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Yield Performance of Woody Crops on Marginal Agricultural Land in Latvia, Spain and Ukraine

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Abstract: Agricultural land abandonment due to biophysical and socioeconomic constraints is increasing across Europe. Meanwhile there is also an increase in bioenergy demand. This study assessed woody crop performance on several relevant types of marginal agricultural land in Europe, based on field experiments in Latvia, Spain and Ukraine. In Latvia, hybrid aspen was more productive than birch and alder species, and after eight years produced 4.8 Mg ha^{-1} y^{-1} on stony soil with sandy loam texture, when best clone and treatment combination was selected. In Spain, Siberian elm produced up to 7.1 Mg ha^{-1} y^{-1} on stony, sandy soil with low organic carbon content after three triennial rotations. In Ukraine, willow plantations produced a maximum of 10.8 Mg ha^{-1} y^{-1} on a soil with low soil organic carbon after second triennial rotation. The productivity was higher when management practices were optimized specifically to address the limiting factors of a site. Longer rotations and lower biomass yields compared to high-value land can be expected when woody crops are grown on similar marginal agricultural land shown in this study. Future studies should start here and investigate to what extent woody crops can contribute to rural development under these conditions.

Keywords: abandoned agricultural land; bioeconomy; bioenergy; biophysical constraints; birch; black alder; hybrid aspen; short-rotation forestry; Siberian elm; willow

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1. Introduction

An increase in abandoned and marginal agricultural land area can be observed in most parts of Europe [1,2]. In a large portion of Eastern Europe, land abandonment is driven by socioeconomic factors, where landowners are often absent or uninterested in pursuing conventional agronomical practices [3]. However, biophysical constraints and inappropriate land management leading to degradation of the land are the main reasons for land abandonment [4]. Such land is often referred to as marginal. Passive restoration processes and natural succession happens on the abandoned land, if it is left unmanaged. The succession and ecological value of the land can be very diverse depending on a wide range of site conditions [5]. In cases where the natural vegetation cover development is impeded by biophysical constraints or if there is a high risk of colonization by invasive species, active restoration may be more suitable [6,7]. Such abandoned and marginal areas could be purposefully utilized for tree plantations or woody crops and contribute to meeting the bioenergy demand that is increasing throughout Europe [8]. Despite demand for bioenergy being expected to rise and that solid biomass already makes up about half of renewable energy sources, energy crops take up only a small percentage of European land [9–11]. While short- and medium-rotation tree plantations on agricultural land have become common in some countries, there is a lack of knowledge regarding the yields that can be expected from plantations established on unfavorable or marginal land. Knowledge on associations between specific biophysical constraints, species and biomass accumulation is also lacking. This complicates evidence-based decision-making for landowners. When planting woody crops on agricultural land, stakeholders primarily turn to short-rotation poplar and willow plantations, as these are well known for their rapid growth rate and are easy to propagate via cuttings. However *Salicaceae* species are rather water demanding and in areas with arid climatic conditions appropriate species for the region should be favored to avoid irrigation costs [12–14]. Some such species with fast biomass accumulation rates are Siberian Elm (*Ulmus pumila*), Black locust (*Robinia pseudoacacia*) and *Eucalyptus* spp. [15,16]. In addition, species can be selected with intention to alleviate a particular land constraint or to improve a specific ecological function of the land [17–20], thus, (unless established on high nature-value land) ensuring ecosystem services of higher quality than abandoned marginal land or marginal land that is under high input management [21–27].

While there is still ongoing discussion about a common definition of marginality and lack of united marginality factor classification [28–35], the limiting factors are similar across Europe; however, appropriate management practices are specific to each geographic location. The aim of this study was to obtain yield data from field studies carried out on marginal land in Latvia, Ukraine and Spain that represent the three environmental zones of Europe–boreonemoral, Atlantic and Continental. The objectives were to evaluate the survival of plantations on marginal land, and to summarize the yield results from these case study sites in the context of other research carried out on marginal land across Europe.

2. Materials and Methods

2.1. Case Study Sites and Data Collection

Marginal land area was determined using MAGIC-Maps [36]. Local marginality factors were assessed in accordance with Elbersen et al. [37] marginality factor classification thresholds.

Leading marginality factors in the case study countries are mainly associated with adverse climate and low soil fertility and limitations in rooting (Table 1). Adverse climate in Latvia refers to cold winters and short vegetation period (length of growing period $\leq$ 180 days; or degree days $\leq$ 1500 days). In Spain and Ukraine it is associated with the lack of precipitation in some areas (annual precipitation/potential evapotranspiration $\leq$ 0.5).

Table 1. Leading marginality factors affecting countries where case studies were carried out (according to MAGIC-Maps [36,37]).

Country	Leading Marginality Factors	Affected Area (km^2)	Affected Area of Total Utilized Agricultural Area (%)
Latvia	Adverse climate	8980	30
	Excessive wetness	3602	12
	Limitations in rooting	1475	5
	Total:	12,161	41
Spain	Adverse climate	77,490	23
	Limitations in rooting	76,179	22
	Low soil fertility	33,166	10
	Total:	148,496	44
Ukraine	Low soil fertility	37,000	9
	Adverse climate	30,000	7
	Limitations in rooting	29,100	7
	Total:	133,920	31

2.1.1. Latvia

The field experiment was conducted in Skrīveri municipality, Latvia (coordinates can be found in Table 2). Five fast-growing tree species were planted in the spring of 2011: hybrid aspen (*Populus tremula* L. × *P. tremuloides* Michx) clone 4 and clone 28, gray alder (*Alnus incana* (L.) Moench.), black alder (*Alnus glutinosa* (L.) Gaertn.), hybrid alder (*A. incana* × *A. glutinosa*) and birch (*Betula pendula* Roth) grown in different nursery containers—type 1 (Lannen Plantek 35F) and type 2 (Rootrainers Sherwood). Hybrid aspen clones were grown in three densities, with 2 × 2 m, 3 × 3 m and 2.5 × 5 m distance between trees (planting density of 2500, 1273 and 1227 trees ha^{-1} respectively); alder and birch were grown in plots with 2.5 × 2.5 m distance between trees (1636 trees ha^{-1}). Hybrid aspen was grown under four fertilization treatments applied prior to planting—control, wood ash (6 Mg_{DW} ha^{-1}, total N 2.6, total P 65, total K 190 kg ha^{-1}), sewage sludge (10 Mg_{DW} ha^{-1}, total N 259, total P 163, total K 22 kg ha^{-1}) and digestate (30 Mg ha^{-1}, total N 65, total P 12, total K 100 kg ha^{-1}) in four replications, with plot size of 240 m^2 for spacing 2 × 2 and 3 × 3 m, and plot size 360 m^2 for 2.5 × 5 m spacing.

Table 2. Summary of case study design considered in this article.

Country	Location	Establishment Year	Marginality	Density, Plants ha^{-1}	Species	Treatment
Latvia	56.69 N, 25.14 E	2011	Poor rooting conditions—unfavorable soil texture and stoniness	2500; 1273; 1227;	Hybrid aspen	Control; Wood ash; Sewage sludge; Digestate
				1636	Gray alder	Control; Wood ash; Sewage sludge
				1636	Black alder	
				1636	Hybrid alder	
				1636	Birch	
Spain	41.36 N, 2.30 W	2009	Unfavorable soil texture, stoniness and soil organic carbon < 1%	6666	Siberian elm	Rain-fed; Irrigated
Ukraine	48.99 N, 27.46 E	2016	Soil organic carbon < 1%, soil pH < 5	20,000	Willow	Fertilizer (N60)
		2013	Soil organic carbon < 1%			Control
		2016; 2011;	Clay soil (clay content > 50%), soil organic carbon < 1%			
		2011; 2013; 2016;	None			

Birch and alder species were grown under three fertilization treatments—control, wood ash (6 Mg_{DW} ha^{-1}, total N 2.6, total P 65, total K 190 kg ha^{-1}), sewage sludge (10 Mg_{DW} ha^{-1}, total N 259, total P 163, total K 22 kg ha^{-1}) in four replicates with plot size of 240 m^2.

Marginality of the site includes poor rooting conditions—unfavorable soil texture and stoniness (Table 2). The type of soil was classified as Luvic Stagnic Phaeozem (Hypoalbic) or Mollic Stagnosol (Ruptic, Calcaric, Endosiltic) according to the FAO [38] with the dominant loam (at 0–20 cm depth) and sandy loam (at 0–20 cm and 20–80 cm depth) soil texture. The climatic conditions of the site during the study period can be seen in Table A1 and Figure A1.

Tree height and diameter at breast height (DBH) were measured for all species after eight growing seasons. Biomass was calculated according to a methodology Liepiņš J. [39] specifically developed for young tree stands in local conditions.

2.1.2. Spain

The experimental fields are located in the north-central part of Spain, in Cubo de la Solana municipality at an altitude of about 1100 m above sea level (coordinates can be found in Table 2). Fields with a total area of 2500 m^2 were established manually, using Siberian elm (*Ulmus pumila* L.) rooted plants in 2009. The site was divided in to two plots, rain-fed and under irrigation conditions. The average water supplied in the irrigated plot was 1500 m^3 ha^{-1} $year^{-1}$ during the summer months (from June to September). Irrigation was applied every year using a drip system. Density was 6666 trees per hectare. The experimental duration was nine years. Siberian elm was harvested every 3 years. Therefore, three harvests of the crop have been obtained.

The marginality factors of the planting site are unfavorable soil texture, stoniness and low soil organic carbon (Table 2). The soil analysis was performed on samples collected at depths of 0–30 cm. The soil has a sandy texture (sand 86%, lime and clay < 10%), about 28% coarse elements with good drainage. Moreover, it has pH of about 6, content in oxidable organic matter (0.4%), nitrogen content (0.03%) and its cation exchange capacity (CEC) is 3 cmol kg^{-1}, field capacity 6.6%, water utility 3.9% and wilting point 2.7%. The climatic conditions of the site during the study period can be seen in Table A2 and Figure A2.

Siberian elm trees were harvested by hand using a chainsaw. Each plant was cut down to 10–15 cm above the ground level. The number of tree samples were 15 per treatment and harvesting cycle. The fresh weight of each tree over the studied period was determined by weighing whole plants immediately after harvesting at the field. The representative biomass samples were taken to the laboratory to determine the dry matter content by drying it in an oven at 60 °C. Dry biomass yield per hectare and mean annual increment (MAI) was estimated from the harvest data of each plot.

2.1.3. Ukraine

Experiments were carried out at the Yaltushkiv Experimental Breeding Station, Chereshneve, Vinnytsia region, Bar district (coordinates can be found in Table 2). The fields are located in the forest steppe zone of sufficient moisture, which covers 33% of the territory of Ukraine. The climatic conditions of the site during the study period can be seen in Table A3 and Figure A3.

Willow (*Salix viminalis*) variety Zbruch was used in the experiments. Willow planting density was 20,000 plants ha^{-1}. Experimental plots have various marginality factors and were established in different years. One willow plot was established in 2011 on clay soil with low soil organic carbon. In 2013, another willow plot was laid out on soil with low soil organic carbon. In 2016, one more plot was laid out on clay soil with low soil organic carbon and unfavorable soil texture and another on soil with low organic carbon and high soil acidity (Table 2). In addition, in each establishment year, one plot was also established on land with no marginality factors serving as a control. Weed control was carried out, and fertilization with N rate of 60 kg ha^{-1} was done in plots established in 2016 on soil with low organic carbon content and low pH. Willow was harvested triennially. Only the data of latest harvest biomass yield was further assessed (first rotation data of plots established in 2016, second rotation data of plots established in 2013 and third rotation data of plots established in 2011).

2.2. Statistical Analysis

Data analysis and visualization was done using R version 4.0.5 [40]. The Shapiro−Wilk test was used to test normality of data and Levene's test was used to test homogeneity of variances assumptions. Data was not normally distributed; therefore, the Mann−Whitney U test was used to compare the two groups for the case study in Spain and Kruskal−Wallis and Dunnett's multiple comparison tests were used to compare groups for the case study in Latvia.

3. Results

3.1. Latvia

The MAI of studied species is shown in Figure 1. In the studied conditions, fastest biomass accumulation was achieved by the hybrid aspen clone 4 under digestate treatment and in the densest planting density (2 × 2 m).

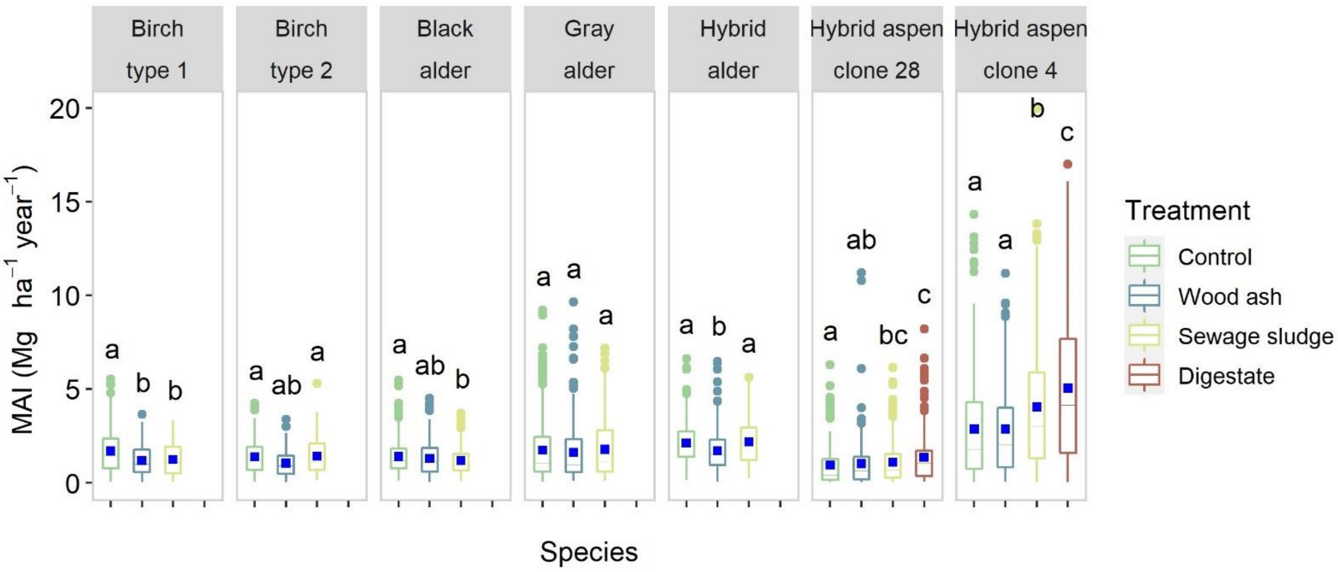

Figure 1. Mean annual increments (MAI) of dry above-ground biomass of eight-year-old fast-growing tree species stands depending on fertilization treatment (boxes represent interquartile range; median is shown as center horizontal line in the box; whiskers show minimum and maximum observed values; dots show outliers; mean values are represented by the blue squares; different letters represent significant ($p < 0.05$) differences among treatments within each species).

The hybrid aspen clone 4 showed significantly ($p < 0.05$) more rapid growth compared to clone 28 across all treatments and had a better survival rate (94% and 89% respectively). Across all treatments, the MAIs of hybrid aspen clones 4 and 28 were 3.7 and 1.1 Mg ha^{-1} y^{-1} after eighth growing season. Both clones responded in a similar pattern to stand density. In this study, the highest stand density yielded the most biomass (Figure 2). Tree height and mean breast height diameter followed the same pattern and were also the largest in plots planted in a grid of 2 × 2 m (2500 trees ha^{-1}).

Application of digestate had a positive effect on hybrid aspen yield, except in the cases of the 3 × 3 m plots for both clones and the 2 × 2 m plot for clone 28. Plots where wood ash was applied performed the worst in terms of biomass accumulation across all densities and regardless of clone. Sewage sludge did not have a positive effect in most cases, compared to the control—a positive effect on yield was observed only in planting density of 2.5 × 5 m for both clones; however, this was more likely due to soil differences across fields rather than interaction between density and fertilization treatment.

For birch, there were no significant differences between container types when initial planting material height differences were taken into account ($p = 0.09$). Birch stands with type 1 planting material produced an average of 1.5 Mg ha^{-1} y^{-1} and type 2 planting material produced 1.3 Mg ha^{-1} y^{-1} after the eight growing season. Compared to control, there was no evidence of a significantly positive effect of any of the fertilization treatments, either on birch type 1 or birch type 2.

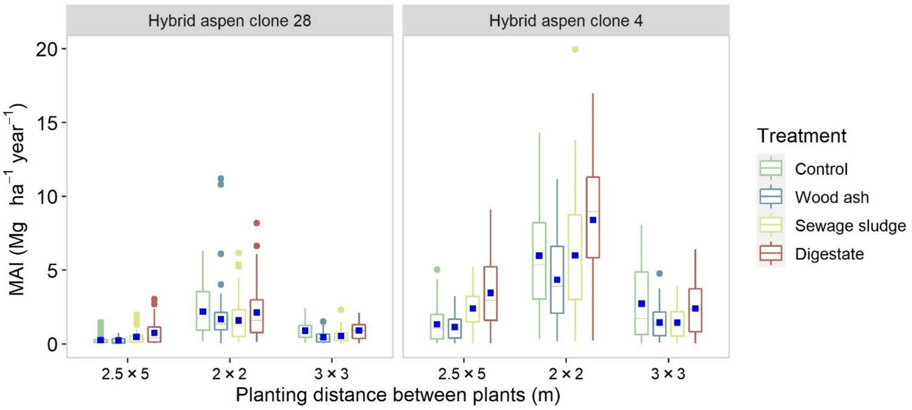

Figure 2. Mean annual increments (MAIs) of above-ground biomass dry matter of eight-year-old hybrid aspen stands depending on planting distance (boxes represent interquartile range; median is shown as center horizontal line in the box; whiskers show minimum and maximum observed values; dots show outliers; mean values are represented by the blue squares).

Similarly, neither of the fertilization treatments had a positive effect on any of the alder species' biomass accumulation rate. Hybrid alder, black alder and gray alder after the eight growing season produced 2.0, 1.7 and 1.3 Mg ha^{-1} y^{-1}, respectively, (mean of all treatments).

From the studied species, hybrid aspens', hybrid alders', black alders' and gray alders' overall survival rate was higher than 88%. Birch had the lowest survival rate—73% and 76% (type 1 and type 2, respectively).

3.2. Spain

The Siberian elm plantation exhibited a 100% survival rate during the study period. Irrigation had a statistically significant positive effect on biomass accumulation in Siberian elm in the first and third rotation (p = 0.004 and p = 0.02, respectively) but not in the second rotation ($p > 0.05$). The yield in irrigated plots was double of that in rain-fed plots. MAI increased with every rotation; however, the difference between rotations was not statistically significant. The increase from first to third rotation was from 1.79 to 3.66 and from 4.54 to 7.05 Mg ha^{-1} y^{-1} in rain-fed and irrigated plots, respectively (Figure 3).

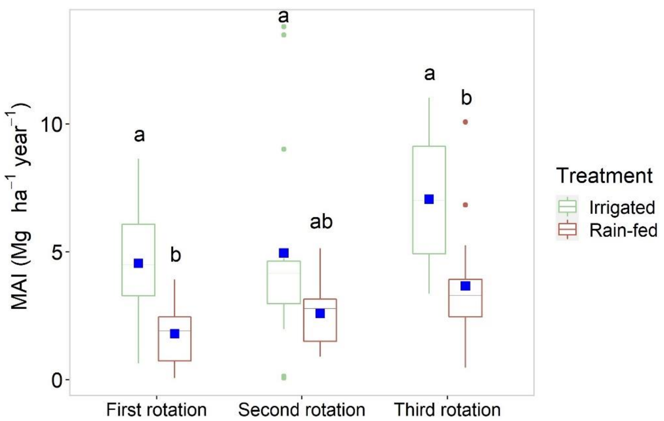

Figure 3. Mean annual increment (MAI) of Siberian elm above-ground biomass dry matter after first, second and third triennial rotation depending on treatment (boxes represent interquartile range; median is shown as center horizontal line in the box; whiskers show minimum and maximum observed values; mean values are represented by the blue squares; different letters represent significant ($p < 0.05$) differences between all treatments and rotations).

The acquired MAI corresponds to total yield per area of 5.37 and 13.63 Mg ha^{-1} after first rotation, 7.76 and 14.83 Mg ha^{-1} after second rotation and 10.97 and 21.14 Mg ha^{-1} after third rotation in rain-fed and irrigated plots respectively.

3.3. Ukraine

Willow plots established in 2016 yielded 8.35 and 8.63 Mg ha^{-1} y^{-1} during the first three-year rotation in unfertilized plots of soil with low soil organic matter and unfavorable soil texture and fertilized plots of soil with low soil organic matter and low pH, respectively (Figure 4). In the plots established in 2013 on land with low soil organic matter, MAI was 10.82 Mg ha^{-1} y^{-1} in the second three-year rotation. The plot established in 2011 on soil with low organic matter and unfavorable soil texture yielded slightly less—9.54 Mg ha^{-1} y^{-1} in the third three-year rotation. Survival rate was above 88% in all stands regardless of stand age or treatment. In plots with no known marginality factors, survival rate was above 94%. The yield was also higher in all plots on non-marginal land—12.66, 14.83 and 14.04 Mg ha^{-1} y^{-1} after first, second and third rotation, respectively.

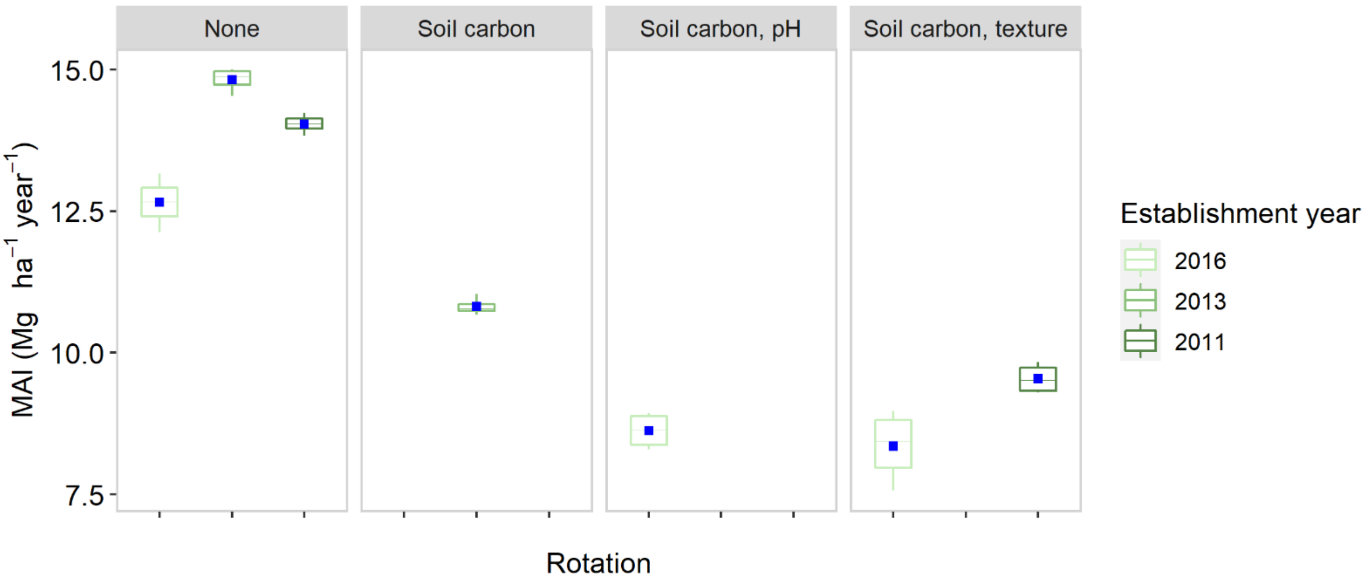

Figure 4. MAI (mean annual increment) of willow above-ground biomass dry matter in Ukraine after first, second and third rotation, under different marginality factors—no marginality (none), low soil organic matter content (soil carbon), low soil pH (pH), unfavorable soil texture (texture) (boxes represent interquartile range; median is shown as center horizontal line in the box; whiskers show minimum and maximum observed values; mean values are represented by the blue squares).

Both total biomass per hectare and the weight of individual plant was the highest (32.5 Mg^{-1} ha^{-1} and 1.8 Kg plant^{-1}, respectively) after the second rotation, in the plots that had only one marginality factor at play—low soil organic carbon—compared to plots with two marginality factors.

4. Discussion

4.1. Yield Performance

Depending on the intended application, biomass yield and crop performance can be measured in various ways. To alleviate the comparison between the case studies and available literature, we focus on MAI expressed as Mg$_{DW}$ ha^{-1} y^{-1} as it is one of the prevailing measurements used in other studies regarding woody biomass.

Similarly to results of other studies (Table A4) on both marginal land and on land with no known marginality, high variation in yield within a plantation was observed in the case studies [41–45]. Yield results from the case study in Latvia show that at the age of eight years, productivity of all planted species was low, compared to yields acquired in other studies. This can mainly be attributed to relatively low initial stand density, as the trees were grown for their trunks. Longer rotations (10 years and above) would be recommended in such a case, as is also recommended by other authors [46]. In similar density stands, similar growth results have been obtained [44,47]. Planting density is related to the target produce—lower stand density allows for thicker trunks and more dry matter per tree, but denser stands typically output more biomass per ha [48,49]. Hybrid aspen offers better financial returns, if grown for log production, according to Tullus et al. [50]. Thus, lower stand densities and longer rotations are favored in the current state of the market. Density effect on total biomass yield is more evident in the early age of the stand, but later on in-group competition causes natural thinning and suppresses tree growth, thus, in older stands density affects tree dimensions more than total yield per area [51–53]. However, in relatively low-density hybrid aspen stands in Latvia, the densest stand design (planted in 2 $\times$ 2 m) showed a slightly better survival rate; furthermore, no in-group competition was observed, as both the height and the DBH was bigger in the densest stand. This suggests that denser stands ($\geq$2500 trees ha^{-1}) of hybrid aspen can be established without compromising wood quality. Survival of Siberian elm in a short-rotation plantation (6666 plants ha^{-1}) was 100% in trials based in Spain, and survival did not decrease with stand age. Similarly, no effect of in-group competition on survival was observed in high-density stands in Ukraine, where willow survived equally well in all established plots (survival rate 88–90%), when planted in density of 20,000 plants ha^{-1}. In coppice systems, willow (or poplar) is typically grown in density of 10,000–20,000 plants per hectare (with 10,000–15,000 plants per hectare being recognized as the highest yielding [54]) for up to a total of 25 years with typical rotation length being 3–5 years [55,56]. Rotation of 3–5 years is considered optimal for willow short-rotation coppice (SRC) plantations even on marginal land [52]. MAI typically increases with stand density and stand age (up to certain point), thus providing a basis to favor longer rotation periods for non-coppice woody crops. However, in coppicing systems, the opposite trend can be observed, where MAI is increasing during first rotations, but in the long term it is often negatively correlated to the number of harvests, with some clones showing a decline in yield sooner than others [57–60]. Due to different establishment years and results from only three rotations, it is complicated to assess the rotation count effect on yield in the case study based in Ukraine. In this study, MAI was initially low in younger plots, established in 2016 (8.5 Mg ha^{-1} y^{-1}) compared to plots established earlier, in 2013 and 2011 (10.8 and 9.5 Mg ha^{-1} y^{-1}). However, the marginality and treatment of these plots also varied and therefore the differences in yield cannot be clearly attributed to plot age, especially since the establishment year was not the same for all plots. Regardless of the stand age, all plots established on marginal land produced around 30% less biomass per year compared to plots established on non-marginal land. On marginal land, total yield per hectare was the highest after the second harvest in plots established in 2013, possibly due to being affected only by one marginality factor—low soil organic matter—whereas other plots had two constraining factors—low soil organic matter combined with low pH or unfavorable (clay) soil texture. The obtained yields are within the range found in other studies on marginal lands (typically a wide range from 3 up to 12 Mg ha^{-1} y^{-1}) and, possibly due to the small scale of the experiment, even exceed the estimated bioenergy crop yields that can be achieved at a production scale (around 6 to 7 Mg ha^{-1} y^{-1}) (Table A4) [61,62]. Vande Walle et al. [63] found lower yields under similar soil conditions—on sandy soil with low organic matter and high acidity (3.4 Mg ha^{-1} y^{-1} after four growing seasons and 20,000 plants ha^{-1} density).

The biomass yield of Siberian elm trees depended on age and even more so water regimen. Siberian elm produced twice as much biomass under irrigated conditions compared to rain-fed, and the biomass accumulation increased with each rotation (even though not significantly). Therefore, the regrowth capacity of Siberian elm after harvesting can be considered as good. However, the biomass yields were lower than in the studies carried out in Madrid and Teruel under rain-fed conditions. In Madrid with the same planting density, the average biomass yield when elms finished the second cycle was estimated at

5.2 Mg ha^{-1} y^{-1} and after 3 years at 13.2 Mg ha^{-1} y^{-1} [64], while in Villarquemado (Teruel) the biomass yield was 5.1 Mg ha^{-1} y^{-1} with a density of 3333 trees ha^{-1} [65], although the biomass yield was similar to that in Oropesa (Toledo) 1.86 Mg ha^{-1} y^{-1} in second cycle [66]. In eastern Kansas, elm biomass yield varied from 4.7 to 9.8 Mg DM ha^{-1} y^{-1} with planting density of 1400–7000 trees ha^{-1}, respectively, harvested 7 years after planting in rain-fed conditions [67]. However, the biomass yield after 3 years ranged from 0.7 Mg ha^{-1} y^{-1} to 5.2 Mg ha^{-1} y^{-1} in different plots distributed throughout the state of Kansas [68] and between 4.5 and 16.9 Mg ha^{-1} when elms were cut annually for 6 years using a spacing of 0.3×0.3 m^2 in the same North American state [15].

According to available research (Table A4), on agricultural land that is simply classified as abandoned or fallow, yields are higher compared to those on land with known and defined land constraints. Comparison of marginality factor effect on yield is complicated as there are multiple factors at play, and the marginality itself can be of various degrees. Woody crop productivity is generally still good on sites with low soil organic matter. Spoil heaps and extracted mining sites, on the other hand, are especially limiting for growth, as these often include a combination of unfavorable soil qualities—adverse chemical conditions, limitations in rooting, low soil fertility and also adverse terrain conditions [69–71].

Some research suggest that yields presented based on small-scale experimental plantation sites are overly optimistic (due to increased edge effect, intense tending, limited pest damage, etc.) [72,73]. However, it is not clear if the same is expected on marginal land, but if the management practices are kept the same when upscaling the cultivation, results will most likely be similar to what has been obtained in smaller-scale experiments.

4.2. Species Suitability

Due to numerous possible species and marginality factor combinations, there is still lack of knowledge regarding each species' performance under unfavorable conditions. Attempts to narrow the knowledge gap can be made by compiling existing research on marginal land and knowledge on growth requirements of particular species. However, the intra-species variation can be high [52,74] as can also be seen from hybrid aspen clone 4 and clone 28 results from the case study in Latvia. Even more so for some clones, high inter-replicate variation can be observed [75]. Besides yield, characteristics of each genotype should be considered in context of the site. Depending on current and future risks, and intended target produce-stress tolerance, chemical composition, physical properties and disease susceptibility may be more important in planting material selection than tree growth rate [76]. Mixed genotype stand composition can be expected to increase the overall stand stability and resilience.

4.2.1. Willow and Aspen

Willow and hybrid aspen both are *Salicaceae* family species. The performance of willow is more studied compared to hybrid aspen; however, in terms of growth requirements and recommended management practices hybrid aspen is similar to another widely grown species from this family, poplar [47]. Compared to poplar, aspen is at higher animal browsing damage risk, but can better withstand colder temperatures and poorer site conditions [46]. It has been found that willow uptakes more nutrients from the soil compared to poplar, but poplar uptakes more than eucalyptus or paulownia, which can lead to faster soil depletion, and could be especially problematic if the land is initially low in nutrients [77,78]. In general, these species are not suited for highly acidic soils, soils that are poor in nutrients and sandy soils with low water availability [26,55,63,79,80]. Being water demanding, these species can withstand moderate flooding, with some clones being more tolerant than others [46,81]. The growth difference depending on clone was also evident in the case study in Latvia; however, the response of both clones to fertilization treatment and stand density followed the same pattern. The *Salicaceae* species can also be grown on contaminated soils, but due to their phythoremediating properties (especially of willow), accumulation of heavy metals in biomass can occur and compromise the quality and safety of obtained feedstock [82]. Willow is better adapted to colder climates, where poplar can suffer frost damage [62]. Overall, higher willow and poplar yields can be expected in milder climates—British Isles, Central and west Europe—but lower yields can be expected in Northern and Eastern Europe due to a colder climate and in Southern Europe due to limited precipitation, and thus, water availability [83].

4.2.2. Siberian Elm

Under arid climatic conditions, species such as Siberian elm, black locust and eucalyptus can be grown on marginal land. There are limited data on Siberian elm cultivation for biomass in Europe. In Spain, elm started to be studied as an energy crop in short-rotation coppices (SRCs) around 2000 [65]. Siberian elm is a hard wooded and a fast-growing tree that features greater resistance to Dutch elm disease than other species in genus *Ulmus*. Its drought tolerance, adaptation to different environments and sprouting capacity determine that this species grown as a SRC can produce high-biomass lignocellulosic yield under low input management [84,85]. However, this species can have an invasive nature, as seen in North America [86] and Serbia [87] and has a potential of hybridization with native species [88]. So far there is limited data on its invasiveness in the conditions of Europe, and in Spain it is not considered invasive at the moment [89]. Caution should be taken when planning Siberian elm plantations. Siberian elm plantations can successfully be established on unfavorably textured soil, as was also evident from the study case results. In the case study, the survival rate was equal to that in trials in Madrid, 100%, and higher than that at Villarquemado (Teruel), 96.5% [65], and Casale Moferrato (Alessandria), between 68–87% (Pérez et al., 2012). It is suited to conditions where other species fail to thrive, especially stony and coarse soil, as it is typically found occurring naturally in such soil [90], making it a very suitable species for marginal lands. In addition, SRC plantation can enhance soil carbon content. In a study carried out in Spain, the capacity to sequester C in the uppermost layer of the soil (0–30 cm) of black locust, Siberian elm and Euroamerican poplar was 0.36–0.83 Mg ha^{-1} y^{-1} of C [91]. Alternative species for warmer and dryer climatic conditions are black locust and eucalyptus. Unfortunately, similar to Siberian elm, these two species also possess the potential to become invasive in some areas of Europe. Eucalyptus species vary in tolerance to different constraints. Most are heat and drought tolerant and some can withstand saline soils, flooding relatively well [16]. The yield of black locust is negatively affected by dryness during the initial planting and growth period; under such conditions low yield has been found in Spain—0.91 Mg ha^{-1} y^{-1}—ten times higher biomass has also been obtained on well managed (weed control, fertilizer and irrigation) sites with sandy soil and low organic matter—9.20 Mg ha^{-1} y^{-1} [92,93]. Black locust is often found on well aerated, relatively dry and stony soil, but is not suited for areas with compact or shallow soil and stagnant water. It can tolerate a broad range of soil reactions [94]. As a benefit to soil, black locust is a nitrogen-fixing species and can grow on nitrogen-poor soils [71,95].

4.2.3. Birch

Birch (*B. pubescence* and *B. pendula*) is another typically planted species across Europe and, if left abandoned, natural afforestation of agricultural land in a large portion of Europe happens with birch as a pioneer species. The high natural regeneration capacity of this species suggest its suitability for growing under a wide range of site conditions. Due to birches' ability to effectively propagate via seeds, dense naturally afforested birch stands can be used for biomass harvesting, thus avoiding the initial planting costs [96]. Compared to the *Salicaceae* family, birch is better suited to acidic soils and lower moisture levels, but due to its slower growth rate, should be grown in longer rotations if intended for bioenergy production. In the Baltic region with assumed stand density of 2000 trees per ha, birch stand MAI on marginal land can be expected to be 1.7 and 3.9 Mg ha^{-1} y^{-1} at the age of 8 and 15 years, respectively, but on non-marginal land 2.9 and 4.7 Mg ha^{-1} y^{-1} (based on Daugaviete et al., 2017). In the case study plot, an 8-year-old birch stand produced

1.4 Mg ha^{-1} y^{-1} due to a relatively low initial planting density and low survival rate of around 73%. Even lower survival rates have been observed in 15-year-old birch stands in Latvia (both marginal and non-marginal) and in 4-year-old stands on a reclaimed oil shale mining area in Estonia [70,97]. The survival of birch can be significantly affected by the lack of sunlight, as it is light-demanding species [98].

4.2.4. Black and Gray Alder

Other pioneer species typical to Europe are black and gray alder. These species are known to be tolerant of extended periods of flooding and can grow in a relatively broad soil pH range [99]. Low soil pH and excess moisture is typical to the northern part of Europe. Alder is suited to coppice systems and is fit for short-rotation forestry, since it reaches half its mature height at around 25 years [48,81,100]. On marginal land biological rotation can be expected to be reached later than on non-marginal land. The most productive period is also reached later on marginal land, and longer rotation periods are advisable [52]. Due to nitrogen fixing bacteria, alder has shown to be beneficial to nitrogen-poor soil, and thus, to growth of admixed woody species [101–104]. Based on performance data from stands established some 15–20 years ago in Latvia, on marginal land black alder produced 2.1 Mg ha^{-1} y^{-1} at the age of 8 and 7.0 Mg ha^{-1} y^{-1} at the age of 15 at assumed stand density of 2000 trees per hectare (based on Daugaviete et al. [97]). MAI had almost tripled from 8 to 15 years, thus confirming that longer rotations are better suited to low-density forest species stands. The results showed high variance both within a stand and between the stands. In the experimental plot studied in this research, trees were planted at a lower density (1636 trees ha^{-1}) and the plantations of black alder, gray alder and hybrid alder yielded 1.3, 1.7 and 2.0 Mg ha^{-1} y^{-1}, respectively. In studies conducted on abandoned agricultural land, but no defined constraints, gray alder produced 15.86 Mg ha^{-1} (3.2 Mg ha^{-1} y^{-1}) in Estonia after 5 growing seasons. On average, the performance of plantations established on marginal land is around 60–80% of that on non-marginal land, based on research done in Latvia [97]. However, due to high variation, pests, lack of management or initially unidentified site constraints, some less productive plantations on non-marginal land are comparable in terms of yield to promising plantations on marginal land.

4.3. Treatment

Management practices determine the environmental impacts as well as the financial feasibility of forestry. It has been shown that economically viable woody crop plantations can be achieved by selection of appropriate planting material and management practices [16,46,105]. To secure profitability and more importantly, survival, on marginal land, treatment, such as soil preparation, weed control, fertilization, liming, irrigation or animal damage prevention is often necessary. Based on other research (Table A4), mechanical or chemical weed control is most commonly applied treatment in the early stage of plantation establishment [69,106–108]. Removal of competing vegetation has been shown to increase the biomass production twofold in small-scale field trials in Latvia. Weed control by covering the surrounding area with plastic film had an adverse effect on tree survival, when used for shallow-rooted trees [97].

Treatment is expected to be the most effective when it is selected to counteract the main limiting factors. However, species vary in their sensitivity to site conditions [109]. A particular marginality factor can have little effect on some species, but can be determining to other. Treatment can have indirect effects as well. For example, in this study irrigation had a significant positive effect on yield of Siberian elm planted in experimental plots established in Spain, where soil texture was recognized as the main marginality factor. Evidently, Siberian elm was also significantly affected by the water regimen of the site. Siberian elm withstands high temperature periods by increasing its transpiration rate [90]. Therefore, despite it being drought tolerant, sufficient water supply is needed to support the transpiration demand and to allow better nutrient uptake and resource allocation to biomass accumulation instead of defense mechanism processes [110–113]. Irrigation has also show a positive effect on willow plantations in more temperate climate [114,115].

With unfavorable soil texture and stoniness at the experimental site in Latvia, the fertilization effect was species-specific, with hybrid aspen being the only species showing a clear positive response to fertilization with digestate. Even some negative growth response to sewage sludge and wood ash was observed. This could be induced by changes in soil that affect either nutrient availability by raising the pH or mycorrhiza of these species [116]. Other studies have also found that response to fertilization is clone-specific [69]. It is important to consider the necessity of fertilizer application, as it does increase management costs and pose environmental risks (surplus nutrient leeching), but does not always lead to increased yield [57,69]. The effects of fertilization have shown to be more prominent on land, where plant growth is directly limited by nutrient availability [117,118]. Even in such cases, the lowest effective dose should be applied because increasing the dose typically does not provide significant additional effect on yield. Multiple applications of low-dose fertilizer are preferred over a single application of high-dose fertilizer in terms of environmental safety. In the Ukraine-based case study of a willow plantation with low soil organic matter, nitrogen fertilizer had minimal positive effect on yield. Just like in the case study carried out in Latvia, fertilization did not address the main limiting factors. Furthermore, high soil acidity was also present and could have an immobilizing effect on the added nutrients. Thus, in case of acidic soils (for example peat soils in Northern Europe) liming should be combined with fertilization. Liming agents often possess absorption and adsorption properties—soil treatment with lime and bisphosphonates, as well as biochar has shown a positive effect on willow growth on contaminated soils, most likely due to sorbent properties [108,119]. If the soil is already alkaline, different sorbents should be used. In addition, by promoting biomass accumulation, treatment can be used to improve phytoremediation of such sites.

Treatment is crucial when trying to establish a tree plantation or woody crop on especially challenging land, such as post-mining sites, spoil heaps and highly acidic soils (Table A4) [71,120,121]. While acidity can be mitigated by application of liming material that often also promotes nutrient availability, mining sites and spoil sites are more complicated to recultivate.

There are also some unconventional tools to improve site conditions for growth of woody crops, for example, utilization of other species as nurse plants that provide shade, improve soil structure and water-holding capacity or nitrogen fixation in soil [101,122–124].

5. Conclusions

It was found that tree plantations and woody crops can be successfully established in terms of survival on marginal land across Latvia, Spain and Ukraine. While the marginality factors addressed in this article are similar across the study sites and countries, the management and species vary depending on specific soil and climatic conditions of each site. In the more northern region, Latvia, hybrid aspen performed better than the indigenous pioneer species birch and alder on a site with loam and sandy loam texture, but there was significant difference between the hybrid aspen clones. Thus, the specific genetic material might be even more determining than the species. In the warmer and dryer climate of Spain, Siberian elm proved to be suitable for cultivation on stony soil with sandy texture and low organic carbon content, where most other crops would fail to thrive. In the continental agro-ecological zone of Ukraine, high-density stands of willow proved to be tolerant to low soil organic carbon content and produced yields that can compete with forest residues in terms of financially feasible biomass supply. This suggests high-density SRC woody crops are more productive for cultivation on marginal land compared to tree plantations. However, the feasibility strongly depends on the current state of legislation and socioeconomic factors that are a subject to constant change. Future studies should investigate the potential of growing woody crops and tree plantations on marginal land to contribute to rural development, biodiversity conservation, environmental protection and climate change adaptation.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. Average climatic conditions of the study site located in Latvia during the study period.

Yearz	Precipitation (mm)	Mean Temperature (°C)	Maximum Temperature (°C)	Minimum Temperature (°C)
2011	692.7	7.2	31.1	−24.7
2012	935.4	6.0	31.8	−29.6
2013	652.5	6.9	31.5	−21.1
2014	855.5	7.3	32.3	−18.8
2015	687.4	7.6	31.7	−18.2
2016	894.4	6.9	31.6	−24.4
2017	874.7	6.7	30.6	−28.1
2018	363.9	7.4	32.9	−23.8
Annual average	744.6	7.0	31.7	−23.6

Table A2. Average climatic conditions of the study site located in Spain during the study period.

Year	Precipitation (mm)	Mean Temperature (°C)	Maximum Temperature (°C)	Minimum Temperature (°C)	Solar Irradiance (kWh/m^2)
2009	107.4	4.8	18.9	−12.8	98.0
2010	598.5	9.6	33.4	−11.0	1508.0
2011	379.6	11.1	35.7	−11.9	1629.2
2012	344.4	10.6	37.0	−10.3	1659.6
2013	594.5	9.5	33.8	−8.8	1547.8
2014	595.5	10.7	33.3	−6.7	1599.6
2015	488.1	11.0	36.0	−9.5	1605.8
2016	540.2	10.7	34.7	−7.5	1404.5
2017	314.8	11.9	35.3	−11.7	1654.6
2018	668.7	10.4	35.3	−8.3	1294.5
Annual average	463.2	10.0	33.3	−9.8	1400.2

Table A3. Average climatic conditions of the study site located in Ukraine during the study period.

Year	Precipitation (mm)	Mean Temperature (°C)	Maximum Temperature (°C)	Minimum Temperature (°C)
2011	446.0	8.3	30.8	−17.2
2012	497.4	8.4	36.8	−28.2
2013	618.2	8.6	29.7	−19.0
2014	549.0	8.5	32.9	−23.5
2015	372.0	9.8	35.2	−18.5
2016	466.5	9.0	33.1	−22.2
2017	538.1	9.0	33.4	−21.6
2018	566.1	8.8	30.0	−22.3
2019	535.8	9.9	33.1	−12.5
Annual average	509.9	8.9	32.8	−20.6

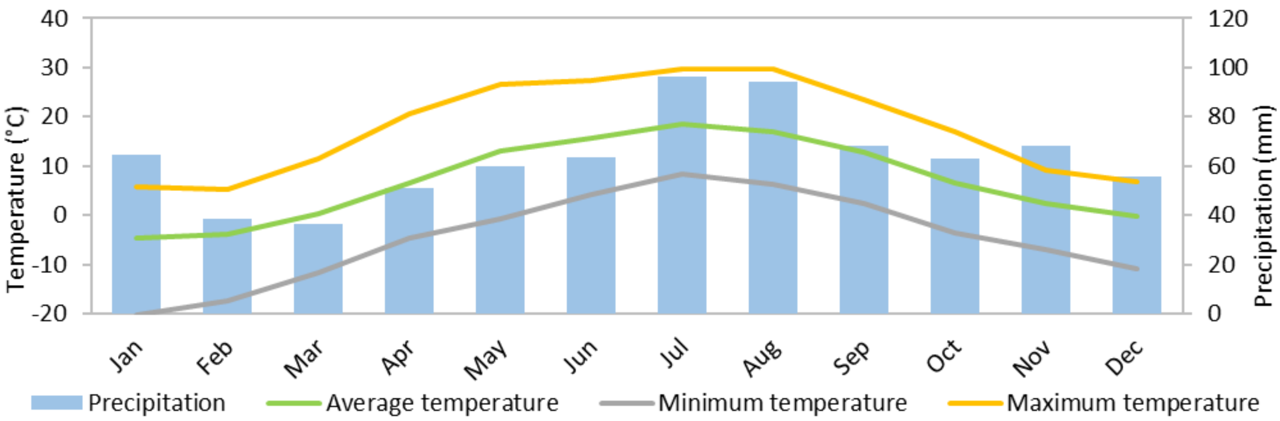

Figure A1. Average monthly climatic conditions of the study site located in Latvia during the study period 2011–2018.

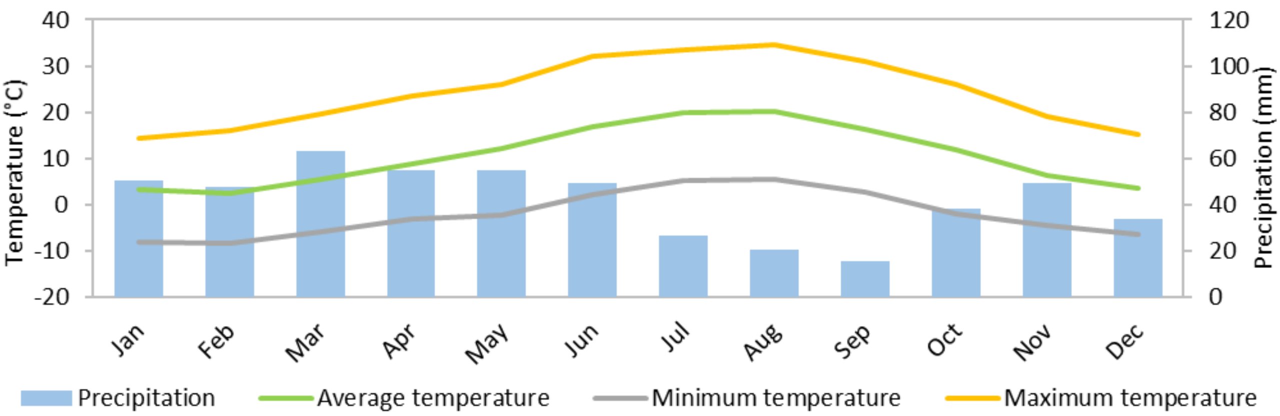

Figure A2. Average monthly climatic conditions of the study site located in Spain during the study period 2009–2018.

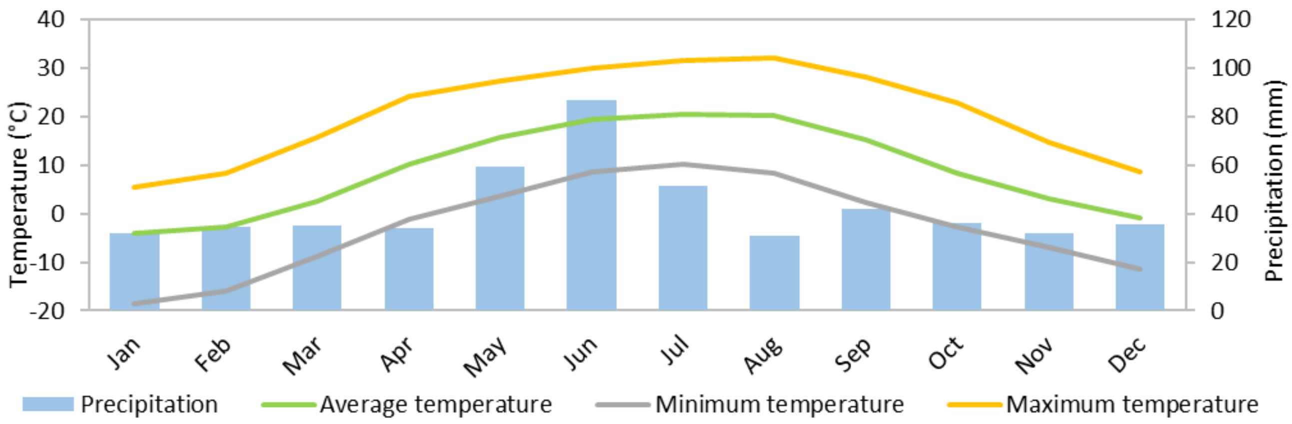

Figure A3. Average monthly climatic conditions of the study site located in Ukraine during the study period 2011–2019.

Table A4. Results of woody crop above-ground biomass yield on marginal land based on research done in Europe.

Species	Site Condition	Planting Density, Plants ha^{-1}	Rotation Length, Years	* Above-Ground Biomass Yield, Dry Weight, Mg ha^{-1} y^{-1}	** Treatment	Location	Source
Hybrid aspen (2 clones)	Poor rooting conditions—unfavorable soil texture and stoniness	1261–2500	8	0.9–4.8 depending on clone and treatment	Fertilizer, weed control, animal prevention	Latvia	
Hybrid alder		1636;		2.0			
Black alder				1.3			
Gray alder				1.7			
Birch				1.4			
Siberian elm	Sandy soil with unfavorable soil texture, stoniness and low soil organic carbon (<1%)	6666	3	1.8 rain-fed and 4.5 irrigated (first rotation); 2.6 rain-fed and 4.9 irrigated (second rotation); 3.7 rain-fed and 7.1 irrigated (third rotation);	Rain-fed and irrigation	Spain	
Willow	Clay soil with low soil organic carbon	20,000	3;	8.4 (first rotation); 9.5 (third rotation);		Ukraine	
Willow	Soil with low soil organic carbon	20,000	3;	10.8 (second rotation)		Ukraine	
Willow	Soil with low soil organic carbon and high soil acidity	20,000	3;	8.6 (first rotation)	Fertilizer	Ukraine	
Poplar (12 clones)	Former agricultural land with sandy soil and limited drainage	8000	2	1.5–7.2 (3.0–14.4 Mg ha^{-1}) (first rotation) and 7.4–16.2 (14.8–32.4 Mg ha^{-1}) (second rotation) depending on clone	Weed control	Belgium	[45,76]
Poplar (17 clones)	Former waste disposal site covered with a 2 m thick layer of sand, clay and rubble	10,000	4	2.2–11.4 depending on clone	Weed control	Belgium	[75]
Birch	Former agricultural land, sandy soil with soil organic matter <1% and pH$_{KCl}$ 4.5	6667 (birch, maple); 20,000 (poplar, willow)	4	2.6		Belgium	[63]
Maple				1.2			
Poplar				3.5			
Willow				3.4			

Table A4. *Cont.*

Species	Site Condition	Planting Density, Plants ha^{-1}	Rotation Length, Years	* Above-Ground Biomass Yield, Dry Weight, Mg ha^{-1} y^{-1}	** Treatment	Location	Source
Willow	Contaminated, dry, nutrient poor, sandy soils	18,000	3	4.2–6.6	Weed control	Belgium	[26]
Poplar				1.1–1.5			
Willow	Former agricultural land	14,800; 17,800;	5	3.1 (15.4 Mg ha^{-1}) control and 4.9–5.3 (24.7–26.3 Mg ha^{-1}) irrigated	Irrigated	Estonia	[114]
Birch	Naturally afforested abandoned agricultural land (and 1 planted site)	36,200	8	2.9 (22.8 Mg ha^{-1})		Estonia	[53]
		13,900		2.8 (22.0 Mg ha^{-1})			
		28,260		1.3 (10.2 Mg ha^{-1})			
		3060		0.8 (6.0 Mg ha^{-1})			
		4400 (planted)		1.7 (13.3 Mg ha^{-1}) (planted)			
Birch	Leveled quarry spoil	1017	7	0.02 (0.2 Mg ha^{-1})		Estonia	[121]
Alder		2100		0.36 (2.6 Mg ha^{-1})			
Pine		3042		0.27 (1.9 Mg ha^{-1})			
Willow	Restored landfill	1000–10,500	3	10.5; 18.8–22.6 (irrigated);	Irrigation	Finland	[115]
Birch and willow	Naturally afforested cut-away peatland	12,800	14	2.7–4.4	Fertilizer	Finland	[117]
Hybrid aspen	Fallow agricultural land	900	1	5.2;	Fertilizer (in second season)	Finland	[125]
			2	8.7 (17.4 Mg ha^{-1}) control and 9.95 (19.9 Mg ha^{-1}) fertilized			
			3	7.9 (23.9 Mg ha^{-1}) control and 9.5 (28.9 Mg ha^{-1}) fertilized			
Birch	Organic soils—cutaway peatlands—naturally afforested		10–27	3–4		Finland	[126]
Poplar (14 clones)	Trace element contaminated site		7	3.1–8.5		France	[82]
Poplar	Abandoned agricultural land	7272	2	1.9 (3.7 Mg ha^{-1}) (first rotation) 4.3 (8.6 Mg ha^{-1}) (second rotation)	Weed control	France	[77]
Willow	Abandoned agricultural land	9697	2	2.07 (4.1 Mg ha^{-1}) (first rotation) 11.0 (21.9 Mg ha^{-1}) (second rotation)	Weed control	France	[77]
Poplar (8 clones)	Disturbed, marginally fertile post-mine site	8333	8	0.4–6.0 (3.5–46.7 Mg ha^{-1})	Fertilizer	Germany	[120]
Black locust	Post-mine site with substrate from overburden sediments dumped during opencast lignite mining and low nitrogen content	6579;	14	2.7	Fertilizer	Germany	[71]
		10,929;	3	1.9, 2.5 and 1.8 (first, second and third rotation)			
		9200;	4	0.5			
		8736;	4	-			
Willow, poplar and black locust	Land with high sand content	6700	2	4.3, 7.7 and 9.2 (first, second and third rotation)		Italy	[57]
Willow, poplar and black locust	Land with low soil organic matter	6700	2	3.3, 12.9 and 12.2 (first, second and third rotation)		Italy	[57]
Birch; Pine;	Unfavorable soil texture, limited drainage	3300 (birch); 5000 (pine)	8	0.7 (birch) and 0.3 (pine)	Weed control, animal prevention	Latvia	[97]
			15	1.9 (birch) and 3.8 (pine)			

Table A4. *Cont.*

Species	Site Condition	Planting Density, Plants ha^{-1}	Rotation Length, Years	* Above-Ground Biomass Yield, Dry Weight, Mg ha^{-1} y^{-1}	** Treatment	Location	Source
Aspen	Limited soil drainage, periodic flooding, low temperatures	3300	8	0.5	Weed control, animal prevention	Latvia	[97]
			15	4.5			
Spruce	Acidic soil	3300	8	0.5–1.5 (depending on site)	Weed control, animal prevention	Latvia	[97]
			15	2.8–8.4 (depending on site)			
Black alder	Acidic soil	3300	8	1.3–3.3 (depending on site)	Weed control, animal prevention	Latvia	[97]
			15	2.5–15.9 (depending on site)			
Birch	Acidic soil	2000–3300	8	0.7–4.0 (depending on site)	Weed control, animal prevention	Latvia	[97]
			15	2.4–7.4 (depending on site)			
Birch; Spruce;	Acidic soil, excess moisture, low P and N content, low temperatures	3300 (spruce)	8	2.1 (birch) and 1.0 (spruce)	Weed control, fertilizer, animal prevention	Latvia	[97]
			15	4.9 (birch) and 4.5 (spruce)			
Willow	Marginal gley soils	20,000	3	12–15	Weed control	Northern Ireland	[56]
Siberian elm	Heavy black soil with a heavy clay granulometric composition	3448–51,282	7	5.2 (first rotation)	Rain-fed	Poland	[127]
Willow	Poor agricultural soils (loose, sandy soil with periodical dryness)	11,000	4	5.1–10.3	Weed control, fertilizer	Poland	[118]
Poplar				5.5–10.5			
Black locust				1.6–3.7			
Siberian elm	Sandy soil with low organic matter content (0.92%), low nitrogen (0.03%), many gravels (39.9%) and pH 5.90	3333	3	1.18 rain-fed and 2.43 irrigated (first rotation)	Rain-fed and irrigation (4167 m^3 ha^{-1}y^{-1})	Spain	[110]
Siberian elm	Sandy soil with low organic matter content (0.92%), low nitrogen (0.03%), many gravels (39.9%) and pH 5.90	6666	3	1.63, 5.19 rain-fed and 4.93 irrigated (first rotation)	Rain-fed and irrigation (2250 m^3 ha^{-1}y^{-1} and 4167 m^3 ha^{-1}y^{-1})	Spain	[110]
Siberian elm	Sandy soil with unfavorable soil texture, stoniness 28% and low soil organic matter content (0.4%)	3333	4	2.6 rain-fed and 6.0 irrigated (first rotation)	Rain-fed and irrigation (3400 m^3 ha^{-1} y^{-1})	Spain	[84]
		6666		2.5 rain-fed and 6.5 irrigated (first rotation)			
Siberian elm	Sandy clay loamy texture, pH 8.30, organic matter 4.0%, total nitrogen 0.35%, 27 ppm P (Olsen) and extreme climate	3333	3	5.1 (first rotation)	Rain-fed	Spain	[65]
Siberian elm	Basic soil with an excess of calcium. Entisol orden and Xerofluvent greatgroup.	6666	2	5.2 (first rotation)	Rain-fed	Spain	[64]
			3	13.2 (first rotation)			
Siberian elm	Sandy loam texture, low organic matter content (0.75%), nitrogen 0.08% and pH 5.87	6666	2.5	3.46 (first rotation)	Rain-fed	Spain	[66]
			2	1.9 (first rotation)			
Poplar	Sandy soil with low organic matter content in semi-arid climatic conditions	10,000	3 (for 9 years)	12	Fertilizer	Spain	[58]
Willow				9			
Black locust				7			
Sycamore				3			

Table A4. *Cont.*

Species	Site Condition	Planting Density, Plants ha^{-1}	Rotation Length, Years	* Above-Ground Biomass Yield, Dry Weight, Mg ha^{-1} y^{-1}	** Treatment	Location	Source
Willow (3 clones)	Former mining area	9876; 14,815;	5	0.3, 0.7, 1.7 (1,.3, 3.6, and 8.6 Mg ha^{-1}) depending on clone, 0.2, 1.1, 1.3 (1.1, 5.4, 6.6 Mg ha^{-1}) depending on treatment, 0.8, 1.0 (4.0 and 5.2 Mg ha^{-1}) depending on density	Fertilizer, weed control	Spain	[69]
Poplar	Degraded soils	5000	3	12.3–17.9 (36.9–53.8 Mg ha^{-1})	Fertilizer, irrigation	Spain	[78]
Eucalyptus				14.7–18.3 (44.2–55.0 Mg ha^{-1})			
Paulownia	Degraded, acidic soils	5000	3	1.1–1.7 (3.3–5.1 Mg ha^{-1})	Fertilizer, irrigation	Spain	[78]
Eucalyptus				13.5–19.7 (40.4–59.2 Mg ha^{-1})			

*- If yield is measured as Mg ha^{-1} in the source, the values are given in parentheses. **- Treatment for all or part of the experimental site (control plots are also present in most cases).

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