extensively managed economic agroforestry zone manual harvesting method may be considered as a viable alternative to mechanized harvesting, especially because whole stem harvesting permits drying of biomass in contrast to instant chipping with self-propelled harvesters [30]. In the extensive model the average increment corresponds to 54 bulk m^3 ha^{-1} of wood chips [30]. Assuming that harvesting takes place once every 4 years, the total amount of wood chips per rotation corresponds to 216 bulk m^3 ha^{-1}. In case of 6 harvests before the regeneration of an agroforestry zone, where the total output of wood chips is 1296 bulk m^3 ha^{-1}, the wood chip selling price is 9.4 EUR bulk m^3 [78]. Under such condition repayment period of a shelter belt is about 10 years, however, a significant increase of forest biofuel leads to higher economic efficiency of the agroforestry zone.

Aspen hybrids are suitable for short-rotation biomass production, because they demonstrate good growth rates during early development. Planting of aspen hybrids in economic agroforestry zone are recommended, if simultaneous cultivation of trees and grasses during certain period of time is envisaged. These agroforestry zones can be harvested after 15 years and replanted after 30 years [63]. For the first 5 years grasses can be mowed and seeds sold. After harvest, main timber products are pulp wood, firewood and wood chips. The calculated agroforestry zone repayment period is about 15 years, if costs and prices of 2021 are used.

In Grey alder plantations duration of a rotation of the SRC for energy wood production is assumed to be 15 years (2 rotations) and the total life span is 30 years. Then the plantation should be restored [30]. Such plantations are managed for production of wood chips. Studies show that it is recommened to keep Grey alder in places, where it has already grown. In this case it is not necessary to purchase and plant seedlings, which significantly improves the economic return of the short rotation plantation of grey alder [30].

Planting of Black alder (*Alnus glutinosa* L.) as a short rotation crop is recommended in economic agroforestry zones with a 30–40 years long rotation period. Plantation is managed for 1 rotation, after which the plantation should be restored [30]. The obtainable products are sawlogs, firewood and wood chips.

CONCLUSIONS

The summary of researches shows that in the Baltic region, it is possible to create economically efficient biomass production factories by properly setting up and managing short-rotation tree plantations. Earlier studies prove that SRC with a life cycle of 15–20 years is recommended for willow (*Salix* spp.) as biomass crop in economic agroforestry zones. The recommended rotation period of willow SRC is 2–5 years (5–7 production cycles per a life cycle) for production of wood chips and 6–15 years for production of firewood. The willows can be used to make firewood, wood chips, pellets and charcoal.

In poplar plantations (SRF) as a biomass producers in economic agroforestry zones the recommended rotation cycle is 20–30 years. The recommended number of rotation cycles is 3–4. After 60-80 years, the plantations should be replanted also considering use of other species.

The recommended life cycle of hybrid aspen in the SRF is 15–30 years, while for energy wood production the life cycle is much shorter – 15 years. The number of rotation cycles per life cycle is 1–3. If the purpose of establishment of the plantation is to produce energy wood, then the first harvest can be done earlier (in about 10 years) and then the plantation can be managed as SRC.

In the Grey alder plantation the life cycle of SRC for energy wood production is assumed to be 15 years (the plantation is managed in 2 rotations) and the total life span is 30 years, after which the plantation should be restored. The plantations are managed to produce wood chips; while it is not an economically viable solution.

The Black alder plantation is managed for sawlog and firewood production with a life span of 20–40 years, after which it can be managed as a SRC or SRF.

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