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Oak Group Planting Produces a Higher Number of Future Crop Trees, with Better Spatial Distribution than Row Planting

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Abstract: Recent studies have reported superior tree quality and comparable tree growth of oaks planted in group compared with row planting. However, a comparative assessment of the potential future crop trees (PFCTs) between group and row planting is still lacking. Here, we compared the density and tree quality of planted oaks and other naturally regenerated trees between group and row planting. We assessed whether the distribution of PFCTs fulfills the goal of maintaining a spatially homogenous distribution of such crop trees at the stand level by geospatial analysis. We selected 10 group and row planting stands that were either 14 to 15 or 21 to 22 years old. Tree density in group plantings was significantly higher than in row plantings. Stand basal area was higher in row planting in younger stands but comparable to group planting in older stands. The proportion of trees with straight stems and monopodial crowns was higher in groups than in rows. The density and species' richness of the PFCTs was significantly higher but the number of oak PFCTs was lower in group than in row plantings. In group plantings, naturally regenerated PFCTs contributed to 43% of total PFCTs, but to only 19% in row plantings. Also, the spatial distribution of PFCTs in group plantings was more uniform than in row plantings. Uniform and homogeneous distribution of the PFCTs in group planting stands can facilitate design and conduct of tending operations. Thus, the group planting technique offers not only cost savings in the establishment phase but also additional benefits, including spreading of risks through increased tree species diversity.

Keywords: oak regeneration; group planting; potential future crop tree; tree quality and growth; forest restoration; low-density planting

1. Introduction

The common oak species *Quercus robur* L. and *Quercus petraea* (Mattuschka) Liebl. are more drought tolerant and resistant to storm damage than other co-occurring species in European temperate broadleaved forests [1–3]. Both species are of high economic, ecological and cultural value [1,4]. Moreover, they are highly preferred for cultivating mixed forests as a strategy for adapting forests to climate change [5–8]. As a result, there has been renewed interest in oak regeneration among forest owners in Germany and neighboring countries to increase oak forest cover [8,9].

Because of the difficulties in regenerating oaks naturally, in Germany, nearly 50% of oak forests are established by planting [10–12]. Planting oaks in rows in high initial densities (between 5000 and 10,000 seedlings·ha^{-1}) is the common way to establish oak forests [1]. However, it is expensive due to the high costs associated with the purchase of seedlings, protective measures against browsing and extensive site preparation, particularly on wind-thrown sites [13–15]. In southwest Germany, for example, planting 5000 seedlings per ha in rows would cost between 15,000 and 18,000€ (including fencing). In addition to such high costs, the regeneration of oak stands by row planting has other drawbacks, such as poor diversity of tree species and forest ground flora [16,17].

The high costs of row plantings motivated foresters in the twentieth century to develop a low-input reforestation technique known as cluster planting [18,19]. This approach combines a reduced number of target tree species planted in clusters with natural regeneration in the remaining area. Group planting is a type of cluster planting which involves the planting of ca. 20 oak seedlings per group with 1 m initial spacing between the trees. The oak trees planted in groups are often surrounded by a varying number (8–16) of planted shade-tolerant trainer trees (*Carpinus betulus* L., *Tilia cordata* Mill., *Fagus sylvatica* L.). The purpose of the trainer trees is to accelerate self-pruning of oaks, and to maintain the desired branch free bole length (at least 25% of tree height) by preventing the formation of epicormic branches. The distance between group centers can vary from 10 to 13 m, resulting in 60 to 100 groups per ha [18]. Accordingly, the initial density of planted oaks and trainers can vary between 1800 and 4200 seedlings per ha, depending on the number of seedlings planted within one group and the number of groups planted per hectare. Ideally, one future crop tree will emerge from each group to ensure the development of the target stand composition.

An important economic goal of oak silviculture is to grow 60 to 70 high-quality crop trees per ha within one production cycle that can range from 120 to 160 years [18,20,21]. Diameter, at 1.3 m height (DBH) for these crop trees, should be more than 70 cm with a straight branch free bole of 8 m or more. Proponents of group planting assumed that the distribution of potential future crop trees (PFCTs) in stands established using oak groups would be uniform. It was also assumed that there would be an adequate distance between the crop trees, which would allow foresters to develop a uniform distribution of high-quality trees during the time of tending. However, such assumptions have never been tested. In addition to the planted oaks, naturally regenerated trees between groups have the potential to produce an additional number of crop trees for the production of high-quality timber. A recent meta-analysis by Saha et al., (2012) showed that group planting could produce the same number of oak future crop trees as row planting. However, the potential of the naturally regenerated trees to produce additional high-quality trees (i.e., PFCTs) in group planting stands is not known.

Whereas the traditional silvicultural goal of oak row planting is to create an oak dominated stand with some shade-tolerant trees (e.g., *Carpinus betulus* L., *Fagus sylvatica* L.) in a secondary canopy layer, the goal of oak group planting may be to create a mixed-species forest where, in addition to dominant oaks, other species contribute to the main canopy and the economic goals. In this study, we assessed the density and distribution of the PFCTs to compare the silvicultural development of stands established by these two different techniques of forest regeneration. We compared the density and distribution of PFCTs growing in 14 to 22-year-old stands established in groups or rows.

Specifically, we tested two main hypotheses:

(1) Total density of potential future crop trees of oaks and other tree species in group planting stands is higher than their density in row planting stands, and
(2) The distribution of future crop trees in group planting stands is spatially more homogeneous than in row plantings.

Also, we compared tree growth, stem quality, and the basal area of group and row planting stands to assess the development of quality and growth for the planted oaks as well as the naturally regenerated species.

2. Materials and Methods

2.1. Study Area

Five pairs of oak group and row planting stands from three locations (i.e., 10 stands in total) were selected for this study. The stands were located in the two German federal states of Baden-Wuerttemberg and Hesse (Figure 1). The stands were selected according to the following criteria: (1) no thinning or pruning since establishment; (2) not more than one early stand tending restricted to the vicinity of the groups (i.e., 1 m from the outermost boundary) within the first eight years after planting; (3), row and group planting stand of similar age (age difference ≤3 years) are located close to each other; (4) to ensure an adequate potential for natural regeneration in the planted stands, sites should be close to mature forest; (5) the genetic material of oak and trainer trees for each pair of group and row planting stands was from the same provenance; (6) the mean annual volume increment of oaks as predicted by yield tables did not differ between the stands; and (7) the minimum size of the selected stands was at least 0.5 ha.

Figure 1. Location of study sites in Germany (map not to scale).

The elevation of stands ranged from 143 to 568 m. The age of the stands in Baden-Wuerttemberg was 14 to 15 years while the stands in Hesse were older (21 to 22 years, Table 1), yet the oak trees were of similar dimensions (Table 2). The row planting control stands in Hesse were 2 to 3 years older than the group planting stands. The average annual temperature and the precipitation of the study sites ranged from 6.5 to 10.2 °C and from 800 to 851 mm, respectively (Table 1). The soil types of the study sites are mainly gleyic cambisols, originating from alluvial deposits covered by a layer of loess, and stagnogleyic cambisols originating from basalt loam, siltstone or sandstone. The study sites are surrounded by mixed broadleaved forest, dominated by oak or coniferous forests (*Picea abies* (L.) H. Karst) except row planting control stands in Altenheim, which shared a boundary with agricultural land. Reforestation by group planting was carried out on sites damaged by the winter hurricanes "*Vivian*" and "*Wiebke*" (1990/1991), and "*Lothar*" (1999). Site preparation was conducted only at patches, where the groups were later planted, unlike conventional row planting where extensive site preparation (e.g., removal of stumps, snags, logs, and slash) was required. The three group planting stands in Baden-Wuerttemberg consisted of 60–70 groups per hectare. In contrast, the two group planting stands in Hesse were established with a higher initial group density (100 groups per ha). Each group was planted with 19 to 27 oaks surrounded by 10 to 15 trainer species (Table 2). In stands established by row plantings, seedlings of oaks and trainer species were planted in 2 × 1 m spacing (Table 3). All stands, except Kümmerazhofen and Voggenreutte in Baden-Wuerttemberg, were fenced after establishment to avoid browsing damage. Kümmerazhofen and Voggenreutte remained unfenced due to low deer browsing pressure at these sites [14].

Table 1. Site characteristics of group and row planting stands. Neighboring stands column contains information about the composition of surrounding forests (BLM: Broadleaved mixed stands dominated by oak, C: Conifer stands dominated by Norway spruce).

Stands' Name	Geographical Area	Size (ha)	Elevation (m)	Mean Annual Temperature °C	Mean Annual Rainfall (mm)	Neighbouring Stands	Soil Type	Mean Annual Increment of the Oaks ($m^3 \cdot ha^{-1} \cdot year^{-1}$)
Group planting								
Altenheim 1	Upper Rhine valley	2	143	10.2	832	BLM	Gleyic cambisols	8.5
Altenheim 2	Upper Rhine valley	2.7	143	10.2	832	BLM	Gleyic cambisols	8.5
Kümmerazhofen	Southwest German Alpine Foreland	0.5	550	7.7	851	BLM. C	Stagnogleyic cambisols	8
Kaisereiche	North-eastern Hessian Mountains	1.2	487	6.5	800	BLM. C	Stagnogleyic cambisols	7.5
Kamphütte	North-eastern Hessian Mountains	1.1	447	6.5	800	BLM. C	Stagnogleyic cambisols	7.5
Row planting controls								
Altenheim	Upper Rhine valley	0.9	143	10.2	832	BLM	Gleyic cambisols	8.5
Ichenheim	Upper Rhine valley	0.5	152	10.2	832	BLM	Gleyic cambisols	8.5
Voggenreutte	Southwest German Alpine Foreland	0.5	568	7.7	851	BLM	Stagnogleyic cambisols	7
Obergrenzebach	North-eastern Hessian Mountains	14.7	361	6.5	800	BLM. C	Stagnogleyic cambisols	7.5
Seigerthausen	North-eastern Hessian Mountains	14.7	361	6.5	800	BLM. C	Stagnogleyic cambisols	7.5

Table 2. Details of group planting designs and current mean diameter at 1.3 m height or DBH (in cm) of planted oaks, trainer and naturally regenerated trees in group planting stands. Standard error and number of trees inventoried are given within brackets.

Stands' Name	Altenheim 1	Altenheim 2	Kümmerazhofen	Kaisereiche	Kamphütte
Oak species planted	*Q. robur*	*Q. robur*	*Q. robur*	*Q. petraea*	*Q. petraea*
Stand age (in years)	14	14	15	22	21
Spacing between oaks within clusters (m)	1	1	1	1	1
Clusters per ha	70	70	60	100	100
Oaks per cluster	19	19	19	27	27
Trainers trees per cluster	12	12	10 to 11	15	15
Trainer tree species	*Tilia cordata*, *Carpinus betulus*	*Carpinus betulus*	*Tilia cordata*, *Carpinus betulus*	*Fagus sylvatica*	*Fagus sylvatica*
Fence/Protection	Yes	Yes	No	Yes	Yes
DBH of oaks	6.02 (0.40, 137)	6.28 (0.29, 135)	5.41 (0.27, 167)	7.06 (0.32, 198)	7.02 (0.27, 231)
DBH of trainer trees	6.48 (0.43, 92)	7.85 (0.27, 130)	5.29 (0.30, 82)	2.75 (0.37, 75)	2.77 (0.31, 123)
DBH of naturally regenerated trees	3.49 (0.13, 411)	3.75 (0.10, 520)	3.92 (0.12, 485)	2.70 (0.17, 1102)	7.05 (0.36, 176)

Table 3. Details of row planting designs and current mean DBH (in cm) of planted oaks, trainer and naturally regenerated trees in row planting stands. Standard error and number of trees inventoried are given within brackets.

Stands' Name	Altenheim	Ichenheim	Voggenreutte	Obergrenzebach	Seigerthausen
Oak species planted	*Q. robur*	*Q. robur*	*Q. robur*	*Q. petraea*	*Q. petraea*
Stand age (in years)	14	14	15	24	24
Spacing between trees in rows (m)	2 × 1	2 × 1	2 × 1	2 × 1	2 × 1
Planted oak trees per ha	3500	3500	3500	4000	4000
Planted trainer trees per ha (approximately)	1500	1500	1000	1000	1000
Trainer tree species	*Tilia cordata Carpinus betulus*	*Carpinus betulus*	*Tilia cordata Carpinus betulus*	*Carpinus betulus*	*Carpinus betulus*
Fence/Protection	Yes	Yes	No	Yes	Yes
DBH of oaks	6.79 (0.33, 165)	6.34 (0.24, 158)	6.49 (0.21, 243)	7.18 (0.22, 433)	6.69 (0.20, 413)
DBH of trainer trees	7.55 (0.33, 155)	8.44 (0.25, 184)	3.32 (0.40, 43)	4.8 (0.60, 28)	4.96 (0.13, 96)
DBH of naturally regenerated trees	4.32 (0.23, 144)	3.88 (0.24, 85)	2.18 (0.18, 233)	6.74 (0.39, 215)	6.96 (0.32, 234)

2.2. Sampling Design and Field Inventory

Three plots (40 × 40 m) were randomly established in each group and row planting stand. A minimum distance of 20 m was maintained between the boundaries of the plots to make the sampling design representative for the stand of interest. Stands were located in flat terrain, and there were no obvious environmental gradients. In summer of 2014, three subplots in the form of strips or quadrats were laid in each of the 40 × 40 m plots in group and row planting stands, respectively. In group planting, subplots (strips) were established from the center of one group to the center of the diagonally located groups. This design allowed us to adequately sample the planted, as well as unplanted parts of the stands established by group planting because we wanted to include planted oaks and trainer trees as well as the naturally regenerated trees between the groups in our inventory (Figure 2). The width of those strips in group planting was the distance between two different trainer trees in one group. The length of the strips in group planting slightly varied within and between the stands because stumps or harvesting slash from the previous stand sometimes forced the forest workers to deviate from the exact planting layout. In total, 45 strips (i.e., three strips per plot, and three plots in each of the five stands) were inventoried in group planting stands with an average strip area of 90 m^2. The sampling was comparatively easier in row planting than group planting due to regular planting design and homogeneity in spacing. There, three 100 m^2 quadrats (as subplots) were randomly installed in each 40 × 40 m plot. Similar to group planting, 45 quadrats were inventoried in five row planting control stands. This sampling design adequately represented the stand conditions in each pair of planting.

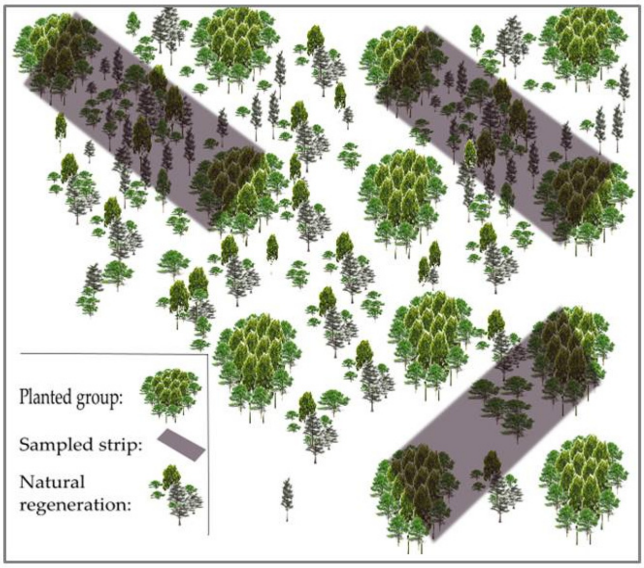

Figure 2. Sampling scheme inside a 40 × 40 m plot in a group planting. In each stand, three such plots were installed for the purpose of sampling. After that, three subplots (or strips) were installed in each 40 × 40 m plot to survey the planted oaks and trainer trees inside the groups as well as natural regeneration between the groups.

All trees within each strip or quadrat with a height greater than 1.3 m were identified, and the following variables were measured: species identity, DBH, crown type and stem form. For the assessment tree quality; morphological classification of stem form and crown type was used as described in Figure 3 [18,22,23]. The dominant and vital trees with straight stems, monopodial crowns without epicormic shoots, and no sign of disease and damage were selected and marked as potential future crop trees (PFCTs) [20,24]. The length of the branch free bole (BFBL) from the base of the trunk to the first non-epicormic green branch (diameter ≥2 cm) was measured additionally for the PFCTs [25,26]. The location of each PFCT was recorded in the following steps: first, the coordinates of one of the corners of the strip or plot were noted by a Global Positioning System (GPS) device and then the distance and azimuth to the PFCT from that corner were recorded.

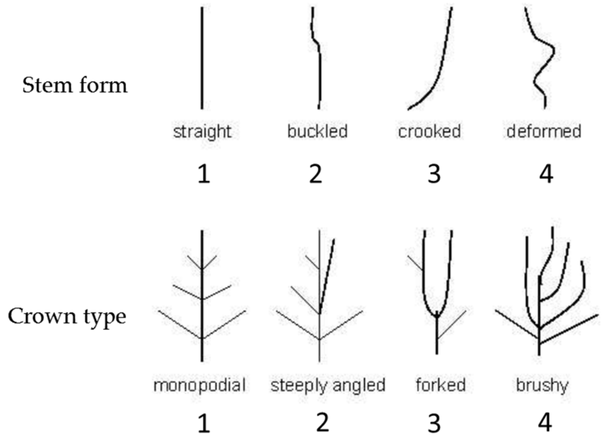

Figure 3. Morphological classification of stem form and crown type.

2.3. Data Analysis

We had five pairs of replicates for the treatments (i.e., group vs. row planting) in this study. However, two pairs in Hesse were older than three younger stand pairs in Baden-Wuerttemberg. Therefore, we compared basal area, the number of PFCTs per hectare, DBH and BFBL of the PFCTs on the basis of the proportional differences (in percent) for each pair of sites and calculated a grand mean and standard error. For comparing the ordinal response variables (i.e., stem form and crown shape) between two nominal classes (i.e., groups vs. rows in a 2×4 contingency table), we used the percentage of trees belonging to a particular class of stem form or crown shape in relation to the total number of trees. The classwise comparison of trees for stem form and crown shape between group and row planting were made by Cramér's V test [27]. The data analysis was carried out using the statistical software SPSS 20.0 [28].

The coordinates of each strip or plot measured in the field were entered in the GIS program *ArcMap* [29]. To construct the geodetic lines from the corner of the plot to every PFCT, the tool "*Bearing Distance To Line (Data Management)*" in the *ArcToolbox* was used by entering the azimuth and distance of each PFCT. Subsequently, the end point of each geodetic line, which in this case represents one PFCT, was displayed using the tool "*Feature Vertices to Points (Data Management)*" in *ArcToolbox*. Information on PFCTs such as tree species identity, planted or naturally regenerated, was added to each point. The first step to analyze the distribution of the PFCTs and to test whether there is a pattern in their distribution in row and group planting stands was the projection of the PFCTs and plots on a projected coordinate system. The European Terrestrial Reference System was chosen for this purpose. To assess the distribution of PFCTs in stands, the "*Average Nearest Neighbor (Spatial Statistics)*" tool in *ArcToolbox* was used. It calculates the nearest neighbor index based on the average distance from each point to its nearest point. The results provided from this analysis are the following: (a) observed mean distance; (b) expected mean distance; (c) nearest neighbor index (or ratio); (d) z-score and (e) p-value. The expected mean distance is the average distance between neighbors in a hypothetical random distribution. The nearest neighbor index is the ratio of the observed mean distance to the expected mean distance. If the index equals 1, then the distribution of points (in this case the distribution of PFCTs) is random; if the ratio is less than 1, then points exhibit clustering and finally, if the ratio is greater than 1 the points tend towards spatial homogeneity with increasing values up to 2.15 [30,31]. Because deviation from 1 in the nearest neighbor index could occur by chance, the z-score and p-value are measures of statistical significance for this index [30]. As proposed by Clark and Evans (1954) the z-score indicates whether the mean observed distance to a nearest neighbour (e.g., a PFCT) is significantly different from the mean random distance [32,33]. The level of spatial homogeneity increases with increasing value of z-score [34]. The point shapefiles that were used as the input for this geospatial analysis contained either all of the PFCTs (planted and naturally regenerated) or only the planted PFCTs (i.e., oaks). Moreover, the strips (in group planting stands) or quadrats (in row planting stands) were used as the cartographic partition for the analysis to subdivide the PFCTs by the quadrats or strips and calculate the average nearest neighbour distance for each strip separately.

3. Results

3.1. Basal Area

Basal area of planted trees (oaks and trainer trees) in groups was 65% of the planted basal area in rows. In contrast, basal area of naturally regenerated trees was nearly four times higher in groups than in rows (368%). The total basal area was only 3% lower in groups than in rows (Figure 4).

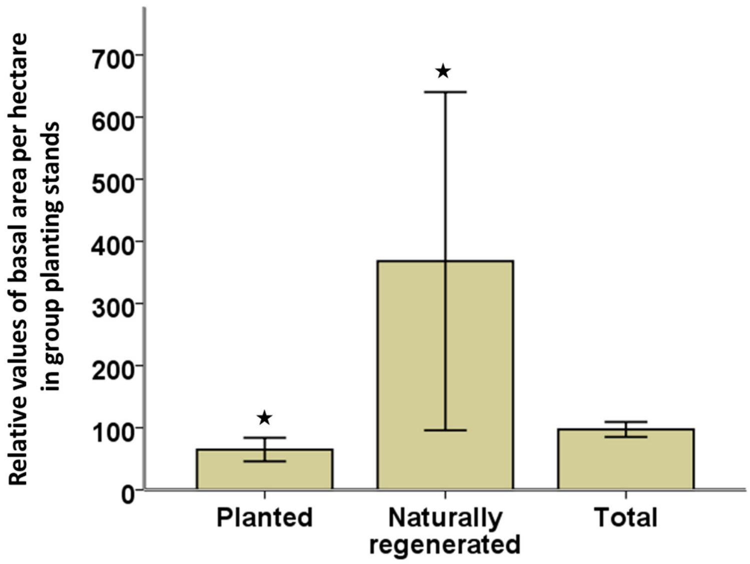

Figure 4. Percent basal area of planted, naturally regenerated and total number of trees in group planting compared to row planting. A value of 100 means no difference in basal area between group and row planting. The bars represent standard error at the level of 95% confidence (*n* = five pairs of group and row planting stands). Stars denote a significant difference in mean basal area per hectare between group and row planting stands.

3.2. DBH and BFBL of the PFCTs

The DBH of oaks and naturally regenerated PFCTs in group planting stands ranged from 10 to 15 cm and 10 to 18 cm, respectively. In contrast, the DBH of oak and naturally regenerated PFCTs in row planting stands were 11–14 cm and 12–16 cm, respectively. Therefore, the proportion DBH of the PFCTs in group planting to row planting did not show a high difference (only 2% higher in groups) (Figure 5).

The branch free bole length (BFBL) of PFCTs in group planting stands ranged from 4.5 to 7 m and 5 to 7.5 m in oaks and naturally regenerated trees, respectively. In contrast, the BFBL of the PFCTs in row planting stands ranged from 5.5 to 7.5 m and 6 to 8 m in planted oaks and naturally regenerated trees. The BFBL was slightly lower (i.e., 3%–5%) in PFCTs in group planting than in row planting stands (Figure 5).

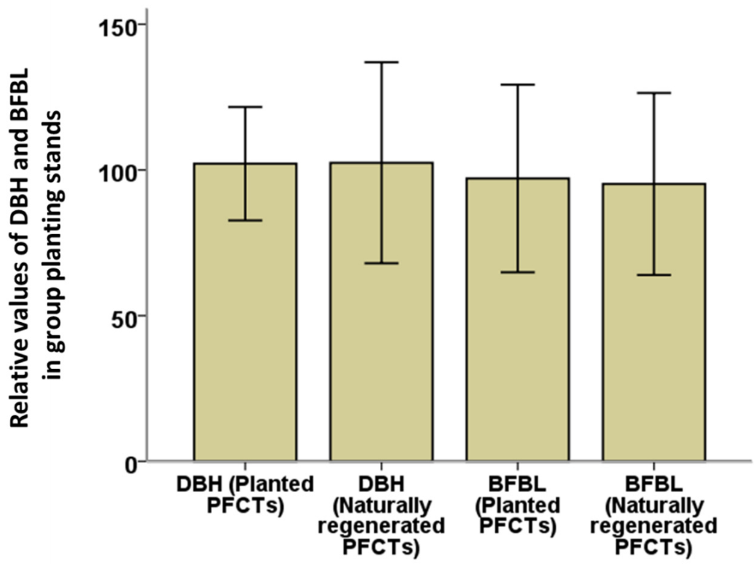

Figure 5. Relative DBH and branch free bole length (BFBL) of potential future crop trees (PFCTs) in group planting stands when compared to and row planting. A value of 100 means no difference between group and row planting. The bars represent standard error at the level of 95% confidence (n = five pairs of group and row planting stands). The mean DBH and BFBL did not differ significantly between group and row planting stands.

3.3. Stem Form and Crown Shape

Oaks growing in group planting stands had a higher proportion of individuals (6%) with monopodial crown than in row planting stands (3%). The percentage of trees with forked and brushy crowns (crown shape class 3 and 4) was 62% in rows compared to 54% in groups. Those differences were found to be significant (Table 4). However, the development of crown shape of naturally regenerated trees did not differ significantly between group and row planting (Table 4).

Table 4. Crown shape and stem form of planted oaks and naturally regenerated trees in group and row planting (n = five pairs of group and row planting stands). Cramér's V values: crown shape of oak trees × planting type = 0.086, $p < 0.01$; stem form of oak trees × planting type = 0.088, $p < 0.01$; crown shape of naturally regenerated trees × planting type = 0.073, $p > 0.05$; stem form of naturally regenerated trees × planting type = 0.070, $p > 0.05$.

	Crown Shape Class	Planted Oak Trees (%)	Naturally Regenerated Trees (%)	Stem Form Class	Planted Oak Trees (%)	Naturally Regenerated Trees (%)
Group planting	**1**	6	11	**1**	22	18
	2	40	51	**2**	47	35
	3	45	30	**3**	26	36
	4	9	8	**4**	5	11
Row planting	**1**	3	12	**1**	20	12
	2	35	42	**2**	39	39
	3	51	38	**3**	35	43
	4	11	8	**4**	6	6

A significantly higher proportion of oak trees with straight stems (22%) were found in group than in row planting stands (20%). The proportion of trees with crooked and deformed stems (stem form class 3 and 4) was significantly lower (31%) in groups than in rows (41%) (Table 4). Proportions of trees in different stem form classes did not differ significantly between group and row planting (Table 4).

3.4. PFCTs in Group and Row Planting

The group planting stands had on average 317 PFCTs (planted and naturally regenerated) per ha compared to 184 PFCTs per ha in row planting (i.e., 172% higher in groups). The planted oak trees had a share of 70% and 90% of the total number of PFCTs in group and row planting, respectively. Only 3% of planted oak seedlings had develeoped into PFCTs in row plantings. In contrast, 15% of oak seedlings developed into PFCTs in group plantings. As a result, the proportion of oak PFCTs was 118% higher in group than row planting. The number of PFCTs from natural regeneration was nearly five times higher in group than in their row planting counterparts (Figure 6). The proportional differences in PFCTs between group and row planting were statistically significant.

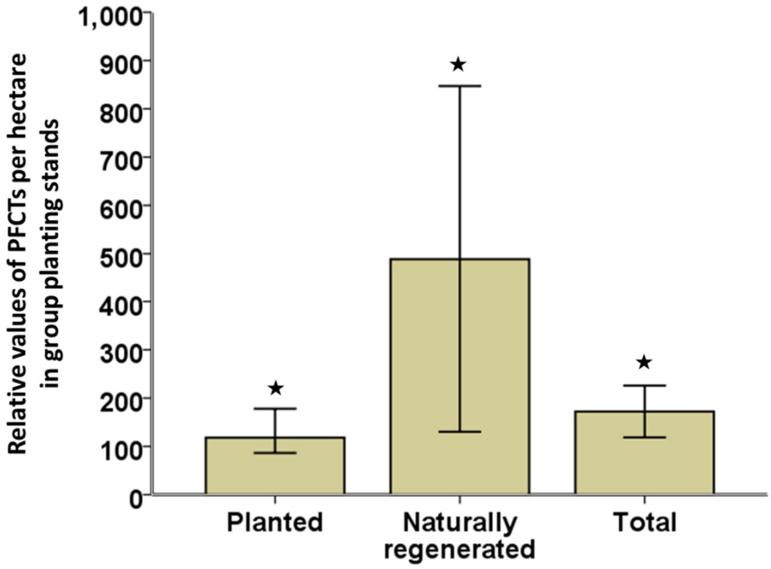

Figure 6. Relative number of planted and naturally regenerated potential futrue crop trees (PFCTs) in group plantings when compared to row plantings. A value of 100 means no proportional difference in PFCTs between group and row planting. The bars represent standard error at the level of 95% confidence (*n* = five pairs of group and row planting stands). Stars denote a significant difference in the number of PFCTs per hectare between group and row planting stands.

Naturally regenerated PFCTs in group planting comprised the following species: Norway spruce (*Picea abies* (L.) H. Karst.) (51%); silver birch (*Betula pendula* Roth) (19%); sycamore (*Acer pseudoplatanus* L.) (16%); European larch (*Larix decidua* Mill.) (8%); common aspen (*Populus tremula* L.) (4%); and wild cherry (*Prunus avium* L.) (2%). In contrast, naturally regenerated PFCTs in row plantings comprised silver birch (80%) and Norway spruce (20%). The average species richness of PFCTs in group planting was 3 instead of 1 in row planting.

3.5. Spatial Distribution of PFCTs

According to the nearest neighbor analysis, the distribution of PFCTs was more even in group than in row planting stands (Table 5). Interestingly, both oak and naturally regenerated PFCTs showed higher values of Nearest Neighbour Ratio and z-score in group than row planting controls when all five stand pairs were combined (Table 5). This indicates a higher spatial homogeneity in PFCTs growing in group than in row planting stands. At the stand level, the distances between the PFCTs in group planting stands were greater than in row planting stands, especially in the case of planted oaks (Table 5). However, in the stands where groups were planted with wider spacing (i.e., Altenheim 1, Altenheim 2 and Kümmerazhofen), the observed mean distance for all PFCTs combined (i.e., natural regeneration plus planted) ranged from 5.3 to 10.5 m, while the average distance between oak PFCTs ranged from 9 to 20 m (Table 6). Nevertheless, in the more densely planted group planting stands

(Kaisereiche and Kamphütte), the mean distance for all PFCTs combined was 4 m, while exclusively for oak PFCTs, this distance was nearly 8 m (Table 6).

Table 5. Results of the Nearest Neighbor Analysis on the distribution of PFCTs by combining all five stands in group and row planting categories (m = meter).

Planting Type	Observed Mean Distance (m)	Expected Mean Distance (m)	Nearest Neighbor Ratio	Z-Score	*p* Value
Group planting					
All PFCTs	5.48	2.65	2.06	22.64	<0.01
Oak PFCTs	8.3	3.49	2.37	22.19	<0.01
Row planting					
All PFCTs	5.05	2.6	1.94	17.37	<0.01
Oak PFCTs	6.24	2.9	2.15	19.08	<0.01

Table 6. Results of the Nearest Neighbor Analysis on the distribution of PFCTs in individual group planting stands (m = meter).

	All PFCTs					Oak PFCTs				
Stands' Name	Observed Mean Distance (m)	Expected Mean Distance (m)	Nearest Neighbor Ratio	Z-Score	*p* Value	Observed Mean Distance (m)	Expected Mean Distance (m)	Nearest Neighbor Ratio	Z-Score	*p* Value
Altenheim 1	6.78	3.10	2.18	9.85	<0.01	8.87	3.91	2.26	8.4	<0.01
Altenheim 2	10.51	4.20	2.49	10.71	<0.01	12.61	4.54	2.77	11.75	<0.01
Kümmerazhofen	5.28	2.31	2.28	13.02	<0.01	19.76	6.11	3.23	8.54	<0.01
Kaisereiche	4.03	2.38	2.69	7.00	<0.01	8.30	1.49	5.53	73.15	<0.01
Kamphütte	4.09	1.91	2.11	12.41	<0.01	7.30	2.56	2.85	15.42	<0.01

4. Discussion

4.1. Development of Basal Area and Tree Quality in Group Planting

The basal area of natural regeneration between the groups was nearly five times higher in group than in row planting stands; see also [16,19]. Owing to the high density of natural regeneration in group planting stands, basal area was comparable between group and row planting stands, even though only 40 to 65 percent of seedlings (2000–3200 trees per hectare) were planted compared to traditional row plantings (5000 trees per hectare) [24]. The higher number of trees with superior crown shapes in group than row planting stands confirm past studies [19,24,35]. The monopodial crown development (i.e., fewer trees with steeply angled branches in the upper crown) was better promoted in group plantings with surrounding trainer trees than in row plantings [18,36]. Shading caused by the oaks, naturally regenerated trees, as well as trainer trees was sufficient for self-pruning of oaks in both group and row planting. The initial growing space per planted oak seedling was 1 m^2 and 2 m^2 in group and row planting, respectively. Results from past studies on the influences of initial growing space on the length of the branch free bole support our findings [37,38].

4.2. Density of the PFCTs

The occurrence of a high proportion of oak and naturally regenerated trees with straight stems and monopodial crowns in group planting stands led to significantly higher numbers of the PFCTs. This high abundance of PFCTs in group planting stands can ensure a sufficient number of trees from which to select the final crop trees [39]. Additionally, the density and richness of the PFCTs in group planting stands was increased through the contribution of a high number of naturally regenerated PFCTs in the matrix between the groups. Based on these observations, we accepted our first hypothesis. This is the first study that has reported the frequency of naturally regenerated future crop trees [36,40]. Intraspecific interactions among oaks combined with the interspecific influence of trainer trees increased the proportion of trees with monopodial crowns and straight stems in group plantings [41–45]. As a result, 15% of planted oak seedlings emerged as PFCTs in group planting in contrast to only 3% in row planting.

4.3. Spatial Distribution of the PFCTs

The proponents of cluster planting suggested that a more homogeneous spacing between the PFCTs can be achieved than with conventional row planting [46–48]. Several studies on group planting trials have shown that 80%–90% of groups had at least one PFCT [14,15,18,35,49]. These studies indirectly supported this assumption given that the groups were regularly spaced throughout the stands. Nevertheless, none of these studies considered high-quality trees that developed from natural regeneration between the groups. The current study was the first attempt to compare the spatial distribution of oak as well as non-oak potential future crop trees in group and row planting stands by geospatial analysis. The results from all inventoried pairs of stands indicate that the spacing between PFCTs growing in group planting stands was more homogenous and wider than PFCTs growing in row planting stands. These results provide the first direct evidence to support the assumption of higher spatial homogeneity of PFCTs in group than in row planting stands and lead us to accept the second hypothesis.

Variation in the distance between neighboring PFCTs, especially for oaks in group planting stands, can be explained by the initial spacing between the groups. The higher initial spacing between groups resulted in increased distance between potential future crop trees in the group planting stands in Baden-Württemberg (Altenheim 1, 2 and Kümmerazhofen). The closer spacing between groups in the stands located in Hesse (Kaisereiche and Kamphütte) resulted in shorter distances between potential future crop trees. The standard silvicultural goal is to obtain at least 60 high-quality oak trees·ha^{-1} (i.e., 12 $\times$ 12 m spacing between crop trees during harvest) for a fully stocked oak stand. It is worth mentioning that the foresters will do the final selection of the oak crop trees from the current stock of "potential" future crop trees during the first commercial thinning, when stands will be between 35 to 50 years old. At this stage, each group will have a high chance to have at least one future crop tree which would result in a final selection of uniformly distributed crop trees over the stand. The homogeneous distribution of PFCTs in groups will help to plan and carry out tending operations. Some of the fast growing naturally regenerated PFCTs (e.g., birch, wild cherry or sycamore) may reach a harvestable diameter in group planting within 40–50 years after planting. The harvesting of these trees will increase the revenue in the stands established by group planting. In contrast, pre-commercial thinning in row planting will mainly generate fuelwood as the number of naturally regenerated fast-growing PFCTs is already low.

5. Conclusions

Potential future crop trees in group planting stands were not only more abundant and diverse but distributed more homogenously at the stand level when compared to rows. Although financial analysis and risk assessment for group and row planting stands was not the aim of this study, it can be assumed that the higher diversity of PFCTs would (1) provide forest managers with greater flexibility in relation to market needs by supplying a greater variety of products; (2) provide more options for risk-averse forest management in the case of failure due to dieback of the target species (e.g., acute oak decline by the oak buprestid beetle, *Agrilus biguttatus* Fabricius, or, by the oak processionary moth *Thaumetopoea processionea* L.); and (3) offer forest managers an earlier return on investment by harvesting faster growing crop trees from the matrix between groups. Nevertheless, these assumptions warrant further investigation. Based on findings of the current study and earlier studies [16,18,19,24,45,50], oak group planting can be recommended as an alternative to conventional row planting, especially when the management aim is to produce diverse mixed forests of high economic and ecological values with low financial input.

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