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13 years of biomass production from three poplar clones in a temperate short-rotation alley cropping agroforestry system

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ABSTRACT

Farmers' interest in establishing agroforestry systems is increasing, as they are considered to have many benefits, such as the possibility of climate adaptation and crop diversification. Growing wood on agricultural land can produce biomass for energy or material purpose. Knowledge of the yield potential of the woody component in an agroforestry system is essential for informed decision making by farmers. The present study investigates the biomass production of the three poplar clones 'Max 1′, 'Koreana' and 'Hybride 275′ during the first 13 years (2008–2021) of their growth in a short rotation alley-cropping agroforestry system in Lower Saxony, Germany, on a vertic cambisol as well as a stagnosol soil. There was a high clonal effect on re-sprouting and mortality of the trees as well as on the mean annual dry matter (DM) woody biomass increment (MAI). Overall, 'Max 1′ showed highest re-sprouting, lowest mortality and highest MAI compared to the clones 'Hybride 275′ and 'Koreana'. The MAI of the three poplar clones was not affected by the rotation length of 3 or 6 years. Over the period of 13 years MAI of 'Max 1′ was 13.3 t Mg ha^{-1} $year^{-1}$ DM, whereas that of 'Hybride 275′ and 'Koreana' was 10.2 and 9.8 t Mg ha^{-1} $year^{-1}$ DM, respectively. The MAI was significantly determined by the factor harvest year. A low MAI was found for the 3-year rotation cycle in 2021, which was most possibly caused by drier and warmer than average vegetation periods in 2018–2020. Under the given site conditions, clone 'Max 1′ proved to be the most productive.

1. Introduction

The increasing concerns about global change and the limited fossil fuel resources have led to more attention being paid to renewable energy sources such as biofuels. Their use is known to reduce greenhouse gas emissions and fossil fuel dependence, and to improve energy resource diversification [1–3]. Besides wind, solar and hydropower, the use of biomass from agriculture and forestry to generate electricity, heat and fuels is gaining importance throughout the EU in the effort to diversify energy supply. In the long term, demand for renewable energy sources is increasing to meet energy needs and limit the environmental impact of fossil fuels, such as the increasing concentration of atmospheric carbon dioxide (CO_2), which contributes to climate change [3]. Agroforestry as a sustainable agricultural land use system has attracted increasing interest in recent years because it combines the production of woody biomass with agricultural crops, where the different plant parts of the woody component can be used as food (fruits and nuts), feed, renewable material or renewable energy. In short rotation alley cropping systems (SRAC), a form of agroforestry, woody biomass can be produced for biofuels. These systems have the potential to reduce atmospheric carbon (C) by storing it in above- and below-ground biomass, soil, and humus, by reducing CO_2 emissions due to changes in management (e.g., reduced use of fertilizers or agrochemicals) and by replacing fossil fuels [4,5]. In the EU-27, about 358.000 ha are used for different forms of arable agroforestry [6] with *Populus* sp. and *Salix* sp. being suitable species in SRC systems [7]. These species are fast-growing and capable of re-growing multiple shoots after being coppiced (re-sprouting). The woody biomass of poplar species is mainly used as energy biomass, which can be excellently processed into wood chips with good combustion properties due to its relatively high lignocellulosic content, low ash and extractives contents [8,9].

In SRAC systems with poplars for energy use, trees are harvested every two-three to five-six years for a total period of cultivation of 15–25 years [10]. Therefore, rotation length may significantly affect annual yields of the perennial woody biomass [11] and has to be taken into account when planning an agroforestry system. Rotation length can

Abbreviations: MAI, Mean annual increase; SRAC, Short-rotation alley cropping system.

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affect the sustainability of an SRAC due to tree mortality or reduced re-sprouting ability after harvest, e.g., caused by diseases or damages during machinery harvest [12,13]. Woody biomass growth is not constant over the tree's lifespan; the time at which trees reach their maximum growth depends on the species and clone due to differences in growth pattern. Site conditions largely determine the optimal growth of poplar trees, with a good water availability being among the most important prerequisites [14,15]. Depending on planting density the mean annual dry matter (DM) increment of poplars in short rotation coppices in Europe ranges between 1 and 38 Mg ha^{-1} year^{-1} DM, with the highest yields under Mediterranean conditions, though these are highly dependent on irrigation [16]. In Germany, the reported annual biomass increment ranges widely from 1 to 11.5 Mg ha^{-1} year^{-1} DM [16,17] depending on the above mentioned conditions. Higher yields, such as those achieved in the Mediterranean, cannot be reached in Germany due to the cooler climate [17].

For short-rotation poplar cultivation to be profitable, the right choice of variety is essential, as there is a high clonal variation in biomass production, resistance to diseases or survival, as variety tests demonstrate [17]. The choice of parental species combination has a strong effect on biomass production, for example hybrids using *P. maximowiczii* as a parent show a good performance under many site conditions [18–20]. Mortality and the ability of re-sprouting, i.e. to re-grow a number of shoots, after coppicing are important clone-specific traits [21], both of which influence woody biomass production in short rotation systems. Further, genotype or clone selection is essential to optimize yields across environmental gradients [20,22]. This can be attributed to the fact that *Populus* species, including hybrid poplars, exhibit a wide range in functional traits such as cold and drought tolerance and chemical defense against insect herbivores [23,24].

Data published to date on biomass yield of fast growing poplars are mainly from early stage agroforestry systems in the temperate zone. Data from mature systems are lacking, but are of great interest for research (e.g. for modelling, economic or socio-economic studies) as well as for practice, consulting, and politics. Establishing agroforestry systems with fast-growing poplars is expensive and labor-intensive, and for these systems to be profitable they must be managed for a period of 20–30 years. The data presented here from a mature agroforestry system could be of relevance to the planning and management of an alley cropping system. This study aimed to examine mean annual increment, re-sprouting ability and mortality of three commercially available poplar clones at a short-rotation alley cropping agroforestry site in northern Germany after the first 13 years of establishment. The effects of clone, rotation length, waterlogging tendency of the soil and harvest year on these parameters were analyzed.

2. Materials and methods

2.1. Experimental site, setup and climatic conditions

The study was conducted on a short rotation alley cropping system, established in 2008 on a clay Vertic Cambisol and Stagnosol soil in Northern Germany at Wendhausen (North 52° 19′ 54″, East 10° 37′ 52″), located directly northeast of the Braunschweig city border. The site is located at a mean elevation of 85 m above sea level. The alley cropping system consisted of nine 225 × 12 m tree rows that were planted by hand from cuttings in 2008 in a north-south orientation (Fig. 1). In the tree rows, the three commercially available fast growing poplar clones 'Max 1' (*Populus maximowiczii* × *P. nigra* L.), 'Hybride 275' (*P. maximowiczii* × *P. trichocarpa)* and 'Koreana' (*P. koreana* × *P. trichocarpa*) were

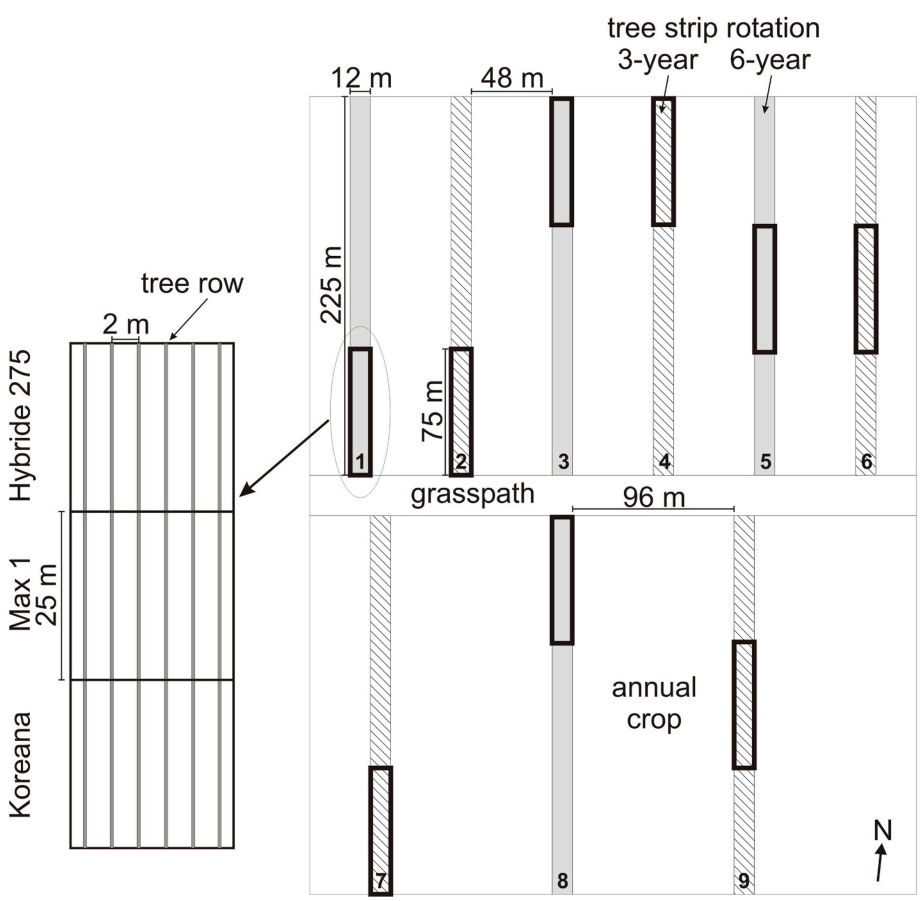

Fig. 1. Overview of the short-rotation alley cropping agroforestry system at Wendhausen. Black boxes represent harvested areas of the tree strips. Tree strips 1, 2 and 7: stagnosol soil; tree strips 3–6, 8 and 9: vertic cambisol soil.

arranged in sections of 25 m length each with a density of 10,000 trees per hectare (0.5 m × 2 m). Poplars were grown for energy woody biomass production and harvested in a 3-year or 6-year rotation cycle. Tree rows were separated by 48 or 96 m wide crop alleys of annual summer or winter crops. Crop alleys were managed site-specific with regular management such as tillage and application of fertilizer and plant protection products. Tree strips were not fertilized, however, it cannot be excluded that the outer tree rows benefited from the fertilizer applied to the crop alleys. This was not tested. The area is slightly sloping from east to west (difference in mean elevation about 5 m). The main part of the experimental site is dominated by vertic cambisol soil (tree strips 3–6, 8 and 9, Fig. 1), which is characterized by sporadic waterlogging at 50 cm soil depth, i.e. just at the lower limit of the effective rooting depth, which is 80–100 cm. However, the effect of waterlogging is only weak and can even help to avoid drought stress due to greater moisture in the subsoil. In the western part of the site (tree strips 1, 2 and 7, Fig. 1) Stagnosol soil is found, which is characterized by water-logging from a soil depth of 25 cm. Field work is complicated by long wet periods in the spring.

The site characteristics are therefore influenced by the soil moisture regime. The soils are only slightly susceptible to erosion due to the high clay content and the relatively weak slope inclination.

The climate at the study site is temperate with a long term (1991–2020) mean annual air temperature of 10.0 °C and a mean annual precipitation of 615 mm. The Sum of monthly precipitation (mm) as well as the average monthly air-temperature at Braunschweig during the growing period (April–September) from 2008 to 2020 are shown in Figs. 2 and 3. All weather data were received from the German National Meteorological Service (DWD).

2.2. Biomass harvest and determination of biomass yield

Trees with a 3-year rotation period were harvested in February 2011, January 2014, February 2017 and February 2021. Those with a 6-year rotation period in January 2014 and February 2021. In 2011, 2014 and 2017 harvest was conducted using a short rotation agroforestry chopper. The harvest planned for 2020 had to be postponed to 2021 due to the lack of frost, which is a prerequisite for harvesting with heavy machinery. Therefore, a woodcracker, chainsaws and a drum chipper was used.

In 2014, 2017 and 2021 the chipped wood was weighted to the nearest on a floor scale directly on the field. In the laboratory, a representative sample (300 g, double determination) of the chipped wood (size in the range of 1.5 × 5 cm) of each poplar clone was oven-dried at 60 °C until constant weight to determine the water content. Dry matter (DM) yield was calculated separately for each clone. To calculate the mean annual DM woody biomass increment (Mg ha^{-1} year^{-1} DM), the woody biomass yield of a harvest (Mg ha^{-1} DM) was divided by the years of the rotation length.

For technical reasons, the planned woody biomass yield determination in 2011 was preponed to December 2010, 12 weeks before machine harvesting. For this, eight trees per poplar clone and tree strip (i.e. total of 40 trees per poplar clone) were cut manually and water content and DM yield were measured as described above.

Annual woody biomass estimates were conducted for clone 'Max 1′ for the 2015–2020 growing years for the 6-year rotation of tree strips 3 and 5 (Fig. 1). The dry matter was predicted from diameter at breast heights (DBH) using allometric power equations [25]: DM = α x DBH$^{\beta}$, where DM is the shoot dry mass, α and β calculated regression coefficients. Details on the method are described elsewhere [26].

2.3. Determination of mortality and re-sprouting rates

Between May and July 2021 the mortality rates of trees as well as the re-sprouting rates after the harvest in February 2021 were determined. Therefore, each stool in the harvested areas of tree strips (Fig. 1) was visually checked and either sprouting or failure of sprouting was noted. Rotten tree stumps and missing tree stumps were recorded as dead. Three hundred stumps each per clone and tree strip were checked, i.e. in total 8100 stools were examined. The mortality rate was calculated by dividing the number of dead trees per tree strip by the total number of trees per strip. Re-sprouting rates were calculated by dividing the number of re-sprouting trees by the number of total trees minus the number of dead trees. Mortality described the stools that died in the rotation cycles prior to the harvest in 2021. Re-sprouting represented whether trees survive (re-sprouting) or not (no re-sprouting) and was an indicator of mortality following the harvest in 2021, i.e. after 13 years of growth.

2.4. Data analysis

Statistical analysis was carried out using RStudio [27]. To analyse the effect of rotation, clone and waterlogging tendency on mortality and re-sprouting rates of trees general linear models (GLM) for proportion data were fitted with harvest rotation length (3 or 6 years), clone ('Max 1′, 'Hybride 275′, 'Koreana') as well as waterlogging tendency (yes, no)

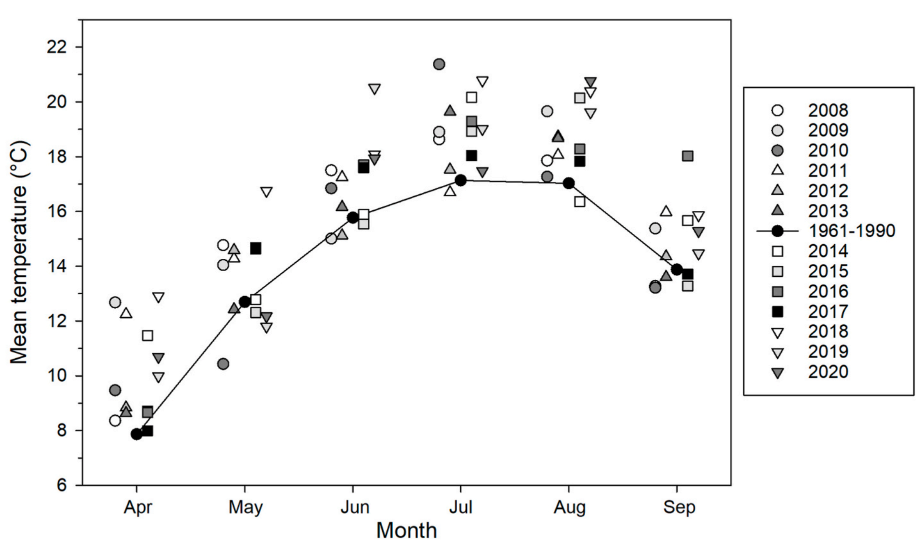

Fig. 2. Sum of monthly precipitation (mm) during the growing period (April–September) from 2008 to 2020 and long term average precipitation sum from the international reference period 1961–1990 at Braunschweig.

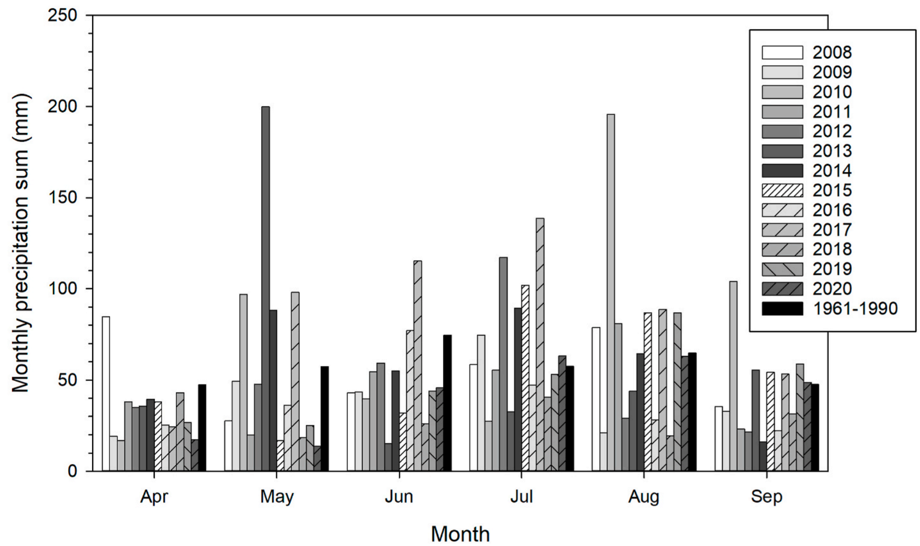

Fig. 3. Monthly average air-temperature (°C) during the growing period (April–September) from 2008 to 2020 and long term average air-temperature from the international reference period 1961–1990 at Braunschweig.

as fixed effects and the tree strip ID (i.e. 1-9, cf. Fig. 1) as random effect using the package glmmTMB [28]. Linear Mixed Effects Models (lme) were applied to analyse the effects of the fixed factors harvest rotation length, clone and their interactions, as well as waterlogging tendency on the annual woody biomass increment by using the nlme package [29]. For all models automated model selection was assessed using the "dredge" function of the MuMIn package [30]. The final models were selected based on the lowest Akaike information criterion (AIC). Subsequent analyses of variance (ANOVA) were followed by post-hoc comparisons of means and multiple contrasts were performed using the emmeans package [31]. Model assumptions were tested graphically for the criteria of normal distribution and variance homogeneity. Significance level for analysis was set at $P < 0.05$.

3. Results

3.1. Re-sprouting rates and mortality of poplar clones

Re-sprouting rates of poplar clones after the harvest in 2021 were explained by the significant interaction of the variables clone, rotation length and waterlogging tendency of the soil. Overall, 'Max 1′ and 'Hybride 275′ showed the highest re-sprouting rates, whereas mean re-sprouting in the clone 'Koreana' was below 60% (Table 1). The rate of re-sprouting in the 'Max 1′ and 'Hybride 275′ clones with different rotation intervals and water-logging tendency of the soil did not differ significantly among each other. With a 3-year rotation interval re-sprouting in 'Max 1′ and 'Hybride 275′ was >72% on both soil types, whereas re-sprouting in 'Koreana' on the low waterlogging soil was lowest, at only 41%.

The mean mortality rates of poplar clones 13 years after planting were 36% for 'Koreana', 15% for 'Hybride 275′ and 9% for 'Max 1'. The mortality rates were explained by poplar clone, but neither by rotation length nor by the waterlogging tendency of the soil. Overall, the three clones differed significantly in their mortality rates, except for 'Max 1′ with 6 year rotation length and 'Hybride 275′ with 3 year rotation. Mortality within clones did not differ significantly by rotation length (Table 2).

3.2. Mean annual woody biomass increment (MAI)

The moisture content of freshly harvested wood chips ranged from 50 to 58%. The mean moisture content for 'Max 1′ was 58, 54, 50 and 53% (2011, 2014, 2017 and 2021, respectively), for 'Koreana' 58, 54, 53, and 51%, (2011, 2014, 2017 and 2021, respectively), and for 'Hybride 275′ 54, 51, 50 and 50% (2011, 2014, 2017 and 2021, respectively). The mean annual dry matter (DM) woody biomass increment (MAI, Mg ha^{-1} year^{-1} DM) was significantly determined by the factors clone ($F = 18.1$, $p < 0.0001$) and harvest year ($F = 20.0$, $p < 0.0001$). Over the total growing period of 13 years, the clone 'Max 1′ showed the significantly highest MAI with 13.3 ± 0.76 SE Mg ha^{-1}

Table 1
Estimated mean re-sprouting rates (%) after the harvest 2021 and standard errors (SE) affected by the interaction of the factors poplar clone × rotation length × water-logging tendency. Means with the same letter are not significantly different ($p < 0.05$).

Water-logging tendency	Clone	Rotation length (years)	Mean re-sprouting rate (%) ± SE
no	'Max 1′	3	81.0 ± 3.4 a
	'Max 1V	6	63.6. ± 5.0 abefik
	'Hybride 275′	3	75.0 ± 4.1 aceg
	'Hybride 275′	6	65.4 ± 4.9 abefik
	'Koreana'	3	58.3 ± 5.4 bdfhijkl
	'Koreana'	6	49.8 ± 5.5 cdghjl
yes	'Max 1′	3	74.9 ± 5.0 abcdefgh
	'Max 1′	6	66.4 ± 8.4 abcdij
	'Hybride 27′5	3	72.4 ± 5.4 abcdefgh
	'Hybride 275′	6	50.0 ± 9.4 abcdefghijkl
	'Koreana'	3	41.1 ± 6.5 ijkl
	'Koreana'	6	41.4 ± 9.3 efghkl

Table 2
Estimated mean mortality rates (%) and standard errors (SE) affected by the factor poplar clone ('Max 1′, 'Hybride 275′ and 'Koreana') across rotations length 13 years after planting. Lowercase letters show significant differences ($p < 0.05$) between the clones within rotation length.

Factor Clone	3-year rotation	6-year rotation
'Max 1′	7.9 ± 0.9 a	10.4 ± 1.3 a
'Hybride 275′	13.2 ± 1.4 b	17.0 ± 1.8 b
'Koreana'	33.1 ± 2.5 c	40.1 ± 3.0 c

year^{-1} DM which is approximately 25% higher than that of the clones ’Hybride 275′ and ’Koreana’ with 10.2 ± 0.76 and 9.8 ± 0.76 SE Mg ha^{-1} year^{-1} DM (Fig. 4). Further, harvest year significantly affected MAI of all three clones with significantly highest increment in 2017 (14.7 ± 0.8 SE Mg ha^{-1} year^{-1} DM) with the harvest of the 3 year rotation length. The harvest years 2011, 2014 and 2021 showed similar MAIs, which were about 33% lower than those in 2017.The length of the rotation (3 or 6 years) did not significantly determine the MAI, nonetheless it is shown in Fig. 5. For all three clones, the MAI of the 3-year rotation peaked in 2017, while the MAI of the 6-year rotation remained constant across both harvest dates (Fig. 5).

The annual woody biomass estimates for clone ’Max 1′ show a steady increase of woody biomass from 2015 to 2020, but with only a small increase in both 2018 and 2019 compared to 2017 and 2020 (Fig. 6). A comparison of estimated and harvested data of clone ’Max 1′ showed that the values of 2020 were 6% overestimated (data not shown).

4. Discussion

4.1. Re-sprouting and mortality of poplars

Both clones with the parental clone *P. maximowiczii*, i.e. ’Max 1′ and ’Hybride 275′, showed highest re-sprouting rates of around 69%, averaged over rotation lengths and waterlogging tendency of the soil. Thereby, the shorter rotation cycle of 3 years tended to reveal higher re-sprouting rates than the 6-year rotation cycle confirming the current recommendation of the breeder Lignovis to use ’Max 1′ in agroforestry systems with short rotation. Especially with good growth, ’Max 1′ clones tend to crown break at longer rotations (M. Weitz, Lignovis, personal communication). Except for ’Koreana’ on soil prone to waterlogging, all hybrids showed lower re-sprouting rates in the 6-year rotation. Vigorous re-sprouting is an important requirement for high yields over the life span of the trees. Low or late re-sprouting can cause stools to be overgrown by weeds leading to competition for light, water, and nutrients [32]. In addition, poplar re-growth can be hindered by oxygen deficiency due to high groundwater or clayey soil substrates [17]. Especially in winter after prolonged humidity or snow melt, water may stand between tree rows at some places at the Wendhausen site due to the high clay content of the soil, which can lead to reduced growth in poplar [33].

The survival rate of poplars in short rotation can be influenced by the clone [34]. Overall, clone ’Max 1′ outperformed ’Hybride 275′ and

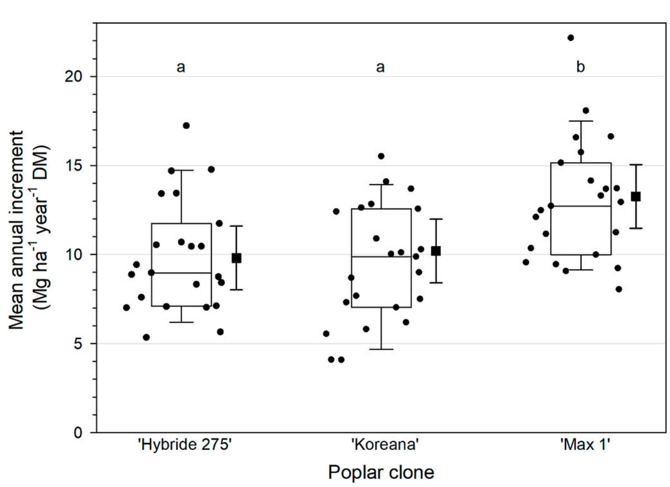

Fig. 4. Estimated mean annual dry matter woody biomass increment (MAI, Mg ha^{-1} year^{-1} DM ± SE) over all harvest years (2011, 2014, 2017, 2021) and rotation lengths (3, 6 years) for the three poplar clones ’Hybride 257′, ’Koreana’ and ’Max 1’. Error bars are the confidence intervals of the candidate model with filled squares as predicted mean values. Lowercase letters show significant differences ($p < 0.05$) between MAI of clones.

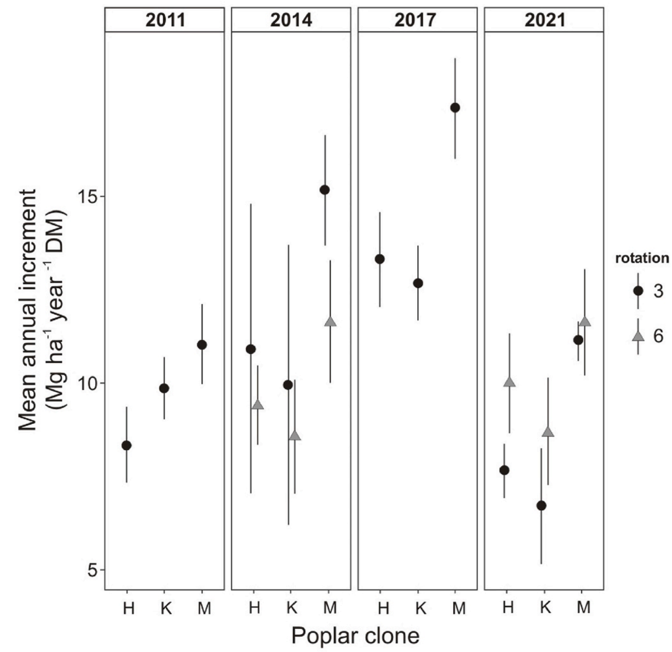

Fig. 5. Mean annual dry matter woody biomass increment (DM Mg ha^{-1} year^{-1} DM ± SE) for the 3-year rotation in 2011, 2014, 2017 and 2021 and the 6-year rotation in 2014 and 2021. H: ’Hybride 257′, K: ’Koreana’, M: ’Max 1’.

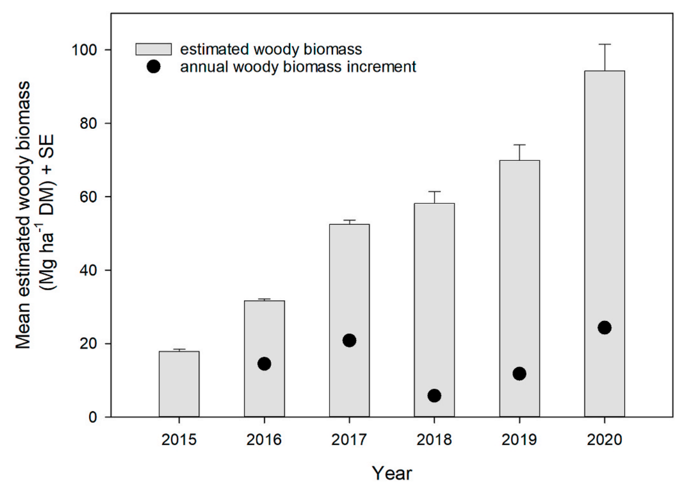

Fig. 6. Mean estimated dry matter woody biomass (Mg ha^{-1} DM ± SE) of the clone ’Max 1′ on tree strips 3 and 5 (cf. Fig. 1) in the years 2015–2020. Filled circles represent the estimated annual dry matter woody biomass increment (Mg ha^{-1} DM ± SE).

’Koreana’ in terms of its low mortality. ’Max 1′ is considered robust and competitive especially in the establishment phase (M. Weitz, Lignovis, personal communication). Also Landgraf et al. [35] reported high survival rates of clone ’Max 1′ in their study of the biomass yield of 37 poplar clones in a short rotation coppice in North Eastern Germany. Survival rates of ’Max 1′ were between 97% and 95% after the first vegetation period and at the time of the first and second harvest (3 year rotation cycles), respectively, whereas other clones showed survival rates between 42 and 53%. Low mortality rates of ’Max 1′ and ’Hybride 275′ after 3 years of growth in northern Germany were reported by Rebola-Lichtenberg et al. [36]. A comparable mortality rate as found in the present study for the clone ’Koreana’ was reported for the clone p-triko-473, like ’Koreana’ a hybrid of *P. trichocarpa* × *P. koreana* [37]. Survival of multiple rotations is an important prerequisite for poplar genotypes used in short rotation coppice systems. Mortality may increase with increasing number of rotation cycles [38]. However, missing trees do not necessarily lead to yield losses. Our field observations indicate that neighboring trees respond with increased growth and more shoots per stool, often filling the gaps left. Greater plant spacing results in a higher number of shoots and allows for greater branch survival [26, 39].

Wood discoloration and signs of wood decay were noticeable after the 2021 harvest. Fruiting bodies of several saprotrophic fungi were found in wood samples. Based on these samples, three pathogens were identified as causative agents of the observed damage (*Cytospora populina, Cadophora spadices, Cytospora chrysosperma*), one weakling pathogen/saprophyte (Chondrostereum purpureum), and two endophytes (*Dichotomopilus funicola*, *Paraphaeosphaeria* cf. *neglecta*) (Enderle and Riebesehl 2021, unpublished). Boring holes corresponding to typical larval galleries of the large poplar borer (*Saperda cacharias*) were noted on the cut surfaces of the stools. It is planned to continue the initial phytopathological studies on the Wendhausen agroforestry site. Unfavorable site conditions, such as waterlogging, can weaken poplars and make them susceptible to diseases [40]. Susceptible poplar clones may have higher mortality and low re-sprouting rates. When establishing an agroforestry system with genetically identical trees from one clone, it should be noted that not only positive but also negative traits, such as susceptibility to certain diseases, affect the entire stand. A mixed cultivation of genetically different clones could counteract mass failure.

4.2. Mean annual woody biomass increment

In the three-year rotation cycle, MAI increased by about 32% from the first to the third rotation. This can be explained by the establishment phase of the trees. After planting, trees in short rotation coppices must first establish a root system, thus they may show lower yields in the first two rotation periods. From the second rotation, the poplar trees benefit from an already established root system [41]. Further, re-sprouting after harvest causes an increase in shoots which, depending on the genotype, consequently leads to an increased mean annual increment [35]. Further, studies indicate a strong relationship between the harvest/-rotation cycle and the productivity of the stand [11]. With very short rotation cycles (1–2 years), harvesting negatively affects aboveground growth [14] and increases stool mortality [11]. However, results of the present study did not indicate a significant impact of rotation length on MAI during the first 13 years of management. Nevertheless, caution should be taken when interpreting our data on harvest year and rotation length and their effect on annual woody biomass increment. Every other harvest year (i.e. 2014, 2021) contained information on two rotation lengths, i.e., when the 6-year rotation was harvested for the first and second time, the 3-year rotation was already harvested for the second and fourth time, respectively. While MAI in the 6-year rotation cycle remained relatively constant over the 13 years period, MAI in the 3-year rotation cycle decreased by 37% from the third to the fourth harvest. This could be due to the age of the trees, as the mean annual increment peaks at a certain tree age, which depends on the tree species and genotype in addition to site conditions [34]. Thus, poplar growth stagnates or declines due to declining vitality and the onset of mortality, both depending on site and genotype [42]. However, biomass yield of the poplar clone ’Max 5′ was not reduced in the third of three consecutive 4-year rotations [43]. Probably, the strong decrease of mean annual increment in 2021 was a consequence of the weather conditions during the fourth rotation period of the 3-year rotation cycle (2017–2021). The years 2018–2020 were special in terms of the combination of temperature and precipitation; they were characterized by too low precipitation and, at the same time, above-average temperatures. There was a sequence of three years in immediate succession that turned out to be considerably too dry and too warm. The annual precipitation totals of 2018, 2019, and 2020 were drier than the long-term average (615 mm) at 380, 578, and 528 mm, respectively. In particular, the spring of 2020 was very low in precipitation, bringing only about half the usual amount of rain. While in 2018 soil water reserves were still well filled at the beginning of the year, in 2019 and 2020 insufficient replenishment of plant-available soil water storage during the non-vegetation period (i.e. October–March) led to early drying of soils in the growing season [44]. Poplars have high transpiration rates and thus depend on an abundant water supply of around 250 mm–300 mm precipitation during the growing season [45,46] with May and June being the most important months [47]. Water availability was the main variable driving biomass production in poplar when impacts of site factors and management intensity on establishment of short rotation coppices were evaluated [15]. In the present study, low annual woody biomass increment of clone ’Max 1′ was observed in both 2018 and 2019. This suggests that water deficiency may be the reason for low MAIs in the fourth rotation cycle of the 3-year rotation.

Regardless of rotation length and harvest year, we found significant differences of MAI among the three poplar clones, with highest increment found in clone ’Max 1’. In terms of re-sprouting and mortality, ’Max 1′ was also superior to clones ’Hybride 275′ and ’Koreana’ in our study. Earlier studies found clone ’Max 1′ exhibiting high yields along a wide range of site conditions, e.g. in riparian buffer strips [18] or in rotations of 2–5 years even on less favorable warmer sites [48]. In contrast, a study on the yield potential of several fast-growing trees in short-rotation plantations at different experimental sites in Brandenburg, Germany, showed that ’Hybride 275′ and several ’Max’ clones (’Max 1′ was not tested) produced the highest yields in the first two rotation periods of three years each [49]. The choice of the species-hybrid combination has a very strong impact on biomass production [19]. A comparative study of the genetic variation and production potential of 36 poplar clones with a rotation length of 5 and 13 years found highest mean annual increment of woody biomass for the poplar clone ’Hybride 275′, which was similar to that found in our study. ’Max 1′ produced only 5.6 t DM ha^{-1} $year^{-1}$, demonstrating the impact of the wide range of site and climate characteristics of the studies and the differences in plant density [19]. Truax et al. [20] showed that unrelated poplar clones respond differently to environmental gradients. In their study, they described elevation and soil fertility being the most important factors determining yield of an 8 year-old hybrid poplar plantation. However, also clone selection, although secondary, also optimised biomass production along environmental gradients. *P. maximowiczii* hybrids had the potential to produce high yields on fertile sites located at lower and higher elevations with different climatic conditions.

5. Conclusions

We found a high clonal effect on re-sprouting, mortality as well as on mean annual increment (MAI) of the three poplar clones. Clone ’Max 1′ performed best on a 3 or 6 year rotation cycle compared to the clones ’Hybride 275′ and ’Koreana’. The MAI of the three poplar clones was not affected by rotation length (3 or 6 years). Thus, biomass of the clones ’Max 1′, ’Hybride 275′ and ’Koreana’ may be used flexible in between a rotation cycle of 3–6 years. Harvest year significantly affected MAI. Low MAI in the 3-year rotation cycle in 2021 may have been caused by drier than average vegetation periods in 2018–2020, confirming the sensitivity of poplars to changing hydrologic conditions. At least in the first 13 years of cultivation, clone ’Max 1′ would be the first choice for sites with comparable growing conditions in temperate zones. However, a final evaluation can only be made in about 10–15 years, when the end of the cultivation period of this experimental agroforestry system is reached.

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Declaration of competing interest

The authors have no competing interests to declare.

Data availability

Data will be made available on request.

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