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- 1 Growth dynamics of fast-growing tree species in mixed forestry and agroforestry
- 2 plantations
- 3 Anaïs Thomas^a, Pierrick Priault^a, Séverine Piutti^b, Erwin Dallé^a, Nicolas Marron^{a*}
- 4 ^{*a*}Université de Lorraine, AgroParisTech, INRAE, UMR Silva, 54000 Nancy, France
- 5 ^bUniversité de Lorraine, INRAE, UMR Laboratoire Agronomie et Environnement (LAE), 54518
- 6 Vandoeuvre, France
- 7 *Corresponding author
- 8 *E-mail address*: nicolas.marron@inrae.fr (N. Marron)
- 9 ABSTRACT

In recent years, plantations of fast-growing tree species have emerged as a possible way to meet 10 the increasing demand for biomass for renewable energy in Europe. Agroforestry plantations 11 including fast-growing tree species could be an attractive option because they reduce land 12 competition for biomass and food production while providing forest benefits. Today, the species 13 interactions that determine whether a given mixture will be more productive than the 14 corresponding monocultures are still poorly understood. Our objective was to assess the 15 performance of fast-growing trees, i.e. poplar (*Populus nigra* \times *P. deltoides*) and alder (*Alnus* 16 17 *glutinosa*), in association with herbaceous species either N_2 -fixing species (succession alfalfa (Medicago sativa) and clover (Trifolium pratense)) or graminoids (succession of wheat (Triticum 18 aestivum) - triticale (Triticosecale) - temporary grassland consisting of mixtures of perennial 19 20 ryegrass (Lolium perenne) and fescue (Festuca ovina)), respectively, and in association together. We compared tree growth in mixed stands to growth in the respective tree monocultures. An 21 22 experimental plantation composed of three blocks including the different treatments was set up in 23 2014 in northeastern France. In the forest mixture, poplar and alder were planted in alternating

rows, and in the agroforestry plots, every second line of trees was replaced by the crops. No 24 fertilizers (of any kind) were used during the experiments. During six growing seasons, tree 25 growth (height and diameter at breast height) was monitored monthly in the agroforestry stands, 26 27 the forest mixture stand and the two tree monocultures. By the end of 2019, poplar stem height in association with N₂-fixing crops (alfalfa, then clover) was higher than in the forest mixture and 28 the monoculture. During the warmest growing season with a marked dry period in June-July 29 (2018), poplar height growth rate in the agroforestry treatment was between three and five times 30 higher than for the poplars in the monoculture and the forest mixture. A facilitation process in the 31 agroforestry plantations could explain this result due to a significant enrichment of the soil in 32 nitrogen by the N₂-fixing crops. This result only appeared several years after tree planting, and 33 management actions were necessary in order to control the strong competition between crops and 34 trees during the early stages. In the forest mixture, poplars associated with alders were smaller 35 36 than in their monoculture, in spite of a stratification of the canopies of the two species. For alders, tree growth did not appear to be affected by either an association with graminoids or with poplar. 37

Keywords: Mixed tree plantations; Agroforestry; Growth dynamics; Fast-growing tree species;
Interactions

40

41 **1. Introduction**

European Union leaders have agreed to increase the share of renewable energy in EU energy consumption to 27% by 2030 (European Biomass Association, 2017). Between 2007 and 2017, renewable energy production increased by 64% in Europe; in 2017, wood (and other solid biofuels) accounted for the largest share of renewable energy at 42% of primary renewable energy production (Eurostat, 2019). In recent years, plantations of fast-growing tree species have emerged to increase the contribution of biomass to renewable energy. Globally, these plantations

accounted for 2% of the forest area in the world in 2012 (Cateau et al., 2018); in Europe, there 48 were between 55,000 and 60,000 hectares of this type of plantation, mainly composed of poplars 49 and willows in 2012 (Mola-Yudego et al., 2017). Fast-growing tree plantations are often 50 51 monocultures (Liu et al., 2018). However, in the context of climate change and resource scarcity, mixed-species plantations can be interesting and several advantages have been highlighted. In 52 particular, a higher stand production in mixtures than in monocultures (over-yielding or 53 transgressive over-yielding) can result from facilitation (i.e. at least one species increases a 54 resource availability for its companion species, especially interesting when mixing N₂-fixing 55 species and non-fixing species) or from complementarity/competitive reduction (Vandermeer, 56 57 1989). In addition, mixed plantations can be more resistant, particularly to diseases and pest attacks (Chamagne et al., 2017; Powell and Bork, 2004). However, mixed plantations are not 58 always more productive than monocultures, and this highlights the need to carefully consider 59 60 species assemblages and specific site conditions (for reviews, see Piotto, 2008, and Marron and Epron, 2019). 61

62 Since fast-growing tree plantations increase around the world and most often on land used for food (Cossalter and Pye-Smith, 2003), using an agroforestry approach in this type of 63 plantations (Lamerre et al., 2015; Tariq et al., 2018; Seserman et al., 2019) could be an attractive 64 65 alternative for farmers. It could reduce land use competition for biomass and food production, while providing forest benefits (Pretzsch et al., 2017). Tropical agroforestry plantations have 66 been widely studied since the last century (e.g. Rao et al., 1998), but in temperate climates, 67 studies of such plantations are still very marginal, even though agroforestry is in progress in 68 Europe (Burgess et al., 2005; Carrier et al., 2019; Swieter et al., 2019) and North America 69 70 (Thevathasan and Gordon, 2004; Reynolds et al., 2007; Borden et al., 2017). Many studies can be found on the effects of trees on crops (Isaac et al., 2014; Bouttier et al., 2014; Inurreta-Aguirre et 71 72 al., 2018; Kanzler et al., 2019), but studies dealing with the effects of crops on trees are less

frequent in the literature (e.g. but see Balandier et al., 2007 for various species of grass associated to wild cherry (*Prunus avium*)). In addition, when studies focus on the tree component in agroforestry systems, they generally deal with overall tree productivity (Lamerre et al., 2015), without more finely studying their growth dynamics, for example, or the interaction processes between species.

78 These interaction processes are still poorly understood, especially when it comes to 79 interactions between herbaceous and woody species in agroforestry, which is at the crossroads of forestry and agronomy. In any plantation, interactions between individuals of the same species 80 81 (intra-specific) or between individuals of two different species (interspecific) can be negative (i.e. 82 competition), positive (i.e. competitive reduction and facilitation) or neutral. The same types of interactions can take place between the woody and herbaceous species in agroforestry plantations 83 (Everson et al., 2009; Jose et al., 2004). The herbaceous component may be negatively impacted 84 by the woody component with regard to the availability of resources such as light (Carrier et al., 85 2019). The competition for light will become more intense as the trees mature due to the increase 86 87 in shading by the canopy (Inurreta-Aguirre et al., 2018). Thus, the yield of crops close to the trees decreases. This was shown by Bouttier et al. in 2014 where the herbaceous cover (Phleum 88 pratense and Trifolium pratense) yield decreased by 75% near poplars (Populus deltoides × 89 90 Populus nigra) in an intercropping system compared to control plots. Larger litter deposition within 1 m of the tree strip can also cause a decrease in the yield of the underlying crop, but, in 91 Swieter et al., 2019, this negative impact did not affect overall crop yields. On the other hand, the 92 93 two components, herbaceous and woody, can be complementary in their use of resources such as soil water. Indeed, trees have been shown to use water more efficiently when they are associated 94 95 with a crop, compared to when they are in monoculture. Fernández et al., 2008, found that pines (Pinus ponderosa) used deeper water resources (below 20 cm) due to the presence of herbaceous 96 97 roots in the top 20 cm of the soil layer in agroforestry than did pines in a monoculture. 98 Facilitation can also occur in these systems. For example, Powell and Bork (2004) observed an 99 increase in overall available soil nitrogen in an agroforestry system composed of poplars 100 (*Populus tremuloides*) and alfalfa (*Medicago sativa*). The performance of species mixture 101 systems is the net result of the above- and belowground interactions between the associated 102 species.

The aim of our study was to compare the performance of fast-growing trees in different 103 104 mixtures and in their respective monocultures: i.e. poplar (*Populus nigra* \times *P. deltoides*) and alder (Alnus glutinosa), in association with herbaceous species either N2-fixing species 105 (succession alfalfa (Medicago sativa) - clover (Trifolium pratense)) or graminoids species 106 107 (succession of wheat (Triticum aestivum) - triticale (Triticosecale) - temporary grassland consisting of mixtures of perennial ryegrass (Lolium perenne) and fescue (Festuca ovina)), 108 respectively. We studied the effects of the different types of species mixtures on tree intra- and 109 inter-annual growth dynamics, compared to the respective tree monocultures. Our main 110 hypothesis was that trees would be larger and taller in mixture plots than in monoculture due to a 111 112 reduction in species competition and/or facilitation provided by the presence of N₂-fixing species (alfalfa – clover and alder), which increase the soil in nitrogen and benefit the non N_2 -fixing 113 species (graminoids and poplar). 114

115 **2. Materials and methods**

116 *2.1. Study area*

117 The experimental plantation is located in an agricultural field at the experimental farm of 118 La Bouzule near Nancy, in northeastern France (48°44′19" N, 6°18′50″ E, 219 m asl). The region 119 is characterized by a warm temperate climate, as shown in the Köppen-Geiger climate 120 classification world map (Kottek et al., 2006). The soil is a Vertic Stagnic Cambisol (IUSS Working Group WRB 2006). The mean annual precipitation and temperatures were, respectively,
550 mm and 10.3°C between 2014 and 2019.

123

124 2.2. Experimental design

The experimental plantation was installed in the spring of 2014 and is 448 m long and 73 125 m wide, for a total area of 3.27 ha (Fig. 1.). The plantation consists of three blocks, each 126 127 containing three types of treatments: (i) two kinds of agroforestry, (ii) one forest mixture and (iii) two tree monocultures or two agricultural plots, each plot measuring approximately 0.15 ha (Fig. 128 1.). The agroforestry plots were composed of herbaceous species associated with woody species. 129 From 2014 to 2017, the alder plots were planted with cereals (spring wheat (*Triticum aestivum*) 130 rotated with a winter wheat and triticale (Triticosecale); and the poplar plots with alfalfa 131 132 (Medicago sativa); then from 2018, temporary grassland mixing perennial ryegrass (Lolium perenne) and fescue (Festuca ovina) replaced the cereals and clover (Trifolium pratense) 133 replaced the alfalfa. The forest mixture plot was composed of alternating rows of poplar and 134 135 alder. The cereals and the temporary grassland are grouped together under "graminoids", hereafter. The forest plots (tree monocultures and the forest mixture) were planted at a density of 136 2000 trees per hectare (2.5 m between the rows and 2 m between the trees in a given row) while 137 138 the agroforestry plots had a density of 1000 trees per hectare, every other row of trees being replaced by crops (5 m between the rows and 2 m between the trees) (Fig. 1.). Tree planting was 139 140 realized with 30-cm-long poplar cuttings of the Euramerican poplar clone Dorskamp (Populus *deltoides* × *Populus nigra*) and one-year-old rooted alder (*Alnus glutinosa*) seedlings measuring 141 from 50 to 80 cm in height. A total of 3649 trees were planted, corresponding to 1836 poplars 142 and 1813 alders. The plantation design leaves sufficient room at the extremity of the rows 143 necessary for the agricultural machinery to pass along. The orientation of tree lines and the 144 spatial distribution of treatments have been chosen to minimize wind and shelter effects (Figure 145

1). To reduce border effects, one border row around each plot was not included in the 146 measurements. In the internal plots, we took into account 732 poplars in monoculture, 697 alders 147 in monoculture, and 440 poplars and 440 alders in the agroforestry and forest mixture. Grass 148 strips of 1 m in overall width were present at the base of the tree lines in agroforestry treatments 149 (0.5 m on each side of the trees). Mechanical and chemical weed control was realized on the tree 150 rows in 2014 and 2015. The plantation was neither watered nor fertilized. No pruning 151 management was performed. In 2019, total tree mortality was 5%, mostly in block 3 where soil 152 was shallower. 153

154

[Insert Fig. 1. here]

155

156 2.3. Monitoring of soil and climate conditions

In 2014, initial soil characterization was carried out on soil cores (0-60 cm in depth, 157 diameter of 8 cm) sampled in the central inter-row of each plot (Clivot et al., 2019). On average, 158 soil composition was 60.9 % clay, 34.8 % silt and 4.4 % sand, between 0 and 60 cm in depth. The 159 pH was 7.4 on average and the exchange acidity (Al³⁺ and H⁺) was 1. There was some spatial 160 variability over the site in the soil parameters, with increasing pH and carbon content from block 161 162 1 to block 3 (Fig. 1.), whereas soil depth decreased due to an outcrop of rocky material (calcareous) near the soil surface in block 3. To monitor soil mineral nitrogen, three soil cores 163 164 were sampled (0-15 cm in depth, diameter of 8 cm) in the central inter-row of each of the five modalities (i.e. poplar and alder monocultures, poplar and alder agroforestry, forest mixture) in 165 July 2018. The soil mineral nitrogen was extracted with 1M KCl (45 min of agitation at 20°C, 1:4 166 soil/solution ratio) and filtered on a Whatman 42 paper disc. The mineral nitrogen in the soil 167 extracts was analyzed by continuous flow colorimetry (Skalar analyzer). 168

Instruments to monitor environmental conditions were set up in the plantation in 2014, and include a rainfall gauge (ARG100, Campbell Scientific, Inc., Logan, UT, USA) and a thermistor (HMP45C probe, Campbell Scientific, Inc., Logan, UT, USA). Volumetric soil water content (SWC, %) was monitored hourly with water content reflectometers (CS615, Campbell Scientific, Inc., Logan, UT, USA) inserted into the soil at an equal distance between two trees in the row at depths of 10, 30 and 80 cm (Fig. 1.). Meteorological and SWC data were recorded and stored on data loggers (CR3000, Campbell Scientific, Inc., Logan, UT, USA).

176

177 2.4. Tree dimension measurements

Tree growth was assessed by measuring the stem height and diameter at breast height 178 (DBH) of all the trees at the end of each growing season. In addition, a representative sample of 179 tree height classes was defined in 2015. During growing seasons (April to August), tree growth 180 181 was monitored every three weeks for 20 poplars and 20 alders in each treatment in the three blocks, for a total of 360 individuals: 20 trees \times 2 species \times 3 blocks \times 3 treatments (monoculture, 182 agroforestry, forest mixture). Height was estimated from the base of the tree to the last bud of the 183 tallest stem with a graduated pole accurate to the nearest centimetre from 2015 on. DBH was 184 measured with a digital caliper to the nearest millimetre from 2017 on. 185

186

187 2.5. Inter- and intra-annual height growth dynamics

In order to visualize inter-annual tree growth dynamics, height growth rate (cm day⁻¹) was
calculated for each tree and each year following equation (1):

190
$$HGR_{inter} (cm \, day^{-1}) = \frac{(H_{final} - H_{initial})}{\Delta_{time}}$$
(1)

191 where

193 H_{final} = the last height value of the growing season,

194 $H_{initial}$ = the first height value of the growing season,

195 Δ_{time} = the time interval between bud break (beginning of April) and bud set (end of

196 August).

For intra-annual height growth dynamics, height growth rate (cm day⁻¹) was defined as the height difference between two successive measurement dates during the growing season, divided by the time between the two dates (equation 2):

200
$$HGR_{intra} (cm \, day^{-1}) = \frac{(H_{n+1} - H_n)}{(T_{n+1} - T_n)}$$
 (2)

- 202 *HGR*_{intra} is the intra-annual height growth rate,
- 203 H_n = the height value at time n,
- 204 H_{n+1} = the height value at time n+1,

205 T_n = the date at time n,

206 T_{n+1} = the date at time n+1.

207 Only the data for 2018 are presented and discussed for intra-annual dynamics, because 208 2018 weather conditions were quite specific, the year being warmer than the other years, with 209 less precipitation (Fig. 2.) and with a net decrease in SWC during the summer (Fig. A1.). Growth 210 rate data for the years 2016, 2017 and 2019 are available as supplementary files (Figs. A2., A3. 211 and A4.).

212

213 2.6. Calculation of competition indices

For each tree, the height to DBH (h/d) ratio (m cm⁻¹), which is a measure of tree shape, was calculated and used as an indicator of the level of competition (Forrester et al., 2004; Ghorbani et al., 2018). In the forest plots only (mixture and monocultures), we also used the Hegyi index to evaluate the strength of neighboring competition (Hegyi, 1974). This index is typically used to characterize local competition (Vanclay, 2006) and was calculated following equation (3) (according to Prevosto, 2005):

220
$$IC_i = \sum_{\substack{j=1\\j\neq 1}}^{n} \frac{d_j}{d_i L_{ij}}$$
 (3)

221 where

- 222 IC_i is the competition index of subject tree i,
- 223 d_i = the DBH of subject tree i,
- 224 d_j = the DBH of competitor tree j,

225 L_{ij} = the distance between subject tree i and competitor j,

226 n= the number of competitors (total = 8 neighboring trees: 2 in the same row and 3 each 227 in the two adjacent rows).

228

229 2.7. Estimation of leaf nitrogen

In 2018, ten fully expanded sun-exposed leaves were collected per treatment and per species once a month in June, July and August. The leaves were oven-dried at 60°C for at least 48h, then ground to powder. Nitrogen concentrations (N_{leaf} , mg g⁻¹) were measured with an elemental analyzer (NA-1500, Carlo Erba, Italy) from a sample of 2.0 ± 0.1 mg of dry powder.

234

235 2.8. Statistical analyses

Statistical tests were done with the free R software, version 4.0.0 (R Development Core Team, 2019). Means were expressed with their standard errors. Statistical tests were considered significant at $*P \le 0.05$, $**P \le 0.01$ or $***P \le 0.001$.

We used the non-parametric Kruskal Wallis test to assess the effect of the species \times treatment interaction on volumetric soil water content (SWC) at different depths (10 cm, 30 cm, 80 cm) for each year. When a significant effect was recorded (*P*≤0.05), we used the Wilcoxon test for pairwise comparisons.

The effects of species, treatment (three treatments: monoculture, agroforestry, forest mixture), date and their interactions (species × treatment, species × date, treatment × date, species × treatment × date) were tested on growth parameters (height, diameter, HGR_{inter} and HGR_{intra}) and on competition indices (Hegyi index, h/d ratio). A mixed-effect model, incorporating both fixed and random effects, was adjusted to the data (lmer function of the lme4 package) with the Maximum Likelihood (ML) method, to test the fixed effects. The model had the following form:

249 Variable ~ Species*Treatment*Year + (1|ID)

Species, treatment and date were defined as fixed effects; ID, corresponding to each treemeasured, was defined as a random effect.

As no date effect on leaf nitrogen contents during the 2018 growing season was recorded, only the following effects were tested with a two-way ANOVA: species, treatment and their interaction. We used the non-parametric Kruskal Wallis test to assess the effect of the modality (five modalities: poplar and alder monocultures, poplar and alder agroforestry, forest mixture) on soil organic nitrogen contents in 2018. When a significant effect was recorded ($P \le 0.05$), the Wilcoxon test was used for pairwise comparisons.

258

259 **3. Results**

260 *3.1. Climate variation over time*

During growing season (April through August), cumulative rainfall ranging between 197 mm and 413 mm (mean 265 mm) and daily temperatures between 15.2°C and 17.5°C (mean 16.1°C) were recorded at the experimental site. From 2016 to 2019, cumulative rainfall during growing season decreased year after year, with 413 mm in 2016 compared to 197 mm in 2019. Year 2018 was the warmest year with an average air temperature of 17.5°C during the April-August period (11.2°C over the whole year). Very little precipitation was recorded in June and July 2018, compared to the other years.

268

[Insert Fig. 2. here]

In 2017, SWC at 10 cm deep was significantly different between species ($P \le 0.001$) and 269 treatments ($P \le 0.001$) (Table 1). The soil was moister for poplars in agroforestry and the forest 270 271 mixture with a SWC of 30.5% and 28.7% (mean values during the growing season), respectively, 272 than for poplars in the monoculture with 20.4%. For alders, soil moisture was 10% higher in the forest mixture than in agroforestry. Soil moisture was also higher in the alder rows (39.3%) than 273 274 in the poplar rows (28.7%) in the forest mixture. In 2018, although the difference was not significant, the soil was moister for poplars in agroforestry than for poplars in monoculture, with 275 a SWC of 36.5% versus 27.7%, respectively. In 2017, SWC at 30 cm deep was significantly 276 higher in agroforestry than in forest mixture for poplars (41.2% versus 27.3%) and, for alders, it 277 was significantly higher in agroforestry (38.9%) than in forest mixture and monoculture (24.6%) 278 279 and 25.7%, respectively).

280

[Insert Table 1 here]

281

282 *3.2. Soil and leaf nitrogen contents*

In July 2018, average N-NO₃⁻ in the soil was significantly higher in poplar agroforestry than in the other modalities ($P \le 0.01$; Table 2). Average levels of leaf nitrogen (N_{leaf}) were higher for alders than for poplars ($P \le 0.001$), except for the poplars in agroforestry. In agroforestry, the poplars also had slightly higher, though non-significant, N_{leaf} values compared to the poplars in the monoculture and in forest mixture (Table 2).

288

[Insert Table 2 here]

289 *3.3. Tree dimensions*

From 2015 to 2017, poplars were taller in forest plots than in agroforestry and, in 2017, 290 reached a height of 276 cm in monoculture and 250 cm in forest mixture versus 223 cm in 291 agroforestry (Fig. 3.). However, the poplars in agroforestry caught up with the poplars in the 292 forest mixture at the end of 2017 and with the poplars in monoculture in 2018. At the end of the 293 294 2019 growing season, agroforestry poplars were significantly taller than the poplars in the forest treatments, with 475 cm versus 382 cm in forest mixture and 437 cm in monoculture. At this 295 296 time, alder heights were not significantly different among treatments (Fig. 3.). From 2015, the 297 poplars in the forest treatments were taller than the alders in any treatment (i.e. 158 cm for poplars in monoculture compared to 101 cm for alders in monoculture, in 2015). From 2018, 298 agroforestry poplars were also significantly taller than alders in any treatment (Fig. 3.). 299

300

[Insert Fig. 3. here]

A significant treatment × date effect was recorded for poplars in terms of DBH: while poplars in monoculture had the largest diameter in 2017 and poplars in agroforestry the smallest, by 2019 the latter exhibited a significantly larger diameter than the poplars in the forest plots (Table 3). At the end of 2019, alder DBH was not significantly different among treatments. Regardless of year and treatment, poplar stems were about 10 to 20 mm larger than alder stems.

306

[Insert Table 3 here]

307 *3.4. Growth dynamics*

308 *3.4.1. Inter-annual growth dynamics*

For poplars, a significant treatment effect on height growth rates was found each year, 309 except in 2016 (Fig. 4.). In 2015, poplars had slower growth in agroforestry plots than in forest 310 mixture: 0.3 cm day⁻¹ and 0.4 cm day⁻¹, respectively ($P \le 0.05$). Inversely, in 2017, the 311 agroforestry poplars were the ones with the highest growth rate: 0.5 cm day⁻¹ for agroforestry vs. 312 0.3 cm day⁻¹ for forest mixture ($P \le 0.001$). In 2018, agroforestry poplars had a height growth rate 313 almost twice as high as the poplars in the forest mixture and in monoculture, with an average 314 height increase of 0.8 cm per day versus 0.4 cm per day and 0.5 cm per day for forest mixture and 315 monoculture, respectively ($P \le 0.001$). In 2019, the same trend as in 2018 was found between 316 agroforestry (0.8 cm day⁻¹) and forest mixture (0.4 cm day⁻¹; $P \leq 0.05$), but there was no longer a 317 significant difference between agroforestry and monoculture (0.6 cm day⁻¹). For alders, there was 318 319 a significant treatment effect in 2016 ($P \le 0.001$) and in 2017 ($P \le 0.01$): agroforestry alders had a height growth rate higher than the alders in forest treatments. A significant date effect was also 320 found for both poplars and alders: for poplars, height growth rates were lower in 2015 and 2017 321 322 than in the other years ($P \le 0.001$); for alders, height growth rates were lower in odd years than in even years ($P \leq 0.05$). 323

324

[Insert Fig. 4. here]

325 *3.4.2. Intra-annual growth dynamics*

For each species and in each treatment, average growth in height per day was the fastest at the beginning of June with between 1.3 cm (the lowest value observed for poplars in agroforestry and in monoculture) and 2 cm (the highest value observed for agroforestry alders). A species effect was also observed in early June: alders in forest mixture had significantly higher height growth rates ($P \le 0.05$) than did poplars in the same treatment (1.75 cm day⁻¹ versus 1.4 cm day⁻¹ on average, respectively).

During summer, there was a significant species \times treatment effect on HGR_{intra} only in 332 333 2018 (Table A1). In July and August, agroforestry poplars exhibited a higher height growth rate than did the poplars in monoculture and forest mixture ($P \leq 0.001$, Fig. 5., Table A1). Indeed, in 334 July, poplar growth in agroforestry was between three and five times higher than for poplars in 335 336 monoculture and forest mixture, respectively. In August, poplar growth in the forest plots nearly stopped while the agroforestry poplars continued to gain 0.4 cm per day on average. For alders, 337 there was no significant treatment effect on height growth rates in 2018: the alders in each 338 339 treatment followed the same dynamics, i.e. a peak in growth in early June followed by a gradually decreasing rate. In September, poplar and alder height growth stopped in all treatments. 340

341

[Insert Fig. 5. here]

342 3.5. Intra- and inter-specific competition

343 *3.5.1. Hegyi index*

Irrespective of the year, there was a significant species \times treatment effect with a 344 significantly higher Hegyi index for poplars in monoculture and alders in forest mixture than for 345 poplars in forest mixture and alders in monoculture (4.57 and 5.72 versus 4.05 and 4.21, 346 respectively, in 2017; Fig. 6.). A significant date effect was also found. For alders, the gap 347 348 between monoculture and forest mixture was more pronounced in 2019 than in 2017 and 2018, with a significant increase in the Hegyi index in forest mixture (5.95 in 2019 versus 5.72 in 2017 349 and 5.61 in 2018). For poplars, the contrary was observed (although the trend was non 350 significant): the gap between monoculture and forest mixture was less pronounced than in 2017 351 and 2018, with a decreasing index in the monoculture (4.82 in 2019 versus 5.57 in 2017). 352

353

[Insert Fig. 6. here]

354 *3.5.2. Height to DBH (h/d) ratio*

There was a significant date effect irrespective of treatment and species, with h/d355 decreasing over time (Table 4). Each year, the species × treatment interaction was significant. In 356 357 2017, there was a higher h/d ratio for poplars in agroforestry than for poplars in monoculture and forest mixture; alders in all treatments also had a higher h/d ratio than poplars in monoculture and 358 forest mixture (Table 4). From 2018, there was a clear decrease in h/d for both poplars and alders 359 in agroforestry. In 2019, agroforestry poplars showed a lower ratio than monoculture poplars with 360 a value of 1.25 m cm⁻¹ versus 1.53 m cm⁻¹, respectively. Agroforestry alders had a lower h/d than 361 alders in forest mixture with a value of 1.36 m cm⁻¹ versus 1.58 m cm⁻¹, respectively. The h/d was 362 lower for poplars than for alders in forest mixture (1.41 m cm⁻¹ vs. 1.58 m cm⁻¹). 363

364

[Insert Table 4 here]

365 **4. Discussion**

We investigated how the performance of fast-growing trees, i.e. poplar and alder, in 366 monocultures is affected when the species are associated in mixed stands and when they are 367 associated with herbaceous species (with an alfalfa-clover succession for poplar and with 368 graminoids for alder). In particular, we present six years of growth monitoring of a large number 369 370 of trees. Our main hypothesis was that interspecific competition in mixture plots (both mixed forest stands and tree-crop mixtures) would be less strong than intra-specific competition in tree 371 372 monocultures, due to ecological niche sharing between species and/or facilitation processes caused by the presence of N₂-fixing species (alfalfa, clover, alder) in the mixtures. We therefore 373 expected that the trees would grow faster and be larger and taller in mixtures than in 374 monocultures. 375

376 *4.1. Climate conditions*

The weather conditions measured from 2016 to 2019 were contrasted among years. 377 Conditions were particularly dry during the 2018 growing season with a drastic decline in 378 precipitation during precisely those months where tree growth is usually high (June-July). 379 Moreover, both mean annual temperature and April-August temperatures were, on average, 380 higher in 2018 than in the other years. This resulted in a marked decrease in SWC in July and 381 August 2018: in August, at 10 cm in depth, the minimum value was measured for poplars in 382 monoculture with a SWC of 15% and the maximum value was recorded for poplars in 383 agroforestry with a SWC of 28%, corresponding respectively to 41% and 77% of field capacity 384 (Fig. A1.). 385

386 *4.2. Trends over time*

387 *4.2.1. Agroforestry vs. monoculture*

Shortly after planting, the agroforestry poplars exhibited a delayed growth rate compared 388 389 to the poplars in the monoculture and forest mixture. This may be due to belowground competition between the poplars and the alfalfa immediately after planting. Indeed, crops can 390 391 reduce the nutrient and water available to trees, thereby reducing their growth (Burgess et al., 392 2005); this is especially true for legumes such as alfalfa, which can have deep, competitive roots like trees (Dawson et al., 2001). Similar results were highlighted by Gakis et al. (2004), who 393 showed that trees (Acer pseudoplatanus and Pinus sylvestris) associated with legumes (Trifolium 394 395 *repens*) had a lower height and a smaller stem diameter than in monoculture. Moreover, Powell and Bork (2004) showed that the height and diameter of poplars (Populus tremuloides) were 396 reduced by 30% when they were associated with alfalfa (Medicago sativa) during the early stages 397 of development. In our study, alfalfa was replaced by clover during the fifth growing season 398 (2018). At this stage, the trees were well established and the belowground competition with the 399 400 crop was probably less strong. Indeed, in 2019, the agroforestry poplars had an average height and diameter greater than the poplars in the monoculture. Moreover, from 2018 on, the heightgrowth rate of the agroforestry poplars was consistently higher than for the monoculture poplars.

After six years of growth, the monoculture poplars exhibited a higher h/d ratio than did 403 the agroforestry poplars. This result suggests that the intra-specific competition in the 404 monocultures was more intense than the interspecific competition faced by the trees in 405 agroforestry. Our results are in line with those of Rivest on Populus spp. for intercropping with 406 soybean (Glycine max) and cereals (Rivest et al., 2009). In the latter study, shortly after planting, 407 the intercrop was not beneficial to poplar growth, but after four years, DBH and stem height were 408 higher in agroforestry than in the monoculture. The authors argued that these results were mainly 409 410 due to the effect of intercrop fertilization applied during their study. At our experimental site, the crops were not fertilized but the alfalfa and then the clover, which are both N₂-fixing species, 411 may have had a positive effect on poplar growth. Indeed, the diameter increment of the poplars in 412 the agroforestry treatment was approximately 15 mm per year between 2017 and 2019, vs. 8 mm 413 in the monoculture. Similarly, Taghiyari and Efhami (2011) showed a positive effect on the 414 415 diameter increment of Populus nigra in mixtures with alfalfa, with an average annual increment 416 of 13.8 mm over ten growing seasons vs. 12.2 mm without alfalfa. Recently, Shults et al. (2020) also showed an increase in soil N-NO3⁻ ranging between 150 and 220% in a poplar (Populus 417 $nigra \times P$. maximowiczii) short rotation plantation intercropped with clover (*Trifolium pretense*) 418 419 compared to a bare-soil control; this increase caused a 25% increase in poplar leaf nitrogen 420 concentrations, but poplar productivity was not significantly increased within two years. In our study, soil mineral nitrogen (N-NO₃⁻) content was more than five times higher in agroforestry 421 422 than in the monocultures five years after planting. This is likely due to the symbiotic fixation of atmospheric dinitrogen by the alfalfa and the clover but also due to increased nitrogen availability 423 through root deposition. Many studies have shown that alfalfa has very high N_2 fixation rates 424 (Burity et al., 1989; Russelle and Birr, 2004) and that legumes release nitrogen rhizodeposits with 425

a low C/N ratio that are assumed to represent a significant return of nitrogen to the soil (Mayer et 426 al., 2004). Excess soil nitrogen may therefore have benefited the trees, as evidenced by the 427 slightly higher leaf nitrogen content in the agroforestry poplars. This result could be evidence of a 428 429 facilitation process (Powell and Bork, 2004). Moreover, the different tree planting density in the agroforestry treatment, where every second row of trees was replaced by the crop, probably 430 reduced the competition for light among the trees. Indeed, as the spacing between trees increases, 431 the competition for light decreases (Benomar et al., 2013). The predominant interaction in 432 agroforestry therefore seems to shift from competition, during the first years after planting, to a 433 combination of reduced competition and facilitation. 434

In agroforestry, poplar growth did not seem to be affected by the dry and warm summer in 435 2018. Indeed, height growth rates remained high during the summer months, compared to 436 monoculture where growth nearly stopped as of July. Overall, soil water content was the highest 437 438 in the agroforestry treatment and the lowest in the monoculture. In our study, at 10 cm in depth, the SWC was between 7% and 12% higher in agroforestry than in forest treatments (both in 439 440 monoculture and mixed stands) for the dry period in 2018 (July-August). This is consistent with 441 Powell and Bork's (2004) findings; they showed that alfalfa can facilitate soil moisture retention. A dense herbaceous cover (as alfalfa provides) limits evaporation from the top soil by reducing 442 the exposure of the soil to wind and sun (Powell and Bork, 2004). Moreover, poplar and the crop 443 (alfalfa – clover) may have different spatial distributions of their root system, thus reducing the 444 competition for soil water. This was shown by Thevathasan and Gordon (1995) for a poplar / 445 barley mixture (Populus spp. and Hordeum vulgare) where the barley roots were mostly confined 446 447 in the top 10 cm of the soil while the poplar roots were deeper. This could be another positive effect of agroforestry on poplar growth, once the dominant effect of the crop on water 448 competition with tree roots in the first few years is passed. 449

450 *4.2.2. Forest mixture vs. monoculture*

At the end of the experiment, the poplars in the forest mixture were shorter and narrower 451 than the poplars in the monoculture. A recent meta-analysis has shown that mixed-tree 452 plantations including a N₂-fixing species like alder were globally more productive than the 453 corresponding monocultures of the non-fixing species (Marron and Epron, 2019), and that this 454 effect was more pronounced on poor soils (Binkley 1983). Despite this general trend, the meta-455 analysis also inventoried studies where mixture plantations were less productive than 456 monocultures (e.g. Marron et al. 2018), as is the case in the present study. Indeed, the mean 457 diameter we recorded in our study was significantly lower for poplars in forest mixture than in 458 monoculture. The soil nitrogen content was slightly, but not significantly, higher in alder 459 460 monoculture and in forest mixture compared to poplar monoculture, suggesting that symbiotic fixation by alders did occur but had no significant effect on the growth of the non-fixing species, 461 at least during the time span of our study. Teissier du Cros et al. (1984) also showed that, a few 462 463 years after planting, nitrogen fixation by alder (Alnus glutinosa) was not yet sufficient to benefit poplar (*Populus trichocarpa* \times *deltoides*) growth, at stand level. 464

465 We found no significant treatment effect on tree height or DBH for alders. According to Piotto's meta-analysis (2008), forest mixtures have little or no effect on tree height growth rates 466 at stand level, but generally do have a positive effect on stem diameter increment. However, in 467 mixtures including N₂-fixing species, the diameter of the fixing species was negatively affected. 468 Sayyad et al. (2006) showed similar results in a poplar/alder mixture (Populus deltoides and 469 470 Alnus subcordata) where alder diameter was significantly higher in monocultures than in association with poplars. In this association, poplar growth only benefited from the presence of 471 472 the other species. In our study, the absence of effect on alder may be due to the fact that, as alder growth is slower than poplar growth, it was simply too soon to observe interaction effects. 473 Poplars were significantly taller than alders in forest mixture, i.e. slightly less that one and a half 474 times taller. Moreover, from 2015 to 2018, alders had an average height growth rate of 54 cm per 475

year while for poplars, the average rate was 75 cm per year. Our results are in agreement with 476 Côté and Camiré (1987), who showed that poplars (Populus nigra × Populus trichocarpa) were 477 between one and a half and two times taller than alders (Alnus glutinosa) in forest mixture. We 478 479 suppose that these size differences between species creates a stratification of their canopies in the mixture, thus bringing about a reduction in competition for light. A study of competition indices 480 supports this theory. Based on the Hegyi index for poplars, it appeared that the intra-specific 481 competition in the monocultures was higher than the interspecific competition in the forest 482 mixture, in agreement with the trend observed for the h/d ratio. According to Vanclay (2006), a 483 high Hegyi index means that the subject tree has more and/or larger neighbors, resulting in a 484 485 decrease in the growth of the subject tree. In our study, with similar tree densities in all the forest plots, a high Hegyi index therefore means that the subject tree has larger neighbors. In forest 486 mixture, the lower Hegyi index (reduced competition) for poplars compared to their monoculture 487 488 may indicate that canopy stratification reduced the competition for light (Ghorbani et al., 2018). According to Forrester et al. (2004), canopy stratification is a factor to consider as long as there is 489 490 a significant difference in height between the species in the same treatment, which is what we observed in our study. Furthermore, considering that the individuals of a given tree species have 491 similar ecological requirements and therefore more potential niche overlap than individuals from 492 different species (Yang et al., 2019), we assume that poplars probably competed for the same 493 resources, and this may explain why the Hegyi index of poplar was higher in the monoculture. 494 For alders, on the contrary, intra-specific competition was less strong than interspecific 495 competition. We assume that, because poplars were taller and the forest cover was gradually 496 497 starting to close, the alders suffered from poplar competition for light and allocated more carbon to height than to diameter (Benomar et al., 2013). In other words, the alders sought light by 498 499 favoring growth in height in the forest mixture, whereas in alder monoculture, the canopy had not vet started to close. 500

It is supposed that the stratification of the canopy and the root systems in mixed 501 plantations allows the trees to more efficiently capture light (Kelty, 1992), water (Bai et al., 2016; 502 Battipaglia et al., 2017) and nutrient resources (Binkley et al., 1992). However, at 30 cm in depth, 503 504 the soil water content was the lowest in the forest mixture, irrespective of the year. The roots of the poplars and alders may have overlapped and been competing for water. Indeed, poplars in 505 general (Populus spp.) are highly competitive at this depth, compared to other species (e.g. 506 Juglans nigra and Quercus rubra), due to their high concentration of fine and coarse roots 507 508 (Borden et al., 2017). In our study, reduced competition could have occurred aboveground, thus improving light capture in the mixture, at least for poplar, but belowground, competition for the 509 water resource could have remained strong, thus resulting in lower tree performances in terms of 510 growth in the forest mixture compared to the monocultures of the two species. 511

512 **5. Conclusion**

After six years of growth, positive interactions seem to be at play in the poplar / legume 513 association, in agreement with our main hypothesis. Our results show that intercrops with N2-514 fixing species can significantly improve poplar growth. However, careful weeding of tree rows 515 516 during the first years after planting is necessary in order to control the strong interspecific competition between the trees and the herbaceous species. On the other hand, in the poplar / alder 517 518 association, poplar growth was negatively affected compared to its monoculture, despite a stratification of the canopy suggesting aboveground niche sharing. This negative effect could be 519 due to a stronger competition for soil water between species than in the monoculture, and to the 520 521 fact that nitrogen fixation by the alder was not yet sufficient to benefit the poplars. Alder growth did not appear to be affected by the different kinds of mixtures, suggesting that alder is not 522 523 limited by soil resources and/or the experiment ended too soon to observe interaction effects for 524 this species.

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803

804 Figure captions

Fig. 1. Experimental design of the La Bouzule site. Size of the plots and locations of humidity
probes and data loggers are indicated. Details of the forest mixture and agroforestry plots are also
presented, showing spacing between trees and crops.

Fig. 2. Cumulative monthly rainfall (histograms, mm) and mean temperatures (dots, $^{\circ}$ C) between April 1st and August 31, from 2016 to 2019 at the experimental site. CAR = cumulative annual rainfall (mm); MAT = mean annual temperature ($^{\circ}$ C).

Fig. 3. Inter-annual dynamics of stem heights (in cm) of poplars and alders in monocultures, forest mixture and agroforestry between 2015 and 2019. The shaded areas show the 95% confidence intervals. Different uppercase letters indicate significant differences between dates; different lowercase letters indicate significant differences between treatments at the end of the experiment. For each effect (D, date; S, species, T, treatment) and their interactions (S×T, T×D, S×D, S×T×D), significant differences are indicated by asterisks: $P \le 0.05^*$, $P \le 0.01^{**}$, $P \le 0.001^{***}$, *ns* for non-significant.

Fig. 4. Annual-based height growth rates (HGR_{inter} , cm day⁻¹) for poplar (A) and alder (B) since 818 819 2015 in agroforestry, forest mixture and monocultures (n=60). Different letters indicate significant differences between treatments for each growing season (April to August). For each 820 effect (D, date; S, species, T, treatment) and their interactions (S×T, T×D, S×D, S×T×D), 821 significant differences are indicated by asterisks: P≤0.05*, P≤0.01**, P≤0.001***, ns for non-822 823 significant. Each box represents the quartile below (Q1) and above (Q3) the median value. The diamond in the box represents the mean of all trees. Vertical bars represent minimum and 824 825 maximum values. Grey dots are individual values.

Fig. 5. Intra-annual height growth rates (HGR_{intra} , cm day⁻¹) for poplar (A) and alder (B) in monocultures, forest mixture and agroforestry between April and August 2018 (n=60). For each effect (D, date; S, species, T, treatment) and their interactions (S×T, T×D, S×D, S×T×D), significant differences are indicated by asterisks: $P \le 0.05^*$, $P \le 0.01^{**}$, $P \le 0.001^{***}$, *ns* for nonsignificant. Each box represents the quartile below (Q1) and above (Q3) the median value. Vertical bars represent minimum and maximum values. Dots are outliers.

Fig. 6. Hegyi index for diameter for poplar and alder in monocultures and forest mixture in 2017, 2018 and 2019. Different uppercase letters indicate a significant difference between dates; for each date, different lowercase letters indicate significant differences for the $S \times T$ interaction. For each effect (D, date; S, species, T, treatment) and their interactions (S×T, T×D, S×D, S×T×D), significant differences are indicated by asterisks: $P \le 0.05^*$, $P \le 0.01^{**}$, $P \le 0.001^{***}$, *ns* for nonsignificant.

Fig. A1. Time course of soil water content (SWC, %) at the experimental site between April and
August 2018 at 10 cm (A), 30 cm (B) and 80 cm (C) in depth, depending on the treatment and
species (P, poplar / A, alder). SWC values shown are the mean value for each month. Means ±
standard errors.

Fig. A2. Time course of intra-annual height growth rates (HGR_{intra} , cm day⁻¹) for poplar (A) and alder (B) in monocultures, forest mixture and agroforestry between April and August 2016 (n=60). The effects of date (D), treatment (T) and their interaction ($D \times T$) are indicated for $P \le 0.05^*$, $P \le 0.01^{**}$ and $P \le 0.001^{***}$, *ns* for non-significant. Each box represents the quartile below (Q1) and above (Q3) the median value. Vertical bars represent minimum and maximum values. Dots are outliers.

Fig. A3. Time course of intra-annual height growth rates (HGR_{intra} , cm day⁻¹) for poplar (A) and alder (B) in monocultures, forest mixture and agroforestry between April and August 2017 (n=60). The effects of date (D), treatment (T) and their interaction ($D \times T$) are indicated for $P \le 0.05^*$, $P \le 0.01^{**}$ and $P \le 0.001^{***}$, *ns* for non-significant. Each box represents the quartile below (Q1) and above (Q3) the median value. Vertical bars represent minimum and maximumvalues. Dots are outliers.

Fig. A4. Time course of intra-annual height growth rates (HGR_{intra} , cm day⁻¹) for poplar (A) and alder (B) in monocultures, forest mixture and agroforestry between April and August 2019 (n=60). The effects of date (D), treatment (T) and their interaction ($D \times T$) are indicated for $P \le 0.05^*$, $P \le 0.01^{**}$, and $P \le 0.001^{***}$, *ns* for non-significant. Each box represents the quartile below (Q1) and above (Q3) the median value. Vertical bars represent minimum and maximum values. Dots are outliers.

860 **Table captions**

Table 1 Variations in volumetric soil water content (SWC %) depending on the treatment between 2016 and 2019 at the experimental site. SWC values shown are the mean values during the growing season (April to August). Within columns for each depth, significant differences between species and treatment are indicated: $P \le 0.05^*$, $P \le 0.01^{**}$, $P \le 0.001^{***}$, *ns* for nonsignificant.

Table 2 A) Soil organic nitrogen content (N-NO₃⁻) in the upper 15 cm of the soil in the central inter-row, depending on the modality (5 modalities: poplar/alder agroforestry, poplar/alder monoculture, forest mixture) in 2018. Different letters indicate significant differences between modalities. Means \pm standard errors; n=9. B) Leaf nitrogen content (N_{leaf}) for poplar and alder depending on the treatment (3 treatments: agroforestry, forest mixture, monocultures) in 2018. Different letters indicate significant differences between species and treatment. Means \pm standard error; n=30.

Table 3 Diameter at breast height (DBH in mm, means \pm standard errors) for poplar and alder depending on the treatment at the end of each growing season (2017 to 2019). Different uppercase letters indicate significant differences between dates; within each column, different lowercase letters indicate significant differences between treatments. For each effect (D, date; S, species, T, treatment) and their interactions (S×T, T×D, S×D, S×T×D), significant differences are indicated by asterisks: $P \le 0.05^*$, $P \le 0.01^{**}$, $P \le 0.001^{***}$, *ns* for non-significant.

Table 4 Height to DBH ratio (h/d, m cm⁻¹) for poplar and alder in monocultures, forest mixture and agroforestry at the end of each growing season (2017 to 2019) (means ± standard errors). Different uppercase letters indicate significant difference between dates; within each column, different lowercase letters indicate significant differences between treatments. For each effect (D, date; S, species, T, treatment) and their interactions (S×T, T×D, S×D, S×T×D), significant differences are indicated by asterisks: $P \le 0.05^*$, $P \le 0.01^{**}$, $P \le 0.001^{***}$, *ns* for non-significant.

Table A1 Intra-annual height growth rates (*HGR*_{intra}, cm day⁻¹) for poplar and alder in monocultures, forest mixture and agroforestry between April and August 2018 (n=60). Different letters indicate significant differences between species and treatments for each month. The effects of species (*S*), treatment (*T*) and their interaction (*S*×*T*) are indicated for $P \le 0.05^*$, $P \le 0.01^{**}$, and $P \le 0.001^{***}$, *ns* for non-significant. Means ± standard error.

Figures and tables







Fig. 2.

Table	1

		2016		2017 20		2018		2019	
SV	WC %	Poplar	Alder	Poplar	Alder	Poplar	Alder	Poplar	Alder
10 cm	∆ graforestry	376 ± 03	388 ± 0.4	$30.5 \pm 0.3^{\circ}$	28.7 ± 0.4 bc	365 ± 0.5^{ab}	319 ± 0.6^{ab}	353+06	24.8 ± 0.8
in depth	Forest mixture	37.0 ± 0.3 38.4 ± 0.7	33.6 ± 0.4 43.6 ± 0.5	28.7 ± 0.4 bc	$39.3 \pm 0.3^{\text{d}}$	30.3 ± 0.3^{a}	42.4 ± 0.5^{b}	33.3 ± 0.3 32.7 ± 0.3	24.6 ± 0.6 31.6 ± 0.5
	Monoculture	35.2 ± 0.6	38.9 ± 0.6	20.4 ± 0.3^{a}	36.2 ± 0.3^{d}	27.7 ± 0.8^{a}	39.9 ± 0.6 ^{ab}	28.2 ± 0.9	26.7 ± 0.8
		ns, P =	0.06					ns, P =	0.39
30 cm	Agroforestry	47.4 ± 0.3 ab	44.0 ± 0.1 ^{ab}	41.2 ± 0.2 ^b	38.9 ± 0.3^{b}	45.0 ± 0.3 ^b	34.5 ± 0.6^{ab}	37.1 ± 0.7	32.0 ± 0.7
in depth	Forest mixture	36.0 ± 0.6 ab	36.1 ± 0.5^{a}	27.3 ± 0.4^{a}	25.7 ± 0.3^{a}	29.9 ± 0.4^{a}	29.2 ± 0.7 ^a	35.3 ± 0.4	28.3 ± 0.7
	Monoculture	$\pm 45.1 \pm 0.3$ ^b	39.6 ± 0.5 ab	38.6 ± 0.3 ^b	24.6 ± 0.7 ^a	42.3 ± 0.4 ab	32.8 ± 0.7 ^{ab}	39.4 ± 0.5	28.8 ± 0.9
								ns, P =	0.37
80 cm	Agroforestry	48.4 ± 0.1 ^c	46.4 ± 0.0 bc	42.5 ± 0.1 ^b	42.8 ± 0.1^{b}	42.6 ± 0.2^{b}	44.9 ± 0.1^{b}	41.8 ± 0.3 ab	41.7 ± 0.2 ab
in depth	Forest mixture	$\pm 47.5 \pm 0.1$ ^c	45.0 ± 0.1 bc	42.6 ± 0.2 ^b	39.3 ± 0.2^{b}	45.0 ± 0.3 ^b	42.4 ± 0.3^{b}	42.9 ± 0.3^{b}	40.7 ± 0.3 ab
	Monoculture	$\pm 40.7 \pm 0.1$ ^a	39.7 ± 0.1^{a}	35.5 ± 0.3^{a}	36.2 ± 0.2^{a}	37.4 ± 0.2^{a}	37.9 ± 0.2^{a}	36.0 ± 0.3^{a}	36.6 ± 0.5 ab

Table 2

A

A						
Modelity	,	N-NO ₃				
		$(mg kg^{-1} soil)$				
Poplar a	groforestry	28.7 ± 4.34	c			
Poplar n	nonoculture	3.91 ± 0.37	а			
Forest m	nixture	5.53 ± 0.91	ab			
Alder ag	roforestry	6.89 ± 0.80	b			
Alder me	onoculture	4.94 ± 0.46	ab			
B						
Creation	Tuestresent	N _{leaf}				
species	Treatment	$(mg g^{-1} leaf)$				
Poplar	Agroforestry	19.3 ± 1.5	ab			
	Forest mixture	16.5 ± 2.4	а			
	Monoculture	17.4 ± 1.9	а			
			C			
Alder	Agroforestry	26.7 ± 1.6	C			
	Forest mixture	25.4 ± 1.5	bc			
	Monoculture	258 + 22	bc			

Table 3

			2017	Α	2018	В	2019	C	
Trait	Species	Treatment	Mean ± SE	Variation	Mean ± SE	Variation	Mean ± SE	Variation	
DBH (mm)	Poplar	Agroforestry	15 ± 0.6	b	27 ± 0.9	с	46 ± 1.4	d	
		Forest mixture	19 ± 0.5	с	24 ± 0.7	b	33 ± 0.9	b	
		Monoculture	21 ± 0.5	с	27 ± 0.6	c	37 ± 0.9	с	<u> </u>
	Alder	Agroforestry	11 ± 0.3	а	19 ± 0.4	а	24 ± 0.5	а	S *** T *** D ***
		Forest mixture	11 ± 0.3	а	17 ± 0.4	а	22 ± 0.5	a	D * * * * $S \times T *$
		Monoculture	11 ± 0.2	a	17 ± 0.3	а	22 ± 0.3	a	1×D *** S×D *** S×T×D ***



Fig. 3.



Fig. 4.







Fig. 6.

			2017	A	2018	B	2019	C	
Trait	Species	Treatment	Mean ± SE	Variation	Mean ± SE	Variation	Mean ± SE	Variation	
$h/d (\mathrm{m \ cm}^{-1})$	Poplar	Agroforestry	2.09 ± 0.05	b	1.66 ± 0.04	а	1.25 ± 0.03	ab	
		Forest mixture	1.83 ± 0.04	а	1.68 ± 0.04	а	1.41 ± 0.03	bc	
		Monoculture	1.75 ± 0.03	а	1.67 ± 0.03	а	1.53 ± 0.04	cd	C ***
	Alder	Agroforestry	2.16 ± 0.05	b	1.61 ± 0.03	а	1.36 ± 0.03	ab	T ns
		Forest mixture	2.20 ± 0.06	b	1.89 ± 0.05	b	1.58 ± 0.03	d	D^{***} S×T *
		Monoculture	2.19 ± 0.04	b	1.79 ± 0.03	ab	1.49 ± 0.02	bd	T×D *** S×D *** S×T×D ***

Appendix



$HGR_{intra} (\mathrm{cm day}^{-1})$		2018				
		Apr.	May	Jun.	Jul.	Aug.
Poplar	Agroforestry	0.31 ± 0.03 ^a	1.01 ± 0.15	^a 1.09 ± 0.09 ^{ab}	0.86 ± 0.10	^b 0.43 ± 0.06 ^b
	Forest mixture	0.18 ± 0.04 ^a	1.10 ± 0.46	^a 0.70 ± 0.42 ^a	0.18 ± 0.04	^a 0.02 ± 0.01 ^a
	Monoculture	0.27 ± 0.03^{a}	0.86 ± 0.22	^a 0.99 ± 0.10 ^{ab}	0.24 ± 0.08	^a 0.08 ± 0.06 ^a
Alder	Agroforestry	0.62 ± 0.05 ^c	1.37 ± 0.10	^a 1.14 ± 0.13 ^{ab}	0.18 ± 0.03	^a 0.00 ± 0.01 ^a
	Forest mixture	0.47 ± 0.03 ^b	0.97 ± 0.41	^a 1.32 ± 0.32 ^b	0.27 ± 0.06	^a 0.00 ± 0.06 ^a
	Monoculture	0.46 ± 0.03^{b}	1.31 ± 0.21	^a 1.12 ± 0.09 ^{ab}	0.24 ± 0.03	^a 0.00 ± 0.10 ^a
		S ***	S ns	S ns	S ***	S ***
		T ***	T ns	T *	T ***	T ***
		$S \times T ns$	$S \times T ns$	$S \times T ns$	$S \times T * * *$	$S \times T * * *$









03/05 15/05 29/05 08/06 15/06 27/06 05/07 21/07 04/08 06/09 03/05 15/05 29/05 08/06 15/06 27/06 05/07 21/07 04/08 06/09 03/05 15/05 29/05 08/06 15/06 27/06 05/07 21/07 04/08 06/09







Fig. A4.