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Research paper

Thinning cycles as the key factor to improve stand productivity in alder plantations

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ABSTRACT Considering the high demand for wood and other forest ecosystem services, planning and managing forest plantations to mitigate and answer these increasing issues is necessary. Thinning is one of the most common managing practices for manipulating the growth of planted trees. However, studies about the impact of the thinning-cycle on stand and soil properties are rare for *Alnus subcordata* C.A.Mey. in Hyrcanian Forests. The aim of this study was to investigate the effect of thinning-cycles on stand and soil properties in the *Alnus subcordata* plantation in the Hyrcanian Forests, Northern Iran. Three neighboring alder plantations were selected with different thinning treatment cycles: the one-time thinning-cycle (T1, thinned in 2007), three-time thinning-cycle (T3, thinned in 2005, 2010, and 2015), and no thinning as the control (C). In each plantation, 15 plots (20×20 m) were systematic-randomly established (75×50 m grid). In each plot, the characteristics of trees (diameter at breast height (DBH) and total height) and total percentage of vegetation cover were recorded. Soil physiochemical properties were studied by taking samples (0-10 cm) from each plot. The highest value of DBH, total height, tree volume, and basal area and the lowest amount of the total height to DBH ratio were observed in T3. The highest levels of vegetation diversity, evenness, and richness indices were obtained in T3. Soil moisture was significantly higher in the control. The soil pH, electrical conductivity, nitrogen, and potassium were significantly higher in T3. According to the principal component analysis, there was no difference between T1 and control. For this reason, T3 was a more beneficial treatment. Our findings suggested that in alder plantations, the reduction of above and belowground competition via the three-time thinning-cycle, in addition to the financial benefits, not only improves the quality and quantity of the remaining trees but also has a significant potential to improve soil productivity.

KEYWORDS: Thinning effects, monoculture, *Alnus subcordata*, forest restoration.

Introduction

Considering that anthropogenic activities and the high demand for wood have deforested forest ecosystems in some places of the world, the implementation of plantation practices through the supply of wood could reduce the pressure on natural forest ecosystems. Thus, forest plantations have become common in landscapes all over the world (Humpenoder et al. 2014). Among plantations tending and management practices, thinning is one of the most applied treatments for improving plantation growth (Becagli et al. 2013, Li et al. 2017, Schaedel et al. 2017, Lin et al. 2018). Thinning has the potential to reduce competition between trees and can improve the vigor of the stand, and as well as increase in stability of forest stands against any disturbances (e.g. wind storms, snow crashes); therefore, it could increase the growth and tree volume for commercial purposes (Liu et al. 2017). Thinning promotes the value of harvest through the increase in size, volume, and timber quality (Lo-Cho 1991, Proto et al. 2020). In general, thinning can redistribute the resources of the site (e.g., light, water, and nutrients) for the remaining valuable trees and also reduce the intraspecific competition for these resources, which could lead to the development of canopy and root systems, resulting in the faster growth rate of the remaining trees (Forrester 2013, West 2014).

Thinning practice can be described in terms of the thinning cycle, thinning type, thinning intensity, and remaining tree distribution. Many studies have been conducted on the effect of the thinning type and thinning intensity on the stand and soil properties (Cicek et al. 2013, Chen et al. 2014, Dang et al. 2018, Zhou et al. 2021) but less attention has been paid to the effect of the thinning cycle. The thinning cycle is the interval in years between successive thinning. The usual length of the thinning cycle in plantations depends on the species type (Gonçalves 2020); however, it is usually from four to six years for young or fast-growing crops and about 10 years for older or slower-growing ones (Kerr and Haufe 2011).

The biodiversity of the understory could change as a result of thinning practices because of the change in canopy cover densities and forest microclimate parameters (Dang et al. 2018). The positive, negative, and neutral effects of thinning on understory vegetation were reported in previous studies (Taki et al. 2010, Metlen and Fiedler 2006, Lei et al. 2007). These differences could be related to the site conditions and stand ages (Lei et al. 2007). Therefore, understanding the effects of thinning cycles in plantations on the diversity of understory is important (Taki et al. 2010), but studies on these topics are very rare.

Most studies on thinning have mainly focused on the growth of the tree, stand volume, and stand stability (Cheng et al. 2017, Nishizono et al. 2008, Wang et al. 2013, Chen et al. 2014). However, it should be note that understanding the effects of thinning on

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forest soil is also helpful to understand the appropriate management of forest plantations and should be considered. Thinning can alter the micro-environment in the stands, temporarily increase the soil nutrient availability, and change the soil moisture, soil temperature, root distribution, and consequently the microbial communities (Tang et al. 2005, Lull et al. 2020, Lagomarsino et al. 2020, Zhou et al. 2021). The change in soil properties after thinning practices can impact tree growth, site productivity (Zhou et al. 2015), and soil carbon sequestration (Zhang et al. 2016, Mazza et al. 2019). Therefore, studies on the effect of the thinning cycle on soil properties in plantations are also important.

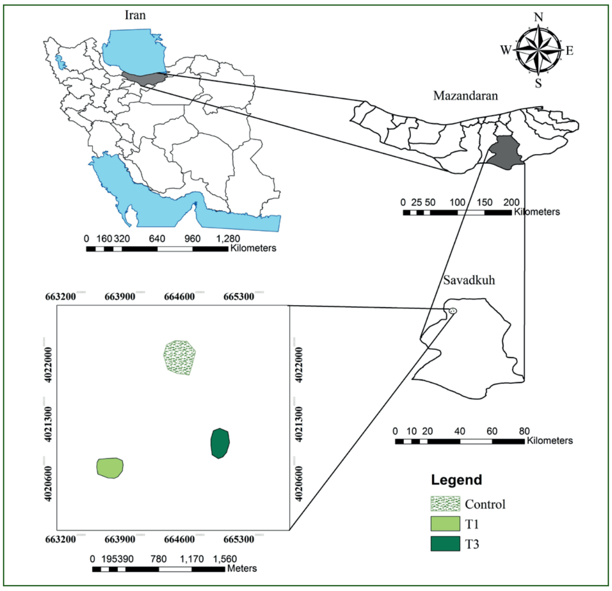
Hyrcanian Forests, which are in the north of Iran, have been recently inscribed in the UNESCO world heritage list. These forests are dominated by the combinations of oriental beech (*Fagus orientalis* Lipsky), Caucasian oak (*Quercus castaneifolia* C.A.Mey.), hornbeam (*Carpinus betulus* L.), and Persian Ironwood (*Parrotia persica* C.A.Mey.). However, over the last decades, human activities have considerably degraded these valuable forests (Sagheb-Talebi et al. 2014). The degradation of Hyrcanian Forests has significant widespread effects on a global scale (e.g. CO_2 emission). In the past few decades, large areas of forest plantations, especially those with native and exotic tree species, have been established to restore the degraded lands and mitigate the social demand for forest ecosystem services. The restoration of degraded areas in the Hyrcanian Forest has been largely established by *Alnus subcordata* C.A.Mey. monocultures, which is a pioneer species able to facilitate the introduction of late-successional hardwoods to reach higher biodiversity and more resilient and resistant ecosystems. After restoration, the common tending practices have been carried out in planted areas. Based on the available information, there has not yet been a study on the effect of the thinning cycles on the alder plantation stand in Hyrcanian Forests. This study aimed to investigate the effects of thinning cycles (one time and three times) on the *(i)* stand characteristic; *(ii)* on vegetation diversity; and *(iii)* on soil properties. Evaluation of tending practices in plantations is important for making decisions in order to obtain better quality and quantity forests in the future.

Materials and methods

Study area

This study was conducted in Babolkenar Forest, central Hyrcanian Forests, Savadkuh City, Mazandaran Province, north of Iran (Fig. 1). The average slope in this region is about 5-15%, the main aspects are south and south-west, and according to the world reference base for soil resources (WRB) the soil type is Cambisol. The climate is temperate humid, and meteorological data indicated that long-term (1993-2015) average annual rainfall is 829 mm. The mean annual temperature is 15°C. The mean elevation in the study area is 200 m (asl). and main tree species include *Quercus castaneifolia* C. A. Mey., *Carpinus betulus* L, *Fagus orientalis Lipsky*, and *Alnus subcordata* C. A. Mey.

Figure 1 - Location of the Study Site.



In order to investigate the effect of thinning cycles on stand and soil properties, three plantations of *Alnus subcordata* were selected. All three plantations were established (the planting distance was 2×2 m intervals) in 1993 following the clear cut. In general, three thinning treatments were considered as follows: one-time thinning cycle (T1), three-times thinning cycle (T3), and no thinning as the control treatment (C). The T1 thinning was conducted in 2007, and the T3 thinning was performed in 2005, 2010, and 2015. In the control treatment, no thinning practice was conducted.

Data collection

In this study, after visiting the field and determining the location of plantations (T1, T3 and C stands), 15 plots (20×20 m) were systematic-randomly established (75×50 m grid) in each stand. In each plot, the number of trees, diameter at breast height (DBH), and total height of each tree were recorded. The volume of the trees (V_t) was calculated using Equation (1):

$$V_t = \frac{\pi}{4} DBH^2 \times H_t \times f \qquad \text{(eq. 1)}$$

Where f is the reduction coefficient of trees (considered 0.5, as mentioned for Hyrcanian forest trees, Zobeiry 2000 and Namiranian 2007). In order to consider soil physical and chemical properties, soil samples were taken from the topsoil layer (0-10 cm) in each plot using the coring method (cylindrical steel columns; diameter: 8 cm, height: 10 cm). In order to study the biodiversity of the herbaceous cover, the total percentage of each species was measured in each plot; and their percentage cover was visually and subjectively assessed by the Braun–Blanquet classification system (Dengler et al. 2008).

Laboratory analysis

In the laboratory, soil samples were passed through a 2 mm sieve (after removing coarse fragments and plant root residuals). The soil moisture content (%) of sub-samples was determined by drying the given amount of fresh soil in a hot air oven at 105 ± 5°C until a constant weight was obtained (24 h). Soil bulk density was measured using the clod method. Soil texture was assessed using the hydrometer method. Soil pH (using Orion Analyzer Model 901 pH meter in a 1:2.5 soil/water suspension) and electrical conductivity (EC) (using Orion Analyzer Model 901 EC meter, in water-saturated soil extract at 20°C) were also measured. In addition, total N (Kjeltec System Instrument, TECATOR) and available P (with Olsen P extracting solution (0.5 M $NaHCO_3$) at pH 8.5 using a UV spectrophotometer) were determined. The Walkley–Black technique was used to calculate the percentage of organic carbon (% OC).

Statistical analysis

Values of diversity indices (Simpson and Shanon-Wiener), richness indices (Margalef and Menhinic), and evenness indices (Camargo and Smith-Wilson) shown in Table 1 were calculated using PAST software. Shapiro-Wilk and Levene's tests were used to assess the normality of the variables and to examine the equality of the variances, respectively. The experimental design was a completely randomized design. The data were analyzed by analysis of variance (ANOVA) using SPSS 22 and the least significant difference test (LSD) at a significance level of 5%. The relationships between soil properties were tested by principal component analysis (PCA) performed on R software (version 3.4.0) (Tab. 1).

Results

Quantitative characteristics of trees

The results showed that there was a significant difference between the treatments in terms of the quantitative characteristics of trees. The number of trees per hectare in the control treatment was significantly higher than T1 and T3. The highest values of DBH, total height, tree volume, and basal area were observed in T3. The lowest value of the total height to DBH ratio (HDR) was observed in T3 (Tab. 2).

Biodiversity indices

In general, seven herbaceous species were identified in this study, which are listed in Table 3. *Rubus* sp. was observed only in the control treatment, and *Viola* sp. was found only in T3. The Simpson and Shannon-Weiner indices were higher in T3 and T1 than in the control treatment. The value of the evenness index was higher in thinning treatments than in the control treatment. The highest values of Menhinick and Margalef were observed in T3 (Tab. 4).

Table 1 - Biodiversity indices.

	Indices	Formula
Diversity	Simpson	D =1- ∑n1(n1 – 1) / (N(N - 1))
	Shannon-Winner	$H=-\sum_{i=1}^{s} (Pi)\ (InPi)$
Richness	Margalef	R =S -1/LnN
	Menhinick	$R=S/\sqrt{n}$
Evenness	Pit	E = H/ln(S)
	Camargo	$E=1-(\sum_{i=1}^{s}\sum_{j=1+1}^{s}(\frac{Pi-Pj}{s}))$

Table 2 - Quantitative characteristics of trees in different treatments.

Quantitative characteristics	Control	T1	T3
Number per hectare	573 ± 8[a]	482 ± 15[b]	473 ± 8[b]
DBH (cm)	19.2±0.2[c]	21.2±0.3[b]	28.2±0.3[a]
Total Height (m)	19.9±0.2[b]	20.3±0.3[b]	22.9±0.4[a]
Basal Area (m^2)	17.22±0.54[b]	17.43±0.57[b]	30.36±1.17[a]
Volume (m^3)	178.61±6.20[b]	184.35±7.17[b]	356.43±13.9[a]
Height/ DBH (HDR)	1.04±0.008[a]	0.96±0.017[b]	0.82±0.011[c]

Different letters indicate significant differences (p<0.05) between treatments.

Table 3 - List of identified herbaceous species in different treatments (* and - indicates the presence and absence of species in the treatment).

Species	Controls	T1	T3
Sambucus ebulus	-	*	*
Oplismenus undulatifolium	-	*	*
Carex sp.	*	*	*
Ruscu hyrcanus	-	*	*
Poa annua	*	*	*
Viola sp.	-	-	*
Rubus sp.	*	-	-

Table 4 - Biodiversity indices of herbaceous species in different treatments.

Biodiversity Indices	Controls	T1	T3
Shannon-Wiener	0.53±0.05[b]	1.16±0.06[a]	1.30±0.04[a]
Simpson	0.29±0.03[b]	0.65±0.05[a]	0.70±0.0[a]
Pilue	0.67±0.02[b]	0.86±0.01[a]	0.89±0.02[a]
Menhinick	0.28±0.01[c]	0.42±0.0[b]	0.51±0.03[a]
Margalef	0.36±0.03[c]	0.63±0.03[b]	0.76±0.06[a]

Different letters indicate significant differences ($p<0.05$) between treatments.

Soil properties

The results showed that among physical properties, only soil moisture was significantly higher in the control treatment than in T1 and T3. There was no significant difference between the treatments in terms of bulk density, sand, and silt percentage. The soil pH and EC were significantly higher in T3 than in T1 and control. Soil nitrogen in the control treatment was significantly lower than in T1 and T3. There was no significant difference in the soil phosphorus content between the treatments. The soil potassium content was significantly higher in T3. The amount of OC in the control treatment was significantly higher than in the other treatments (Tab. 5).

The results of the PCA for stand and soil proper-

Figure 2 - Principal component analysis (PCA) of stand and soil properties (axis 1: eigenvalues = 6.85; axis 2: eigenvalues = 2.60).

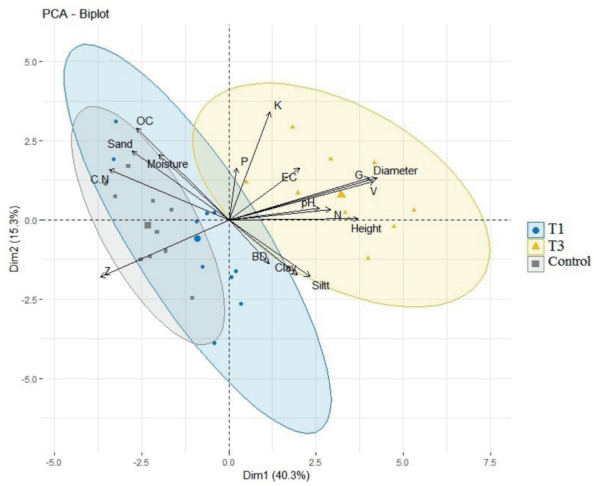


Table 5 - Physical and chemical properties of soil in different treatments.

Soil Properties	Controls	T1	T3
Moisture (%)	54.15±2.45[a]	43.57±3.27[b]	45.70±2.20[b]
Bulk Density (g cm-3)	1.68±0.09[a]	1.58±0.08[a]	1.70±0.06[a]
Sand (%)	54.26±0.92[a]	57.17±2.59[a]	51.12±1.75[a]
Silt (%)	35.20±0.97[a]	32.92±1.99[a]	37.59±1.85[a]
Clay (%)	10.52±0.45[a]	9.91±0.9[a]	11.46±0.75[a]
pH	6.37±0.05[b]	6.39±0.05[b]	6.62±0.09[a]
EC (ds cm-1)	0.49±0.02[b]	0.46±0.02[b]	0.59±0.02[a]
Total N (%)	0.21±0.0[b]	0.28±0.01 a	0.31±0.0[a]
Available P (mg kg-1)	5.73±0.70[a]	7.09±1.22 a	6.80±1.15[a]
Available K (mg kg-1)	544±26.80[b]	503±45.15[b]	666±48.70[a]
C (%)	5.88±0.26[a]	4.85±0.35[b]	4.68±0.32[b]

Different letters indicate significant differences ($p<0.05$) between treatments.

ties indicated that the first and second axes accounted for 40.3% and 15.3% of the total variance, respectively (Fig. 2). The first axis was related to diameter, height, basal area (G), volume (V), HDR (Z), sand, silt, clay, pH, and nitrogen (N). In general, diameter, height, basal area (G), volume (V), pH, EC, nitrogen (N), phosphorous (P), and potassium (K) were correlated with the T3 treatment.

Discussion

In this study, we found that the thinning practice had a significant effect on biodiversity indices as well as stand and soil properties. According to our results, trees' DBH, total height, basal area, and volume were significantly higher in T3 and T1 than in the control. Thinning could increase the availability of resources and reduce the competition between trees (Medhurst et al. 2001, Huong et al. 2016). Increasing the growing space by means of thinning is especially beneficial to smaller trees growing on high-quality sites. This response to thinning is often related to the fast-growing species such as *Alnus subcordata*. Similar to other studies (Klädtke 1997, Štefancík et al. 2018, Bosela et al. 2021), we found positive influences on the diameter due to thinning. The positive effects of thinning on the tree diameter can be related to the higher water, light, and nutrient availability in the thinned stand. The increase in tree diameter in response to thinning could be due to increased water, photosynthetic rate, and nitrogen use efficiency in the thinned stand (Wang et al. 1995).

According to our results, both basal area and volume were higher in T3. The main reason could be the redistribution of site resources (light, water, and nutrients) by thinning, which can concentrate the mentioned site resources to the remaining valuable trees and reduce the competition for these resources (Forrester 2013, West 2014). Bobinac (2004) found lower increments of basal area and volume for the control stands compared with those for the thinned ones. Similar results were observed in beech forests in Germany (Pretzsch 2005), where three types of thinning from below (weak, medium, strong) were compared in stands at the age of 100 years. The total stand volume was the highest after the application of thinning. Similar to the results of our study, thinning increased the basal area growth in some broad-leaved tree species (Pretzsch 2005, Boncina et al. 2007).

According to our results, the DBH, total height, basal area and volume of stand were significantly higher in T3 in comparison with T1. This result could be related to the fact that performing three times thinning practice could provide more resources for the remaining trees and also decreased neighbor competition, consequently leads to increase in volume growth (Lin et al. 2018, Moreau et al. 2020). In other hand, this is attributed to the fact that the remaining trees benefit from more growing space (Kim et al. 2016). This results also suggest that performing one thinning response becomes lower the longer it is delayed (Huong et al. 2016). In addition, it can be concluded that the one-time thinning in comparison with three times thinning, was not enough to cause considerable changes in resources (e.g. light and nutrients) in stand (Park et al. 2018); however, it had positive effect in comparison with control. The similar results about the effect of thinning intensity were reported in previous studies (Cicek et al. 2013, Chen et al. 2014, Dang et al. 2018, Zhou et al. 2021).

Thinning significantly influences the static stability of the stands, which is commonly assessed by the height-diameter ratio (HDR). Generally, smaller HDR indicates lower centers of gravity of trees with longer crown lengths and also higher stability than trees with larger HDR (Sharma et al. 2016). The HDR was significantly lower in T3 than T1, in other hand trees in T3 had higher stability than trees in T1 stand. Thinning reduces the light competition between trees and increases the DBH increment (Kim et al. 2016, Deng et al. 2019), for this reason three times thinning led to more reduction in HDR in comparison with the one-time thinning. Some other benefits of thinning include promoting forest health through removing weak and undesirable trees (insect/disease-susceptible), as well as biodiversity improvement by site component redistribution (Janas and Brand 1998).

Our results showed that the understory diversity significantly increased with the thinning cycle. Similar results were reported in previous studies (Ares et al. 2010, Huang et al. 2014, Zhou et al. 2016, Dang et al. 2018, Dang et al. 2018, Xu et al. 2020). Thinning can decrease the crown coverage and improve the microclimatic conditions (light, soil water, and nutrient availability), which could change the availability of resources and consequently lead to increases in the understory diversity (Li et al. 2020). Zhu et al. (2008) mentioned that light significantly alters the plant composition and diversity in the thinned stand. In addition, thinning can improve the light scattering, reflected light, and transmitted light, which can lead to a higher difference in the quality of light (Hu and Zhu 1999). Therefore, differences in thinning intensities could change the understory species composition and diversity. However, negative effects of thinning on understory vegetation were also reported (Cheng et al. 2017). These discrepancies might be related to the differences in the thinning conditions (choice of pretreatment methods), structure of the plant, intensity of the thinning, and the stand stage (Juodvalkis et al. 2005). After thinning, the understory plants receive more light and nutrients, which consequently leads to the growth of light-demanding plants.

The results showed that the thinning cycle had no significant effect on soil bulk density. However, in a previous study, differences in soil physical properties were reported in the thinned stand in north-central Wisconsin over a 50 year period. Moreover, Bravo-Oviedo et al. (2015) did not find a significant difference in soil bulk density among treatments in a Scots pine (*Pinus sylvestris* L.) stand after 40 years. However, previous studies have reported that some soil physical properties (e.g. bulk density and soil hydraulic parameters) changed after thinning (Page-Dumroese et al. 2010, Chen et al. 2014). In addition, the impact of thinning on soil physical properties could be related to the use of machinery (Page-Dumroese et al. 2010). The soil sand, silt, and clay percentages showed no significant difference between the thinning and control treatments. These results were similar to those reported by Cheng et al. (2017).

The results of this study showed that soil pH, EC, nitrogen, and potassium were significantly higher in T3 than in T1 and control. There was no significant difference between the treatments in terms of phosphorus. Wall (2012) claimed that soil pH and some soil nutrients (P, K, Ca, and Mg) are the main indicators of soil productivity and forest sustainability following management. Thinning could change the microclimate, litter decomposition, and the composition of the understory, which consequently leads to changes in the soil macro and micro elements. The increase of soil N in the topsoil layer in intensive thinning practice could be related to the release of N in the litter decomposition (Vitousek et al. 1989, Cheng et al. 2017). Our results regarding potassium and phosphorus were similar to those reported by Cheng et al. (2017). This might be related to the fact that phosphorus is not absorbed by trees because of its fixation by metal ions, such as Fe^{+3}, in the forest soil (He et al. 2015). In this study, soil carbon was decreased by performing more thinning practices. The findings were similar to the results reported by Zhou et al. (2015) and Jurgensen et al. (2012). These results could be due to the effects of thinning on the carbon contents of the forest floor. Thinning has the potential to reduce the forest floor carbon contents by decreasing litter production from the remaining trees (Navarro et al. 2013) and accelerating litter decomposition (Gliksman et al. 2018). In general, due to changes in the density of canopies and stands following the thinning, the soil moisture and temperature are increased and consequently may create the appropriate conditions for microorganisms in the soil (Barg and Edmonds 1999, Christ et al. 1997). In addition, soil organic matter quantity and quality and the nutrient concentration (Kim et al. 2016) can also be affected.

According to our results, the PCA ordination of the treatments based on the stand and soil properties showed a clear and distinguished pattern. In other words, it can be stated that T3 was different in terms of stand and soil properties from the other treatments. Considering that T1 and control were not seperated, it can be stated that T3 was a more useful treatment.

Conclusion

Our findings suggested that the three-time thinning cycle (with five-year intervals) had a modified impact on biodiversity as well as stand and soil properties. The higher value of the stand volume in T3 indicates that performing the three-time thinning practice could be a good approach for wood production from fast-growing species such as *Alnus subcordata*. From an ecological point of view, the applied methods of thinning contribute to the increase of the stand stability (lower HDR) and plant biodiversity. According to the PCA, there was no difference between T1 and control in terms of stand and soil properties; hence, it can be concluded that T3 was a more useful treatment. Overall, thinning had a positive effect on soil fertility and quality in *Alnus sabcordata* plantation in Hyrcanian Forests. Our findings suggested that in alder plantations, the reduction of above and belowground competition via the three-time thinning cycle, in addition to the financial benefits, not only improves the quality and quantity of the remaining trees but also has a significant potential to improve soil productivity. The results of this study could be beneficial for managing degraded lands and could help managers dealing with afforestation/reforestation practices.

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References

Ares A., Neill A.R., Puettmann K.J. 2010 - *Understory abundance, species diversity and functional attribute response to thinning in coniferous stands.* Forest Ecology and Management 260:1104–1113.

Barg A.K., Edmonds R.L. 1999 - *Influence of partial cutting on site microclimate, soil nitrogen dynamics, and microbial biomass in Douglas-fir stands in western Washington.* Canadian Journal of Forest Research 29: 705–713.

Becagli C., Puletti N., Chiavetta U., Cantiani P., Salvati L., Fabbio G. 2013 - *Early impact of alternative thinning approaches on structure diversity and complexity at stand level in two beech forests in Italy.* Annals of Silvicultural Research 37(1): 55-63.

Boncina A., Kadunc A., Robic D. 2007 - *Effects of selective thinning on growth and development of beech (*Fagus sylvatica *L.) forest stands in south-eastern Slovenia.* Annals of Forest Science 64: 47–57.

Bobinac M. T. 2004 - *Properties of hornbeam (*Carpinus betulus *L.) seedling ontogeny during the first vegetation period in stand conditions*. Acta herbologica 13(1): 219-226.

Bosela M., Štefančík I., Marčiš P., Rubio-Cuadrado Á., Lukac M. - 2021. *Thinning decreases above-ground biomass increment in central European beech forests but does not change individual tree resistance to climate events*. Agricultural and Forest Meteorology 306: 108441.

Bravo-Oviedo A., Ruiz-Peinado R., Modrego P., Alonso R., Montero G. 2015 - *Forest thinning impact on carbon stock and soil condition in Southern European populations of* P. sylvestris *L*. Forest Ecology and Management 357: 259-267.

Chen L., Yuan Z., Shao H. Wang D., Mu X. 2014 - *Effects of thinning intensities on soil infiltration and water storage capacity in a Chinese pine-oak mixed forest*. The Scientific World Journal: 268157. https://doi.org/10.1155/2014/268157

Cheng C., Wang Y., Fu X., Xu M., Dai X., Wang H. 2017 - *Thinning effect on understory community and photosynthetic characteristics in a subtropical Pinus Massoniana plantation*. Canadian Journal of Forest Research 47(8): 1104-1115.

Cheng X., Yu M., Wang G. 2017 - *Effects of thinning on soil organic carbon fractions and soil properties in* Cunninghamia lanceolata *stands in eastern China*. Forests 8(6): 1-14.

Cheng X., Yu M., Wu T. 2013 - *Effect of forest structural change on carbon storage in a coastal* Metasequoia glyptostroboides *stand*. The Scientific World Journal: 830509. https://doi.org/10.1155/2013/830509

Christ M.J., David M.B., McHale P.J., Mitchell M., Rustad L., Fernandez I. 1997 - *Microclimatic control of microbial C, N, and P pools in Spodosol Oa horizons*. Canadian Journal of Forest Research 27: 1914–1921.

Cicek E., Yilmaz F., Özbayram A.K., Efe M., Yilmaz M., Usta A. 2013 - *Effects of thinning intensity on the growth of narrow-leaved ash (*Fraxinus angustifolia *subsp.* oxycarpa*) plantations*. Turkish Journal of Agriculture and Forestry 37(1): 97-104.

Dang P., Gao Y., Liu J., Yu S., Zhao Z. 2018 - *Effects of thinning intensity on understory vegetation and soil microbial communities of a mature Chinese pine plantation in the Loess Plateau*. Science of the Total Environment 630: 171-180.

Deng C., Zhang S., Lu Y., Froese R.E., Ming A., Li Q. 2019 - *Thinning Effects on the Tree Height–Diameter Allometry of Masson Pine (*Pinus massoniana *Lamb.)*. Forests 10(12): 1129.

Dengler J., Chytry´ M., Ewald J. 2008 - *Phytosociology*. In: Jørgensen S.E., Fath B.D. (eds.) Encyclopedia of ecology. Elsevier, Amsterdam, The Netherlands: 2767–2779.

Forrester D.I., Elms S.R. Baker T.G. 2013 - *Tree growth-competition relationships in thinned Eucalyptus plantations vary with stand structure and site quality*. European Journal of Forest Research 132: 241–252.

Gliksman D., Haenel S., Osem Y., Yakir D., Zang, E., Preisler Y., Grünzweig J.M. 2018 - *Litter decomposition in Mediterranean pine forests is enhanced by reduced canopy cover*. Plant Soil 422: 317–329.

Gonçalves A.C. 2020 - *Thinning: An Overview*. In Silviculture. IntechOpen.

He Z., Liu J., Su S., Zheng S., Xu D., Wu Z., Hong W., Wang J.L.M. 2015 - *Effects of forest gaps on soil properties in Castanopsis kawakamii nature forest*. PloS one 10(10): 0141203.

Huang P.S., Lin Hz.C., Lin, C.P., Tso I.M. 2014 - *The effect of thinning on ground spider diversity and microenvironmental factors of a subtropical spruce plantation forest in East Asia*. European Journal of Forest Research 133: 919–930.

Humpenoder F., Popp A., Dietrich J.P., Klein D., Lotze-Campen H., Bonsch M., Bodirsky B.L., Weindl I., Stevanovic M., Muller C. 2014 - *Investigating afforestation and bioenergy CCS as climate change mitigation strategies*. Environmental Research Letters 9: 064029.

Huong V.D., Mendham D.S., Close D.C. 2016 - *Growth and physiological responses to intensity and timing of thinning in short rotation tropical Acacia hybrid plantations in South Vietnam*. Forest Ecology and Management 380: 232-241.

Janas P. S., Brand D. G. 1988 - *Comparative growth and development of planted and natural stands of jack pine*. The Forestry Chronicle 64: 320–328.

Juodvalkis A., Kairiukstis L., Vasiliauskas R. 2005 - *Effects of thinning on growth of six tree species in north-temperate forests of Lithuania*. European Journal of Forest Research 124: 187–192.

Jurgensen M., Tarpey R., Pickens J., Kolka R., Palik B. 2012 - *Long-term effect of silvicultural thinnings on soil carbon and nitrogen pools*. Soil Science Society of America Journal 76(4): 1418-1425.

Kerr G., Haufe J. 2011 - *Thinning practice: a silvicultural guide*. Forestry Commission 1.

Kim M., Lee W.K., Kim Y.S., Lim C.H., Song C., Park T., Son Y., Son Y.M. 2016 - *Impact of thinning intensity on the diameter and height growth of* Larix kaempferi *stands in central Korea*. Forest science and technology 12(2): 77-87.

Klädtke J. 1997 - *Buchen-lichtwuchsdurchforstung*. Allgemeine Forst Zeitschrift fur Waldwirtschaft und Umweltvorsorge 52: 1019–1023.

Lagomarsino A., Mazza G., Agnelli A.E., Lorenzetti R., Bartoli C., Viti C., Colombo C., Pastorelli R. 2020 - *Litter fractions and dynamics in a degraded pine forest after thinning treatments*. European Journal of Forest Research 139(2): 295-310.

Lei X., Lu Y., Peng C., Zhang X., Chang J., Hong L. 2007 - *Growth and structure development of semi-natural larch-spruce-fir* (Larix olgensis–Picea jezoensis–Abies nephrolepis) *forests in northeast China: 12-year results after thinning*. Forest Ecology and Management 240(1-3): 165-177.

Li R.S., Yang Q.P., Zhang W.D., Zheng W.H., Chi Y.G., Xu M., Fang Y.T., Gessler A., Li M.H., Wang S.L. 2017 - *Thinning effect on photosynthesis depends on needle ages in a Chinese fir* (Cunninghamia lanceolata) *plantation*. Science of the Total Environment 580: 900-906.

Lin J.C., Chiu C.M., Lin Y.J., Liu W.Y. 2018 - *Thinning effects on biomass and carbon stock for Young Taiwania plantations*. Scientific reports 8(1): 1-7.

Liu W. Y., Lin C. C., Su K. H. 2017 - *Modelling the spatial forest-thinning planning problem considering carbon sequestration and emissions*. Forest Policy and Economics 78: 51–66.

Lo-Cho C.N., Chung H.H., Chiu C.M., Chou C.F. and Lo S.S. 1991 - *Effects of thinning and pruning on Taiwania* (Taiwania cryptomerioides Hayata) *plantations*. Bull. Taiwan Forestry Research Institute New Series 6(2): 155–168.

Lull C., Bautista I., Lidón A., del Campo A.D., González-Sanchis M., Garcia-Prats A. 2020 - *Temporal effects of thinning on soil organic carbon pools, basal respiration and enzyme activities in a Mediterranean Holm oak forest.* Forest Ecology and Management 464: 118088.

Mazza G., Agnelli A.E., Cantiani P., Chiavetta U., Doukalianou F., Kitikidou K., Milios E., Orfanoudakis M., Radoglou K, Lagomarsino A. 2019 - *Short-term effects of thinning on soil CO_2, N_2O and CH_4 fluxes in Mediterranean forest ecosystems.* Science of the total Environment 651: 713-724.

Medhurst J.L., Beadle C.L. 2001 - *Crown structure and leaf area index development in thinned and unthinned Eucalyptus nitens plantations*. Tree Physiol 21: 989–999.

Metlen K.L., Fiedler C.E. 2006 - *Restoration treatment effects on the understory of ponderosa pine/Douglas-fir forests in western Montana, USA*. Forest Ecology and Management 222: 355–369.

Moreau G., Auty D., Pothier D., Shi J., Lu J., Achim A., Xiang W. 2020 - *Long-term tree and stand growth dynamics after thinning of various intensities in a temperate mixed forest.* Forest Ecology and Management 473: 118311.

Namiranian M. 2007 - *Measurement of Tree and Forest Biometry.* 1st Ed., Tehran University Publications, Tehran, Iran.

Navarro F.B., Romero-Freire A., Del Castillo T., Foronda A., Jiménez M.N., Ripoll M.A., Sánchez-Miranda A., Huntsinger L., Fernández-Ondoño E. 2013 - *Effects of thinning on litterfall were found after years in a* Pinus halepensis *afforestation area at tree and stand levels.* Forest Ecology and Management 289: 354–362.

Nishizono T., Tanaka K., Hosoda K., Awaya Y., Oishi Y. 2008 - *Effects of thinning and site productivity on culmination of stand growth: results from long-term monitoring experiments in Japanese cedar* (Cryptomeria japonica D. Don) *forests in northeastern Japan.* Journal of Forest Research 13(5): 264 274.

Page-Dumroese D.S., Jurgensen M., Terry T. 2010 - *Maintaining soil productivity during forest or biomass-to-energy thinning harvests in the western United States.* Western Journal of Applied Forestry 25(1): 5-11.

Park J., Kim T., Moon M., Cho S., Ryu D., Kim H.S. 2018 - *Effects of thinning intensities on tree water use, growth, and resultant water use efficiency of 50-year-old* Pinus koraiensis *forest over four years.* Forest Ecology and Management 408: 121-128.

Pretzsch H. 2005 - *Stand density and growth of Norway spruce* (Picea abies *(L.) Karst.) and European beech (*Fagus sylvatica *L.): evidence from long-term experimental plots.* European Journal of Forest Research 124: 193–205.

Proto A.R., Bernardini V., Cataldo M.F., Zimbalatti G. 2020 - *Whole tree system evaluation of thinning a pine plantation in southern Italy.* Annals of Silvicultural Research 45(1): 44-52.

Sagheb-Talebi K.H., Sajedi T., Pourhashemi M. 2014 - *Forests of Iran: A Treasure from the Past, a Hope for the Future, Plant and Vegetation.* Vol. 10 Springer Science +Business Media, Dordrecht.

Schaedel M.S., Larson A.J., Affleck D.L., Belote R.T., Goodburn J.M., Page-Dumroese D.S. 2017 - *Early forest thinning changes aboveground carbon distribution among pools, but not total amount.* Forest Ecology and Management 389: 187-198.

Sharma R.P., Vacek Z.,Vacek S. 2016 - *Modeling individual tree height to diameter ratio for Norway spruce and European beech in Czech Republic.* Trees 30: 1969–1982.

Štefancík I., Vacek Z., Sharma R.P., Vacek S., Rösslová M. 2018 - *Effect of thinning regimes on growth and development of crop trees in* Fagus sylvatica *stands of Central Europe over fifty years.* Dendrobiology 79: 141-155.

Taki H., Inoue T., Tanaka H., Makihara H., Sueyoshi M., Isono M., Okabe K. 2010 - *Responses of community structure, diversity, and abundance of understory plants and insect assemblages to thinning in plantations.* Forest Ecology and Management 259(3): 607-613.

Tang J., Qi Y., Xu M., Misson L., Goldstei A.H. 2005 - *Forest thinning and soil respiration in a ponderosa pine plantation in the Sierra Nevada.* Tree Physiology 25: 57–66.

Vitousek P.M., Matson P.A., Van Cleve K. 1989 - *Nitrogen availability and nitrification during succession: primary, secondary, and old-field seres.* Plant and soil 115(2): 229-239.

Wall A. 2012 - *Risk analysis of effects of whole-tree harvesting on site productivity.* Forest Ecology and Management 282: 175-184.

Wang H., Liu W., Wang W., Zu, Y. 2013 - *Influence of long-term thinning on the biomass carbon and soil respiration in a larch* (Larix gmelinii) *forest in Northeastern China.* The Scientific World Journal.

Wang J.R., Simard S.W., Kimmins J.P. 1995 - *Physiological responses of paper birch to thinning in British Columbia.* Forest Ecology and Management 73: 177–184.

West P.W. 2014 - *Growing Plantation Forests.* Springer International Publishing, Switzerland.

Xu X., Wang X., Hu Y., Wang P., Saeed S., Sun Y. 2020 - *Short-term effects of thinning on the development and communities of understory vegetation of Chinese fir plantations in Southeastern China.* PeerJ 8: e8536.

Zhang J., Webster J., Young D.H., Fiddler G.O. 2016 - *Effect of thinning and soil treatments on* Pinus ponderosa *plantations: 15-year results.* Forest Ecology and Management 368: 123–132.

Zhou T., Wang C., Zhou Z. 2021 - *Thinning promotes the nitrogen and phosphorous cycling in forest soils.* Agricultural and Forest Meteorology 311: 108665.

Zhou X., Zhou Y., Zhou C., Wu Z., Zheng L., Hu X., Chen H., Gan J. 2015 - *Effects of cutting intensity on soil physical and chemical properties in a mixed natural forest in southeastern China.* Forests 6(12): 4495-4509.

Zobeiry M. 2000 - *Forest Inventory (Measurement of Tree and Stand).* 1st Ed., Tehran University Publisher, Iran.