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Article

Tending of Young Forests in Secondary Succession on Abandoned Agricultural Lands: An Experimental Study

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Abstract: In Europe the area of forested land is increasing, largely due to forest development on abandoned agricultural lands. We compared the structure and composition of woody species in young stands undergoing secondary succession and within gaps of late-successional (LS) forest in Haloze (Slovenia) to derive management options. In a subset of plots in succession, silvicultural measures were carried out in one half, while the other half was left untreated. The attributes of crop trees and their competitor trees were monitored over five years, and a study on the time investment of tending was conducted. We found lower tree density, a larger share of pioneer and shrub species, and a higher diversity of woody plants in succession compared to regeneration within LS forest gaps. Tending resulted in greater density of crop trees, their better social position, fewer competitor trees, and a larger diameter at breast height (d.b.h.) increment, while differences in crop tree stability and quality between tending and control were not confirmed. Our results indicated great structural complexity and species diversity in young successional forests. Their tending represents a cost efficient method of recovering the long-term commercial value and ecosystem services of forests, if applied less intensively than traditional tending of LS forest.

Keywords: natural forest expansion; forest tending; thicket; pole stand; forest succession

1. Introduction

The succession process on agricultural lands starts with the natural development of vegetation after traditional land use, such as mowing, grazing, tillage, *etc.*, ceases. This is a complex process, which in Europe results in the long-term succession of vegetation to late-successional (LS) forest, if not constrained by environmental factors (climate, soil condition, *etc.*) or disturbance regime. The natural development of vegetation is slow and its course depends on many factors: soil conditions [1], land use history [2], seed bank presence [3], succession phase or the time of cessation of use, the presence of alien species [4], allelopathy [5], competition [6], predatoriness [7], *etc.* In Europe, excluding the Russian Federation, the annual increase in forest area amounted to more than 800,000 ha over the period 1990–2010 [8]. Most of the forest gain was from natural forest expansion, with the highest annual increase in Italy, Spain, and France, with 71,000, 48,000, and 48,000 ha, respectively [9].

The trend of the abandonment of marginal agricultural land in Europe will most likely continue. In the next decades new forest gain can be expected, especially in Eastern Europe, with high rates of agricultural land abandonment after the 1990s [10]. Plantations are often established on abandoned agricultural lands around the world [11]. They have several positive effects [12] and have been the subject of numerous studies [13]. An important question is how to manage them in the future. One of the options is to gradually transform them by thinning into more or less natural forests [11,12,14].

An economically and ecologically interesting alternative to afforestation in the process of forest restoration is the employment of natural processes within secondary succession [15–17], especially if succession is developing within a matrix of LS stands. The establishment of forest management in new forests on abandoned agricultural lands is important given that the area of forest available for wood supply in Europe is decreasing [9] and that such habitats are suitable for many ecologically and economically valuable tree species. At present, most abandoned farmland in natural succession in Southeast Europe is unmanaged. Silvicultural measures can accelerate succession, influence its direction, increase the growth of crop trees and stand stability, advance the goods and services provided, and enhance diversity [17].

The succession process is difficult to manage in terms of space, as mostly large areas with extreme geomorphological features in remote and passive locations undergo succession. Management, which for a long time provided optimal use of space, has become commercially uninteresting in the current circumstances. In Slovenia the share of forest cover is stable, while in the south and west, and especially in Haloze, the share of abandoned agricultural lands in succession is still increasing due to the extreme geomorphology. However, in comparison to other parts of Slovenia, studies on the causes and effects of succession have not been conducted. In Slovenia, forest succession on abandoned agricultural land was first investigated in detail in the second half of the 20th century, when several studies on this subject were carried out [18–20]; these studies, however, more or less examined the natural and socio-economic factors influencing succession.

Due to the steady increase in cost, the tending of young forest in Central Europe is decreasing [21]. The main obstacle is the cost of the traditional tending approach with a high number of crop trees, especially in early developmental stages. Solutions may be found in the optimization of tending models, with concentration on the most important measures in time and space, releasing fewer crop trees, and the employment of all-natural processes ("biological rationalization" *sensu* Schütz [21]) in favor of tending goals (*i.e.*, improvement of the quality, stability and resilience of stands).

These concepts might be especially important for the tending of new forests on former agricultural lands since tending investments are an additional burden for the owner, but beneficial in the long-term [17]. The design of tending schemes requires comparative studies of early- and LS-forests (1) for a better understanding of the processes driving succession; and (2) to carefully adapt tending schemes that were developed for LS forests.

Previous research in Slovenia has documented complex stand structures and high species diversity of new forests on abandoned agricultural lands on the one hand, and their poor mechanical stability, quality and commercial value on the other [18,19]. It has also indicated considerable possibilities for improvement of stands through tending. However, there have been few attempts to describe the possibilities of influencing their successional pathways [22] or to quantify tending efforts [23]. While experimental thinning of such forests in Europe has rarely been studied, there has been some work in the tropics. In a neotropical secondary forest, for example, liberation thinning significantly improved the growth of crop trees in young stands [15]. Other work in the tropics showed that some early-successional trees benefit from experimental shrub removal while some mid-successional species are favored by the presence of other vegetation [24]. Finally, some general guidelines for managing natural succession are described in Whisenant [17]. However, in all of these publications the tending costs were rarely quantified or they are rough estimates based on practical experience in the field.

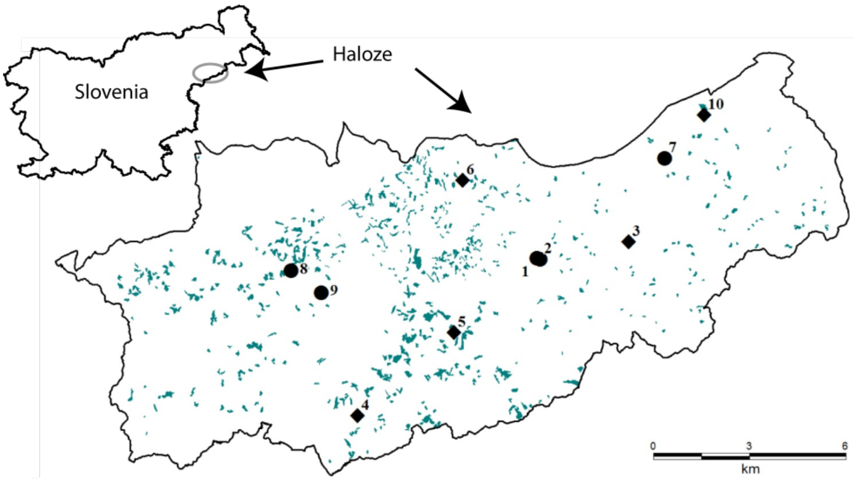
In this study, we concentrated on the tending of young forests on abandoned agricultural lands as one of the management alternatives. The goals of this study were the following: (1) to compare the structure of young stands in secondary succession on former agricultural lands with the nearby gap regeneration of LS forests; (2) to test with a field experiment whether tending improves the mixture, stability and quality of young stands; and (3) to assess the time required and overall costs of tending.

2. Materials and Methods

2.1. Study Site

The research was conducted in the hilly area of Haloze, in the northeastern part of Slovenia (Figure 1). The absolute altitudes in the study area range from 249 to 455 m above sea level (a.s.l.) and slopes from 11° to 35° (Table A1). The climate is Sub-Pannonian, the mean annual air temperature (meteorological station Turski Vrh, 280 m a.s.l.) in the period from 1981 to 2012 [25] was 10.5 °C, and the mean annual precipitation 1024 mm (meteorological station Cirkulane, 241 m a.s.l.). The southwestern part of Haloze is covered by dystric soil on marl or marl sandstone [26], while the northeastern part is covered by calcocambisol on tertiary compact and sandy limestone. Small areas are also covered by pseudogley. The Haloze region is on the Sub-Pannonian margin of the Predinaric phytoclimatic territory [27]. The study area is dominated by *Fagus sylvatica* forest sites. Neutrophilic beech forests (*Hedero-Fagetum* Košir/62, 79/94) grow in rich and moist habitats [27] with transition to communities of *Quercus petraea* and *Carpinus betulus* (*Querco-Carpinetum s.lat.*) in lower, moderately warm and moist forest sites (Table A1).

Figure 1. Location of the Haloze region in Slovenia and tending research plots within the study area; the plots are marked with numbers from 1 to 10 (circle—thicket, diamond—pole stand); dark cyan patches mark new forests on abandoned agricultural lands.



2.2. Design of the Field Experiment and Measurements

This study focused on young stands on abandoned agricultural lands that had not been used for agriculture for at least six years. The Slovenia Forest Service database [28] was used as the basis for the collection of data on spontaneous forest expansion on abandoned agricultural lands. Plot locations were chosen on the basis of digital orthophotos (DOF) (scale 1:5.000) taken within the period of cyclical aerial photography between 1995 and 2005. Each plot's size was 20 m × 20 m. Due to long-lasting successional development on abandoned agricultural lands, a chronosequence method was applied to represent different developmental phases. Five stands were selected in young growth (h < 2 m), 15 stands in thicket, and 17 stands in pole stand (hereinafter: Succession). The number of plots was proportional to the cumulative area of developmental phases. All plots were located in the immediate vicinity of late-successional (LS) forest. Most of the plots were located within former meadows and pastures and a few within orchards. Agriculture was practiced at low intensity and parcels were small.

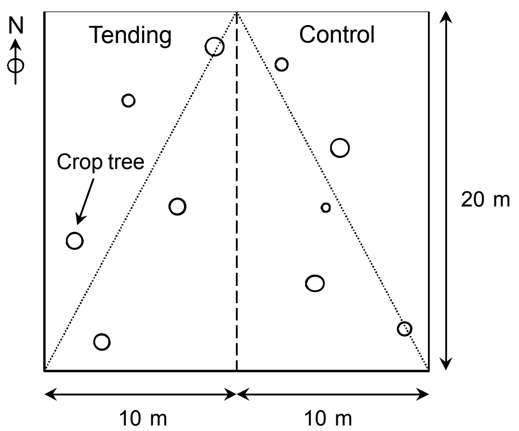
In order to analyze differences between the young stands in Succession and within LS forest, we further selected 15 plots in the regeneration gaps in nearby forests on comparable sites (hereinafter: Forest): five plots (20 m × 10 m) in young growth, five plots in thicket, and five plots in pole stand. The regeneration gaps were created by traditional small-scale management with irregular shelterwood (gaps of up to 0.1 ha); only natural regeneration that had not been managed was present. Forest plots were surrounded by (semi-) natural LS forest stands dominated by *Fagus sylvatica* L. and *Quercus petraea* (Matt.) Liebl., which were being managed for multiple objectives.

Within Forest and Succession, all woody plants were tallied according to species. The trees were grouped into three ecological species groups (*sensu* [29]): (1) early (pioneers); (2) intermediate; and (3) late successional species (climax species). The following were treated as pioneer species:

Acer campestre L., *Fraxinus ornus* L., *Populus tremula* L., *Populus alba* L., *Alnus glutinosa* (L.) Gaertn., *Betula pendula* Roth, and *Salix caprea* L. The following were classified as climax species: *Picea abies* (L.) H.Karst., *Abies alba* Mill., *Pinus sylvestris* L., *Castanea sativa* Mill., *F. sylvatica* and *Q. petraea* (Table A2). *P. sylvestris* was classified as a climax species since in the studied area it mainly grows on acid soils in dry ridge habitats where it is a stand-forming species. In other habitats, only individual trees of *P. sylvestris* are present. Seventeen other species were treated as intermediate successional species, including the following: *Sorbus torminalis* (L.) Crantz, *Tilia cordata* Mill., *Ulmus minor* Mill., and *Fraxinus excelsior* L.

In order to analyze tending effects on stands in succession, five plots in the thicket stage and five plots in the pole stand stage were selected. Each plot was divided into two equal parts measuring 20 m × 10 m. On the left subplot (observed on location from the bottom), tending was carried out (hereinafter: Tending), while the right subplot was left untreated (hereinafter: Control, Figure 2). Division of plots resulted in 10 Tending subplots and 10 Control subplots at the beginning of the experiment. All plots were selected using a stratified random approach to cover the entire research area. For the analysis of tending effects, we merged intermediate and late successional species into one extended group of climax species since crop trees were predominately selected from these two groups.

Figure 2. The division of original plots into two subplots for the tending experiment and the selection of crop trees for measuring heights.



The tending experiment was conducted in three parts and lasted five growing seasons. The first part comprised a survey of the stand parameters and the implementation of tending. Both were carried out in winter 2007 (January and February). The second and third parts comprised two surveys of stand parameters and were carried out after the end of the growing season in autumn 2009 and autumn 2011.

In the first part of the experiment (2007), the following parameters were estimated: the frequency and species composition of all woody plants; diameter at breast height (d.b.h.) of all trees with d.b.h. >2 cm; the number and d.b.h. of crop trees and their competitor trees (hereinafter: competitors); the quality of crop trees; the social position of crop trees; the age of the oldest competitor on the plot; the time needed for marking the crop trees and their competitors; and the time needed to completely carry out silvicultural measures.

On each subplot crop trees were selected and marked with numbers. The selection was based on the following characteristics: the adequacy of tree and shrub species (climax and intermediate successional species as well as fruit bearing trees were favored); the quality of individuals, *i.e.*, the quality of the trunk and the quality of the crown; and the progressive developmental trend regarding neighboring trees (tendency).

The future commercial quality of trees (high, intermediate, and low—according to tree architecture and damage) and their social position (dominant, intermediate, and suppressed—depending on the height class membership) were evaluated according to the IUFRO classification [30,31]. Tending of thickets in Central Europe may be based on positive or negative selection depending on stand structure, although positive selection prevails from the pole stage onwards [30]. In this study, the emphasis was on early positive selection, as the crop trees and their competitors were already selected in the thicket stage. The reasons for early selection were the following: (1) in Succession social stratification was already strongly expressed due to lower tree density; (2) valuable tree species were favored and they were often suppressed and diffusely represented; (3) most crop trees were light-demanding; and (4) only the most necessary tasks were carried out, in accordance with biological rationalization and concentration principles [21].

On each subplot separately, we determined the tending measures following the short-term silvicultural goals [30] based on the current stand status and considering the species composition, site conditions, and developmental phase of the stand. Similar measures were applied in the tending of thicket and pole stands, as the stand structure was small-scale and patchy with unclear transitions between developmental phases. The main focus was on the release of crop trees (positive selection). In thicket, there was slightly more emphasis on favoring groups of trees and negative selection (e.g., the removal of climbers, shrubs, wolf trees, as well as diseased and damaged specimens, regulating stand density). Occasionally, we also carried out the additional measure of pruning (all silvicultural measures *sensu* [30]).

In order to study the costs of tending, the time needed to mark crop trees and their competitors by a local forest ranger was measured. The time needed to carry out each tending measure was also measured. In the latter case, measuring began when a chainsaw (hereinafter: CS; model Husqvarna 154) was already running. The sum of the measured times amounted to the effective or net time. The time needed for transitions from one competitor to another was also measured (the transition time). The time for tending is the sum of the effective time and transition time. This time equals the time needed by a silvicultural worker with a CS. Time was expressed in h:mm:ss. The labor cost of a silvicultural worker with a CS and the labor cost of a local forest ranger, expressed in ha^{-1}, are the product of the time consumed and the cost of a working hour. The sum of both costs is the cost of tending.

The costs of tending were calculated on the basis of costs for the year 2013. In determining the costs of tending for thicket and pole stands, the cost of a working hour of a silvicultural worker with a CS was applied on the basis of the Regulations for State Forests [32] and the cost of a working hour of a local forest ranger employed by the Slovenia Forest Service (*i.e.*, a local forest ranger III; the cost of a working hour in March 2013). The following figures were taken as bases: the cost of a working hour of a silvicultural worker with a CS was EUR 17.78; the cost of a working hour of a local forest ranger was EUR 7.02.

The second part of the experiment was conducted in 2009 when crop trees were selected and analyzed again. Due to stand damage, four subplots (two in Control and two in Tending) were lost.

Therefore, the initial comparison with LS forests and the tending cost study are based on 10 Tending and 10 Control subplots, while comparisons in 2009 and 2011 are based on eight Control and eight Tending subplots. The d.b.h. of all crop trees was measured, their quality was determined, they were classified by appropriate social layer, and once again their competitors were selected. In certain cases the role of a crop tree was taken over by a competitor and occasionally by a new individual.

In 2011 the crop trees were re-analyzed following the same procedure as in 2009. We also added the following parameters (as described below): branchiness, height, slenderness coefficient, and stem inclination. We then selected a network of superior crop trees. Tree heights were estimated based on a sample of the five crop trees closest to the plot diagonal (Figure 2).

The slenderness coefficient SC was calculated using the formula:

$$SC = \text{Height (cm)}/\text{d.b.h. (cm)} \quad (1)$$

A stem inclination score of 1–3 (vertical growth—strongly inclined tree) was assigned to each crop tree based on stem inclination from vertical. In Tending and Control, crop trees at half of the final spacing were identified (superior crop trees). In order to evaluate tending effects, measured variables (the number of crop trees, the number of their competitors, d.b.h., quality, and height) were compared among years (2007, 2009, and 2011) and treatments (Tending v. Control). As the differences in stand structure in Succession between thicket and pole stand almost entirely converged in the five growing seasons, a comparison of the parameter values for both phases combined is presented.

The Central European tending approach allows the adaptation of the crop tree network at each stand entrance [30]. Therefore, evaluation of the thinning effect was done separately for the entire population of crop trees (all crop trees) and separately for the crop trees that remained the same throughout the experiment (identical crop trees).

2.3. Statistical Analyses

The data were analyzed in Microsoft Excel Version 2003 and R Version 2.15.2 [33]. Differences in the parameters of crop trees between Control and Tending were analyzed with linear mixed-effects models (LMM). These models allow nested error structures to account for pseudo-replication since crop trees were nested within plots. Plots were treated as a random factor, while treatment and species groups as fixed factors. The models were built with the "lme4" package [34]. The protocol closely followed the "top-down" strategy described in West *et al.* [35]. For model diagnostics, we examined the confidence intervals of the parameters and analyzed sets of graphical summaries proposed by Robinson and Hamann [36]. The LMM models were specified as:

$$\text{d.b.h.} = a + b_0 \times \text{Tending} \quad (2)$$

$$rd\_i = a + b_0 \times \text{Tree species group} + b_1 \times \text{Tending} + b_2 \times \text{Tree species group} \times \text{Tending} \quad (3)$$

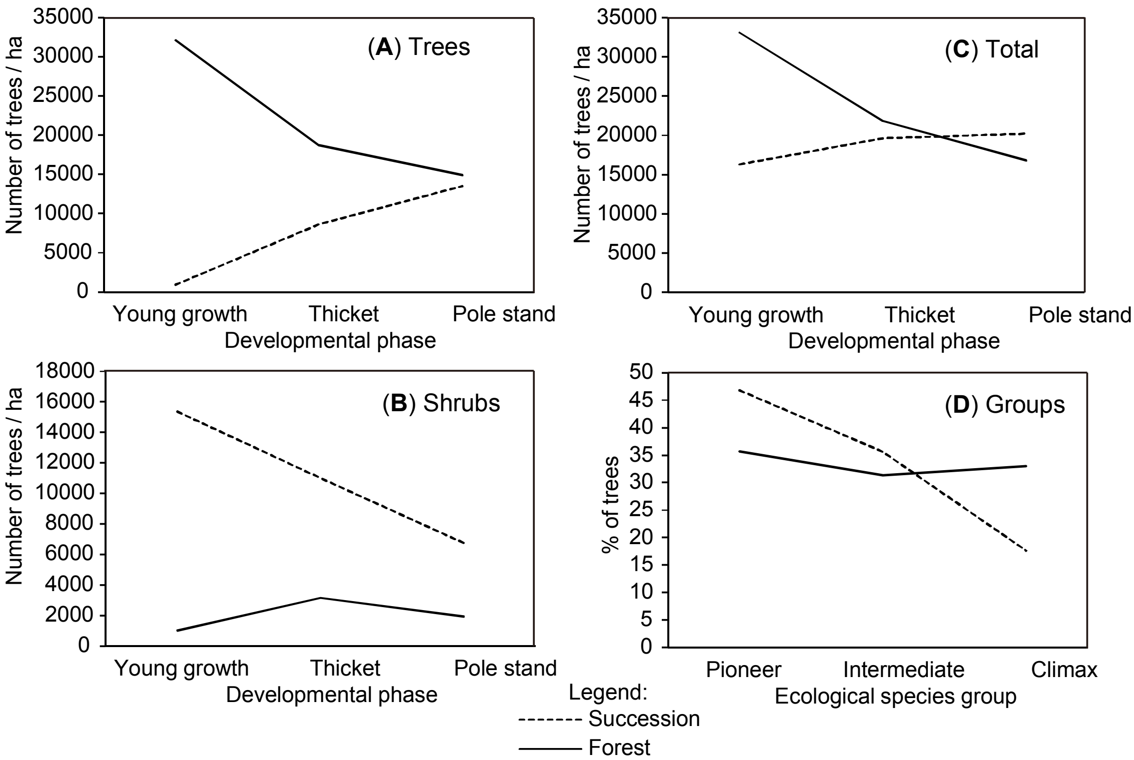
where a and b_0–b_2 are fixed model parameters, d.b.h. is the diameter of a crop tree, rd_i is the d.b.h. increment of a crop tree divided by the initial diameter, and Tree species group (cf. section 3.3.) and Tending are binary variables. Tests of independent samples were carried out for comparison of plot parameters between treatments in Succession and Forest.

3. Results

3.1. Structural and Compositional Differences between Forest and Succession

A comparison of young stands in LS Forest and Succession suggested large differences in the density of woody plants and ecological species groups (Figure 3). While there were only a few trees in the young growth stage of Succession (919 ha^{-1}), regeneration in Forest started with a high tree density (32,070 ha^{-1}). However, in later developmental phases, Forest and Succession almost converged with regard to tree density, with 14,870 and 13,492 ha^{-1}, respectively (Figure 3A). The number of shrubs in Forest remained low across all three developmental phases (1000–3000 ha^{-1}), while in Succession it dropped sharply, from approximately 15,358 to 6743 individuals ha^{-1} in young growth and pole stands, respectively (Figure 3B). The total density of woody plants in Forest steadily decreased with developmental phases, while it increased in Succession (Figure 3C). In pole stands it surpassed the density in Forests, likely due to the higher percentage of pioneer and intermediate successional species, which allow more light to reach the forest floor, thus permitting continuous recruitment. Shares of ecological species groups in Forests, according to tree density across the developmental phases, were comparable (31%–33%), while in Succession a higher share of pioneers and lower share of climax species were found, 45% and 18%, respectively (Figure 3 D). The differences in tree and shrub densities per developmental phase were statistically significant (tree density: *d.f.* = 1, 54; $F = 7.18$; $p < 0.0001$; shrub density: $F = 6.24$; $p < 0.0001$).

Figure 3. The density of trees (**A**); shrubs (**B**); and the total density of woody plants (**C**) by developmental phase in Forest and Succession; the percentage of ecological species groups in Forest and Succession according to tree density (**D**); N = 37 plots for Forest and 15 plots for Succession.



3.2. The Entire Population of Crop Trees

In 2007, when the experiment was initiated, the average age of the oldest competitors on plots in thicket was 10 years (min. six years, max. 13 years), while in pole stand it reached 16 years (min. 12 years, max. 20 years). The average tree density in thicket was lower compared to pole stand (Table 2). The average tree density on all plots within Succession reached only 55% of the tree density in Forest for thicket and pole stand together (16,781 trees ha^{-1}). However, regarding trees with d.b.h. >2 cm, the difference in tree density between Forest (4670 trees ha^{-1}) and Succession (3508 trees ha^{-1}) was smaller, amounting to 25%.

The shapes of the frequency distribution of trees with d.b.h. >2 cm in Succession and Forest had a reverse J-shaped form and did not significantly differ between Succession and Forest (Figure A1, Appendix). Only the density in d.b.h. classes was significantly lower in Succession. The mode of crop trees was in the 5 cm d.b.h. class. In 2007, the mean diameter at breast height of all trees (d.b.h. > 2 cm) in thicket was 4.4 cm, in pole stand 5.3 cm, and on all plots in Succession 4.8 cm. The number of crop trees and their competitors amounted to 10% and 9.5% of the total tree density, respectively. On average 1.19 competitors were selected per crop tree (Table 1), with minor differences in thicket (1.16) compared to pole stand (1.21).

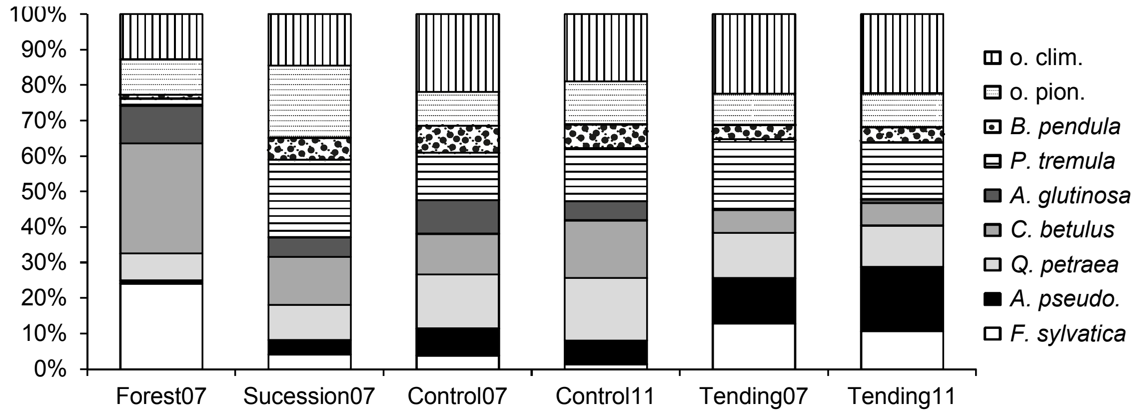
Table 1. Summary of mean stand characteristics of the developmental phases (DF) in Succession for the year 2007; data are shown as the number of individuals per ha (Nt—number of trees, Ns—number of crop trees, Nc—number of competitor trees, D.b.h.—diameter at breast height); standard deviation in parentheses.

DF	N	D.b.h. (cm)	Age (years)	Nt	Ns	Nc	Ns/Nt (%)	Nc/Nt (%)
Thicket	10	4.4 (1.4)	10.0 (2.6)	7,116 (5,859)	625 (366)	725 (551)	10.9 (3.4)	11.5 (3.3)
Pole stand	10	5.3 (2.9)	16.2 (3.0)	11,450 (8,415)	740 (339)	895 (704)	9.1 (4.8)	7.6 (3.9)
All groups *	20	4.8 (2.2)	13.1 (4.2)	9,283 (7,208)	683 (338)	810 (603)	10.0 (4.1)	9.5 (4.0)

* All data were calculated from the plot averages.

The shares of tree species differed between plots and treatments; however, the same species dominated (Figure 4). In Forest there was a higher share of *F. sylvatica*, *Carpinus betulus* L., and *A. glutinosa*, whereas in Succession there was a higher share of *A. pseudoplatanus*, *Q. petraea*, *P. tremula*, *B. pendula* and of pioneer tree species in general. Also, Succession plots differed regarding tree species composition. In Forest, 24 tree species were recorded, whereas 27 tree species were recorded in Succession. The most numerous species present in Forest as well as in Succession were *Q. petraea*, *A. pseudoplatanus*, and *C. betulus*.

Figure 4. Comparison of tree species composition according to density by treatment for all trees with d.b.h. >2 cm; bars from the left to the right represent the following: Forest in 2007, Succession in 2007, crop trees in Control in 2007 and 2011, and crop trees in Tending in 2007 and 2011; legend: o. clim.—other climax species, o. pion.—other pioneer species.



On all Succession plots 20 tree species were selected to be crop trees (Table A2); in addition to the three most numerous mentioned above, the following were selected: *A. campestre*, *A. glutinosa*, *B. pendula*, *C. sativa*, *F. sylvatica*, *F. excelsior*, *F. ornus*, *Juglans regia L.*, *P. alba*, *P. tremula*, *P. avium*, *Quercus cerris* L., *Robinia pseudacacia* L., *S. torminalis*, *S. caprea*, *T. cordata*, and *U. minor*.

In general, in all years, the strongest competitors to crop trees were: *P. tremula* (25%), *C. betulus* (16%), *A. pseudoplatanus* (8%), and shrubs (7%). The latter were more strongly represented among competitors at the beginning of the experiment, while later their share declined (Figure A2). The share of pioneers among competitors to crop trees ranged between 57% and 73%. In Tending, among crop trees of more important climax tree species, the share of *A. pseudoplatanus* increased, while the share of *P. tremula* and *F. sylvatica* decreased. In Control, the share of *C. betulus* and *Q. petraea* increased, while there was also a decline in the share of *F. sylvatica*.

In 2007 the number of crop trees and their mean d.b.h. between Control and Tending differed (Table A3); however, the differences were not statistically significant (LMM; *d.f.* = 1, 221; $F = 0.289$; $p = 0.5914$). After five growing seasons the mean d.b.h. in Control increased to 173% of the initial d.b.h., and in Tending to 179%. The differences in mean d.b.h. of crop trees were also not statistically significant (LMM; *d.f.* = 1, 154; $F = 0.0517$; $p = 0.8205$) after the end of the experiment in 2011. The number of crop trees in Control and Tending decreased by 30% and 25%, respectively.

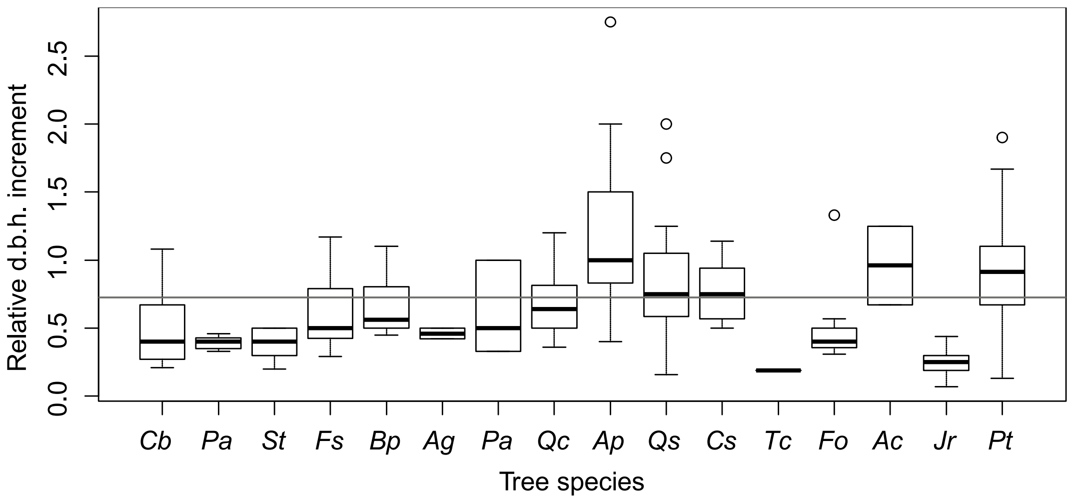
After five growing seasons the number of competitors declined more markedly in Tending (45% *vs*. 67% in Control). The number of crop trees of climax tree species declined in Tending less than in Control (77% v. 68%).

In addition to the division into pioneer and climax species, we were also interested in the division into more and less commercially valuable species. In Tending more valuable species were maintained among crop trees (79% *vs*. 61%), especially in the dominant social position (98% v. 77%).

3.3. The Population of Identical Crop Trees

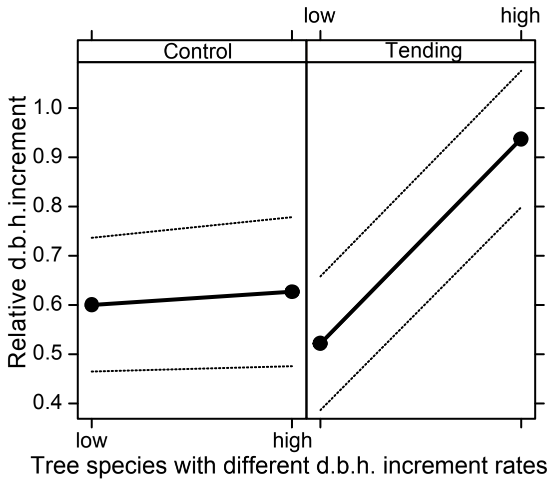
In the period from 2007 to 2011, a higher share of identical crop trees was maintained in Tending 89% on all plots), compared to Control (59%). Among identical crop trees there were more climax species in Tending (51%), compared to Control (31%). In the period from 2007 to 2011, tree species reached different relative d.b.h. increments. Above average values (>0.73) were reached by *A. pseudoplatanus*, *Q. petraea*, *C. sativa*, *A. campestre*, and *P. tremula* (Figure 5).

Figure 5. Comparison of the relative d.b.h. increment according to tree species in the period 2007–2011; latin species names are represented by the initials of the genus and species; e.g., *Cb* stands for *Carpinus betulus*; circles denote outliers; the grey line indicates the average relative d.b.h. increment of 0.73.



The linear mixed-effects model (LMM) was used to analyze differences in the thinning effect on the relative d.b.h. increment with a focus on more responsive species (factors: (1) treatment—Tending, Control; (2) two groups of tree species with different d.b.h. increment responses). The thinning effect on the d.b.h. increment was marginally significant (*d.f.* = 1,134; $F = 4.12$; $p = 0.0442$). The mean relative d.b.h. increment in Control amounted to 0.65 and in Tending to 0.79. There was also a significant interaction between species group regarding the d.b.h. increment rate and treatment (*d.f.* = 1, 134; $F = 15.49$; $p < 0.0001$; Figure 6). Tending facilitated the d.b.h. increment of more responsive species that reacted to an enlarged growing space.

Figure 6. Presentation of the mean relative d.b.h. increment according to treatment and two groups of tree species with different d.b.h. increment rates (see Figure 5); dots and bold lines represent predicted values, holding other variables at fixed values, while dashed lines represent confidence intervals.



A comparison of the relative d.b.h. increment according to treatment and tree species showed that *A. pseudoplatanus*, *Q. petraea*, and *P. tremula* responded well to tending. Quality also declined within identical crop trees; namely, in the period from 2007 to 2011, the share of superior crop trees in Control declined from 22% to 15% and in Tending from 13% to 8%. The share of crop trees with a dominant social position in the same period increased in Control by 7% and in Tending by 16%. The share of climax species among identical crop trees amounted to 52% in Control and 57% in Tending.

A relationship between the tending and stem inclination of crop trees was not confirmed (χ^2 test; *d.f.* = 1; $p = 0.7419$). Significant differences between the slenderness ratio, heights, and branchiness of crop trees according to treatment were also not confirmed. In 2011 the mean slenderness ratios of the same crop trees in Control and Tending amounted to 93.3 and 94.4, heights amounted to 11.1 m and 10.9 m, and branchiness amounted to 37.7% and 32.9%, respectively.

In 2011 in Tending and Control, 125 superior crop trees ha^{-1} were selected. Among them, there were more valuable and climax species in Tending compared to Control, *i.e.*, 70% *vs*. 40% and 80% *vs*. 65%, respectively. The differences in the characteristics of superior crop trees according to treatment were not significant; however, the patterns were similar to those of crop trees.

3.4. A Time Study of Tending

Eight silvicultural measures were determined with regard to the target stand and the developmental phase for each individual plot (Table 2). Tree species that were most adequate, regarding the developmental phase and site conditions, were favored. In thicket, pioneer tree species were maintained, whereas in pole stand valuable broadleaves and climax species were favored. A local forest ranger and a silvicultural worker with a CS on average needed less time ha^{-1} for marking trees and tending in thicket compared to pole stand.

Table 2. The average time consumption per ha for the tending of young forest by developmental phase and silvicultural measure on Tending plots.

		Developmental Phases			
		Thicket		**Pole Stand**	
Time needed to mark trees (h:mm:ss)	Control *	6:04:26		8:09:56	
	Tending	5:32:22		9:46:31	
Time needed for tending according to silvicultural measures	Rcr	2:59:17	55.0%	7:20:35	54.5%
	Rsh	0:49:59	15.3%	3:44:16	27.8%
	Ruc	0:27:15	8.4%	1:22:01	10.2%
	Rsd	0:12:47	3.9%	0:04:45	0.6%
	Rcl	0:24:18	7.5%	0:03:55	0.5%
	Rlk	0:00:00	0.0%	0:52:15	6.5%
	Pru	0:21:42	6.7%	0:00:00	0.0%
	Gir	0:10:51	3.3%	0:00:00	0.0%
Effective time		5:26:08	100%	13:27:47	100%
Transition time		2:47:21		5:27:05	
Total time for tending		8:13:29		18:54:52	

Silvicultural measures: Rcr—release of crop trees, Rsh—removal of shrubs, Ruc—removal of undesirable or competing vegetation (diseased, damaged, pioneer trees), Rsd—regulation of stand density, Rcl—removal of climbers, Rlk—removal of low quality trees, Pru—pruning, Gir—girdling of wolf trees.

The costs of tending thicket and pole stands amounted to EUR 146 and EUR 336 ha^{-1}, respectively, while the costs for tree marking amounted to EUR 39 and EUR 69 ha^{-1} in thicket and pole stands, respectively. Thus, both costs were higher in pole stands compared to thicket (Table 3).

Table 3. Time consumption for young forest tending per ha separately for plots and according to thicket and pole stand.

Type of Work	**Time Consumption of a Silvicultural Worker With a Chainsaw**	**Time Consumption of a Local Forest Ranger**	**Costs (EUR)**		
			Silvicultural Worker with a Chainsaw	**Local Forest Ranger**	**Total**
Tending of thicket	8:13:29	5:32:22	146.24	38.89	185.12
Tending of pole stand	18:54:52	9:46:31	336.30	68.62	404.92

4. Discussion

On plots in Succession, 27 tree species were recorded on the predominant *F. sylvatica* and *Q. petraea* forest site. A similar study was conducted in the Kocevje region [18], where 20 tree species were recorded on *A. alba*—*F. sylvatica* succession sites, and in the Suha krajina region [19], where 19 tree species were recorded on a similar site as in this study. In similar studies conducted in Europe, the number of species was substantially lower. For example, in the Eastern Carpathians, 13 tree species were recorded in abandoned meadows [37], and in Great Britain 10 tree species were found on abandoned arable land [38]. In this study, tree composition was slightly more diverse in Succession compared to the gap regeneration of late-successional (LS) Forest. This may be attributed to the lower light levels and mesic microclimate of LS Forest gaps, which facilitated climax species. In Succession the number of woody plants increased with successional development, while it did not significantly change in Forest. In Succession the number of tree species increased with successive developmental phases, while the number of shrub species initially increased but subsequently started to decline. The authors of similar studies established that species diversity on abandoned agricultural lands increased with succession in the early stages of development [39,40] or that species diversity is greatest within the stage where light-demanding and shade-tolerant species are present simultaneously [41], or that species diversity in succession increased with its progression; however, it does not reach the highest value in climax communities [42]. Baniya *et al.* [43] noted that the low number of species in early successional phases is characteristic of primary succession as well as for succession taking place on abandoned agricultural lands.

In Succession, the overall tree density was only half that in Forest. Also, the tree density in Succession thicket compared to pole stand was lower. The situation was the opposite in Forest, where the density was higher in thicket compared to pole stand. After heavy regeneration fellings, pioneer tree species first invade open areas [44,45]. They seed abundantly, are ecologically adaptable [46] and very quickly take over the entire area. In contrast, on abandoned agricultural lands, soon after mowing, grazing, or tillage ceases, shrub species are the first immigrants, followed by pioneer tree species [47,48]. In vegetation development on abandoned agricultural lands, different mechanisms apply than in the gap regeneration of late-successional (LS) forest. In stands in succession, the density of individuals increases with successional development, while it declines in LS forest, and the density ratio of trees between succession and LS forest increasingly converges; in our study densities converged in pole stand [23]. These findings are similar to those in earlier studies that showed that the number of individuals increased in stands in the early stages of secondary succession [49], while it declined in LS forest [30]. These differences between LS forest and stands in succession must be considered when planning and carrying out tending measures, particularly by employing a lower intensity of tending and favoring rare species in succession. Dominant species in stands in succession are mostly pioneer species. Their share is greater at the beginning of successional development, and later their share declines, while the share of climax species increases. Pioneer tree species initially have protection functions for the forest site, and later they create favorable conditions for the patchy immigration of climax species [48].

The effect of tending measures on species composition and stand parameters was examined on stands in succession over five growing seasons. In 2011, fewer crop trees were found in Control compared to 2007. In Control there was intense competition and strong social re-positioning between individuals. Between 2007 and 2011 the share of crop trees in Tending also decreased. The poor initial stability of stands greatly contributed to the falloff of crop trees. Due to the elimination of competitors, several crop trees bent; therefore, alternative crop trees were selected during subsequent re-evaluations. After tending was carried out in certain parts, climbers (*Clematis vitalba* L.) and the shrub layer expanded. A positive tending effect was shown in social re-positioning, as individual commercially interesting species overgrew pioneer species. In Control, over five growing seasons, in the process of natural selection, the share of crop trees of climax species declined more compared to pioneer species. The situation was the opposite in Tending, where more crop trees of climax species were maintained. In addition, more commercially interesting species were maintained by tending, e.g., *A. pseudoplatanus*. Some minority species, e.g., *S. torminalis*, for some unknown reason, did not respond positively to tending and could not be preserved [24]. More crop trees were maintained in the upper social layer, but their quality slightly declined. Tending thus did not contribute to better quality of crop trees. In the early stages of successional development, many trees grow individually, without neighbors or an understory layer. Trees expand their crowns, and branchiness is high. These are also primarily pioneer species where high commercial quality cannot be expected. A study conducted on lands in succession in the Suha krajina region [19] also indicated poor quality of trees.

Over five growing seasons, a greater number of the same crop trees were maintained by tending compared to Control. By tending, the relative d.b.h. increment of crop trees increased, especially that of the most responsive species [15]. However, the experiment did not confirm a thinning effect on the slenderness coefficient, height, and stem inclination of crop trees. The tending effects indicated a shift in the desired direction regarding the majority of parameters; however, many differences were not statistically significant, which can be attributed, on the one hand, to the short period of observation and, on the other hand, to the exceptional variability of the parameters on the plots.

The calculation of tending costs showed that a local forest ranger marking crop trees and their competitors and a silvicultural worker with a CS carrying out tending on average spent less time in thicket compared to pole stand since in pole stand there was a greater number of trees ha^{-1} compared to thicket, and the number of crop trees and their competitors was on average greater. Consequently, tending costs for Succession in pole stand were greater than in thicket. If the results of our study are compared with a study conducted in LS forest [50], it is evident that a local forest ranger in thicket and pole stand on average needed somewhat less time ha^{-1} to mark crop trees and their competitors than in our study. Very likely this was primarily due to the inexperience of staff regarding this type of work and the complexity of stands in succession. Although, as a general rule, trees are not marked in thicket and pole stands, we recommend special training for the forest workers who are to perform tending of stands in succession in the future.

In order to compare tending costs for thicket and pole stands in succession in this study with the average tending costs for the same developmental phases in LS forest in Slovenia, we used tending standards set in regulations [32], but only for a worker with a CS. For the tending of natural thicket and pole stands in average working conditions (regarding tree species diversity and density, number of wolf trees, roughness of the terrain), the regulations define 36 and 32 $h \cdot ha^{-1}$, respectively. The amount of time for tending without marking trees in our study only amounted to 23% and 59% of the time set in the regulations.

5. Conclusions

This research has indicated high structural complexity of stands on abandoned agricultural lands, especially in view of species mixture and density. Therefore, significant consideration of local conditions is needed when decisions on silvicultural measures are made. However, high diversity is an opportunity to favor light-demanding and thermophilic species, which have difficulty recruiting in the conditions of LS forests. This is especially true for Central Europe, where larger clear-fellings are prohibited.

The findings regarding the thicket stage in succession suggest that for optimum quality of crop trees, moderate intervention (*i.e.*, lower intensity than in this study) is preferable due to the low density of trees and the risks associated with poor architecture and the proliferation of ground vegetation and climbers. On the other hand, the favorable responses of commercially interesting species such as *A. pseudoplatanus* and *Q. petraea* indicated the rationality of intervention, especially during the pole stage. Our research showed lower time consumption and costs for the tending of young stands in succession when compared to gaps within LS forests. Considering this outcome and accounting for the complex stand structure as well as the frequency of valuable tree species, the management of secondary succession in the case of Haloze presents a viable alternative over non-management or afforestation if ecologically balanced forest restoration is the objective.

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Author Contributions

Initial ideas and financing of the research: all authors; data compilation and evaluation: all authors; manuscript drafting and revising successive drafts: all authors.

Appendix

Table A1. General site and stand data of Tending plots. The sampling area was 400 m^2.

Plot	Developmentalphases	Latitude, N	Longitude, E	Elevation(m)	Slope(°)	Aspect	Forest Plant Communities
1	Thicket	57°35′	13°28′	251	16	SW	*Hedero-Fagetum*
2	Thicket	57°36′	13°28′	249	15	SE	*Hedero-Fagetum*
3	Pole stand	57°64′	13°33′	285	22	NW	*Hedero-Fagetum*
4	Pole stand	56°79′	12°79′	455	30	SW	*Hedero-Fagetum*
5	Pole stand	57°09′	13°05′	350	21	NW	*Hedero-Fagetum*
6	Pole stand	57°12′	13°52′	270	22	W	*Querco-Carpinetum*
7	Thicket	57°77′	13°59′	283	22	S	*Hedero-Fagetum*
8	Thicket	56°58′	13°24′	300	35	S	*Hedero-Fagetum*
9	Thicket	56°68′	13°17′	298	20	E	*Hedero-Fagetum*
10	Pole stand	57°87′	13°73′	365	11	N	*Hedero-Fagetum*

Table A2. A list of observed tree species indicating which species were selected as crop or competitor trees, and their classification as pioneer, intermediate or climax species.

Latin name	Classification	Forest	Succession	Crop Tree	Competitor Tree
Abies alba Mill.	climax	√	√		
Acer campestre L.	pioneer	√	√	√	√
Acer platanoides L.	intermediate	√	√		
Acer pseudoplatanus L.	intermediate	√	√	√	√
Alnus glutinosa (L.) Gaertn.	pioneer	√	√	√	√
Betula pendula Roth	pioneer	√	√	√	√
Carpinus betulus L.	intermediate	√	√	√	√
Castanea sativa Mill.	climax	√	√	√	√
Fagus sylvatica L.	climax	√	√	√	√
Fraxinus excelsior L.	intermediate	√	√		
Fraxinus ornus L.	pioneer	√	√	√	√
Juglans regia L.	intermediate	√	√	√	√
Larix decidua Mill.	intermediate	√			
Quercus cerris L.	intermediate		√	√	√
Quercus petraea (Matt.) Liebl.	climax	√	√	√	√
Picea abies (L.) Karst.	climax	√	√		
Pinus sylvestris L.	climax	√	√		√
Pinus strobus L.	intermediate	√			
Pyrus pyraster (L.) Borkh	intermediate	√	√		
Populus alba L.	pioneer		√	√	√
Populus tremula L.	pioneer	√	√	√	√
Prunus avium L.	intermediate	√	√	√	√
Prunus cerasus L.	intermediate		√		
Robinia pseudoacacia L.	intermediate		√	√	
Salix caprea L.	pioneer	√	√	√	√
Sorbus domestica L.	intermediate		√		
Sorbus torminalis (L.) Crantz	intermediate	√	√	√	√
Tilia cordata Mill.	intermediate	√	√	√	
Ulmus minor Mill.	intermediate		√		
Ulmus glabra Huds.	intermediate	√			
shrubs					√

Table A3. Comparison of the number of crop trees (density per ha) and their mean diameter (d.b.h.) on Control and Tending plots according to year of measurement; the standard deviation is given in parentheses.

Year	Control	N	Tending	N
	d.b.h. (cm)		d.b.h. (cm)	
2007	6.3 (4.3)	656	5.6 (3.5)	781
2009	8.7 (5.1)	619	8.4 (4.0)	681
2011	11.0 (5.6)	463	10.1 (4.4)	588
2007/2011	173% (131%)	70%	179% (126%)	75%

Figure A1. Comparison of the frequency distributions of trees according to d.b.h. classes in Succession (**A**) and Forest (**B**) in 2007; for Succession, the d.b.h. distribution of crop trees at the beginning of the experiment is also given.

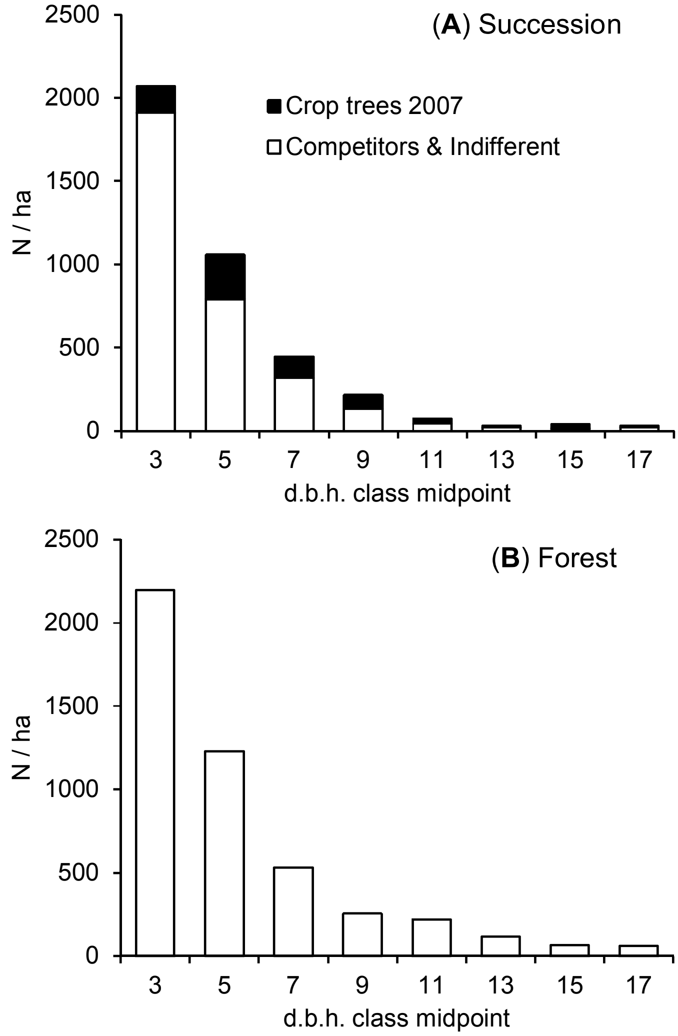
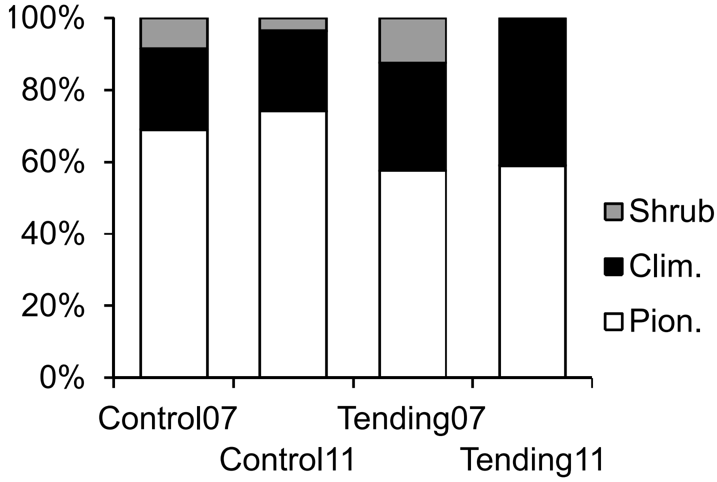


Figure A2. Species groups composition of competitors in 2007 in relation to density according to treatments.



Conflicts of Interest

The authors declare no conflict of interest.

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