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Influence of Different Thinning Treatments on Stand Resistance to Snow and Wind in Loblolly Pine (*Pinus taeda* L.) Coastal Plantations of Northern Iran

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Abstract: Loblolly pine (*Pinus taeda* L.) is one of the main exotic conifer species that has been widely planted for the past fifty years for timber production in the coastal areas of northern Iran. Heavy snowfall and strong winds can cause much damage to these forests over a short time span of only a few years. This study was conducted to estimate snow and wind damage and analyze the role of stand thinning in their resistance to snow and wind. Amount and type of snow and wind damage were examined through systematic (80 m × 80 m) sample plots (each plot area of 625 m^2) in nine different stands (2–10 plots in each stand) in terms of age, structure, and silviculture history in three replications for each stand in April and May 2020. Results showed that the amount of snow and wind damage had a wide range from 1.3% to 30.7%. Snow damage was more than three times that of wind. Snow and wind damage in the young stands were significantly more serious ($p < 0.01$) than in the middle-aged and old stands, and damage was significantly higher ($p < 0.01$) in the unthinned stands than in the thinned ones. Slenderness coefficient (Height/Diameter ratio, HD ratio) of trees resulted to be a good indicator in young and middle-aged stands, while crown form indices (relative crown length and relative crown width) were acceptable indicators in old stands for risk of snow and wind damage. Our results showed that the normal thinning (15% of basal area) decreased snow and wind damage in all the stands, while the heavy thinning (35% of basal area) reduced the snow damage, but it increased the wind one. It is possible to recommend high intensity thinning in young stands, normal thinning in middle-aged stands, and light thinning (15% of basal area) in old ones.

Keywords: loblolly pine plantation; stand age; snow and wind damage; thinning intensity; height-diameter ratio

1. Introduction

Pine forests are one of the most widespread types of vegetation worldwide, both in natural formations and in artificial plantations. Globally, the dominant forest plantation genus is *Pinus*. More than 40% of the world's forest plantations are planted with pines. Many species of pine have shown high productivity when planted outside their natural environment [1]. Due to the wide range of its ecological strategies, pine species can play late and early successional roles [2,3].

Snow and wind damage can cause significant economic losses to forest owners through reduction of timber quality and volume [4]. Trees suffering snow and wind damage are also more prone to consequential damage through insect or fungal attacks [5]. In the future, assuming global warming in northern latitudes, the risk of snow damage could increase even further [6].

A number of complex factors affect the frequency and severity of snow and wind damage in forests, which can be classified into three main categories: weather, site, and stand conditions [7]. Among these, stand conditions are the only ones possible to control and manage. Age, structure, stem density, stem weight, basal area, tree species, slenderness coefficient, width and length of tree crowns, soil depth, soil moisture content, and topography are the main stand characteristics that can influence stand resistance to snow and wind damage [8–12]. Therefore, the effects of stand structure and configuration on snow and wind loading have been analyzed in several studies [13,14]. Focusing on forest stands, with exception of urban areas, the only way to prevent and/or limit snow and wind damage is a suitable forest management practice [15,16].

Currently, one of the most important challenges is how to manage natural and planted pine forests, supporting a synergistic and complementary relationship between various forest ecosystem services while avoiding the generation of ecosystem services trade-offs [2,17]. Among the forest management options that can affect the provision of ecosystem services, an important role is played by silvicultural treatments and their spatial and temporal applications. In particular thinning is one of the important silvicultural treatments which can play an important role in decreasing snow and wind damage to trees and resistance to tree uprooting and stem breakage by wind. According to this, forest managers need basic information on the relationship between thinning and snow and wind damages for reducing damage level and ensuring high quality timber production. This is even more important considering that determining thinning effects on stand resistance against snow and wind is difficult. Previous studies showed that thinning practices generally bring benefits to the stands on stability in the long term, even if the most critical period is 5–10 years after thinning in this time span, a severe storm can threaten stand survival and growth [18]. However, research results on the topic are not always in agreement and therefore studying the effect of thinning on snow and wind damage resistance of plantations is still an interesting issue in silvicultural research.

Plantations are playing an increasingly inevitable role in meeting the world's growing requirements for wood and non-wood forest products [1]. Industrial-purpose plantations provide the raw material for wood processing for commercial purposes, including timber for construction, panel products and furniture, and pulpwood for paper. In contrast, non-industrial plantations are aimed for example at supplying fuelwood, providing soil and water conservation, wind protection, biological diversity conservation, and other non-commercial purposes [19].

In the coastal areas of northern Iran, strong winds damage forests every year, while heavy snow damage occurs every few years, especially in early snow. Complete research on wind damage has not been conducted yet in Iranian forests. In a study [20], snow damage in plantations was compared with four different tree species in the coastal areas of northern Iran, and it was reported that Mediterranean cypress (*Cupressus sempervirens* L.) stand had suffered the most damage (84%), common alder (*Alnus glutinosa* L.) stand had relatively high damage (18.3%), eastern cottonwood (*Populus deltoids* Marsh) stand was less damaged (6%), and velvet maple (*Acer velutinum* Boiss.) stand was undamaged (0%). In an another research [9], the frequency and intensity of heavy snow damage on natural stands and the relationship of damages with the characteristics of trees, stand, and topography were studied in mountainous forests of northern Iran, and the frequency of snow-damaged trees was reported to be 18%, which included the following types: crown damage (8.6%), stem breakage (5.4%), uprooting (3.2%), and bending (1.4%). In another similar study [21], snow damage to trees in the mountain forests of northern Iran was reported to be 28%, with the following types of damage: uprooting (3%), trunk fracture (4%), crown fracture (10%), and bending (11%).

Generally, pine plantations have not only been realized for wood production, but also for other purposes, ranging from soil protection to recreation, and from dune stabilization to windbreak creation.

Extensive plantation with loblolly pine (*Pinus taeda* L.) has been carried out in the coastal areas of northern Iran, like other single-species pine plantations in other areas of the world, in order to produce wood and reduce the pressure on natural forests.

Loblolly pine is native to southern USA; the ecological requirements about climate correspond to an average annual precipitation of about 1000–1500 mm with average annual temperature ranging from 13 to 24 °C. This species can grow on different kinds of soils, even if the best growth is reported on moderately acid soils with imperfect or poor surface drainage. In such climatic and edaphic conditions, loblolly pine reaches annual growth of 8–9.5 m^3 ha^{-1} yr^{-1}. The major damaging agents for this species are strong wind, which can lead to extensive windthrow, whereas freeze damage is less common and reported in the northern extremity of loblolly pine natural range [22].

Similarly to what happened in plantations of other pine species throughout the world, the lack of a management plan to address the problem of snow and wind, as well as the lack of some clear strategies to apply inside the silvicultural treatments, often led to severe wind and snow damages in such stands.

According to that mentioned above, the main aims of this study were to (1) evaluate the level of snow and wind damage, (2) elucidate the influence of stand thinning on snow and wind damage, and (3) provide possible suggestions and best practices in choosing thinning strategies.

2. Materials and Methods

2.1. Study Area

The study area was a loblolly pine plantation located in the Pilambra watershed, in the Guilan province, located in northern Iran (37° 34′ 30″ N and 49° 4′ 50″ E). This study was conducted in 87 ha loblolly pine stands. Planting distance of seedlings was 3 m × 3 m. The area of plantation is a plateau, the slope ranges from 1% to 3%, the elevation is 6 m a.s.l., and the annual precipitation is 1255 mm, with the heaviest precipitation in October (201 mm) and lowest precipitation in July (41 mm). Average annual temperature is 16.1 °C, where in the hottest month of August it reaches 26.7 °C, and in the coldest month of January it is 6.1 °C. The growing season (number of days with mean daily air temperature greater than +5 °C) is 220 days. The number of frost days is 17 days per year. Average air humidity is 84.7%. Average fastest wind speed is 15.7 km/h, which occurs in October and November. Soil is relatively deep (more than 90 cm) with semi-heavy to heavy texture, with poor drainage, and pH value ranges from 6.5 to 7.2. The soil type is pseudogley and is relatively deep with poor drainage that forms wetland during the rainy months [23]. On 9 February 2020, there was an intense snow precipitation with 54 cm in three days. Before the above date, there was no snowfall in that year. During the snowfall, wind speed was 3.7–5.8 m/s, and air temperature was near 0 °C. In Iran, the silvicultural model for these plantations provides even-aged treatment, with clear cutting system, and artificial regeneration by seedling planting. The standard cultural planning can be summarized as follows: planting of seedlings, then thinning (from two to three in about 40 years), and finally, clear cutting at stand age of 50–60 years (when the stand reached the minimal expected average diameter at breast height (DBH) of 50 cm) and contextual re-planting.

2.2. Data Collection

After the 9th February 2020 heavy snowfall, we investigated snow and wind damage in the loblolly pine plantations. To analyze the influence of thinning treatments on stand resistance to snow and wind damage, nine different stands were identified (stand types): Naturally regenerated Young Unthinned stand (NYU), Naturally regenerated Young Normally thinned stand (NYN), Naturally regenerated Young Heavily thinned stand (NYH), Planted Middle-aged Unthinned stand (PMU), Planted Middle-aged Normally thinned stand (PMN), Planted Middle-aged Heavily thinned stand (PMH), Planted Old Unthinned stand (POU), Planted Old Normally thinned stand (PON), and Planted Old Heavily thinned stand (POH). Stand age, area, thinning age and intensity are shown in Table 1. Each stand type was replicated three times, so data collection to analyze snow and wind damage was performed in 27 stands. The stands were categorized in three age classes: young 15–17 years), middle-aged (30–34 years), and old (48–52 years). The thinning operation was done from below by selection method according to the basal area of trees in each stand. Thinning intensity was classified on the base of removed basal area as normal (15%) and heavy (35%). Systematic-random plot sampling was carried out for data collection. The grid dimension was 80 m × 80 m, and each plot area was 25 m × 25 m (625 m^2). The sampling intensity ranged from 6.0% to 10.4%. Diameter at breast height (1.30 m; DBH) and height of trees were measured respectively by a dendrometric caliper in cm and hypsometer in m. The main average dendrometric characteristics shown, in addition to volume and basal area (referred to hectare), are average DBH (diameter of the plant with mean basal area or quadratic mean diameter) and average height (height of the ideal tree that has DBH equal to average DBH, calculated on the respective hypsometric curve). The stands were categorized in three average DBH classes on the base of stand age classes: low (10–20 cm), medium (20–35 cm), and high (35–50 cm). Crown length was measured by a hypsometer in m, and crown diameter was measured by a tape on the ground in cm. The volume of each tree was estimated by using a local tree volume table based on DBH and height of tree [24]. Cracking of trees bole and drying of branches were observed in young trees due to frost, but in accordance with the aim of this study, authors focused only on mechanical damage of snow and wind to trees. Snow and wind damage to trees was recorded in four types: branch breakage (i.e., broken crown branch >10%), bending (i.e., leaning or lying), stem breakage (i.e., broken tree main stem), and uprooting (fallen trees or trees with the majority of their roots out of the soil) [9,25,26]. Trees without the described damage were noted as undamaged. Snow and wind damage were distinguished as follows: tree bending, stem and branch breakage were recorded as snow damage, and uprooted trees considered as wind damage [25,27]. Since there was no strong wind in the study area during the snowfall and until the snow melted, there was no snow-wind interaction damage on the trees. The slenderness coefficient (Height-diameter ratio, HD ratio) was calculated as the ratio of total height (H) to diameter at breast height (DBH) of a tree, where H and DBH were measured in meters.

Table 1. Age and area of studied loblolly pine plantations, properties of thinning operations, and sampling intensity in each stand (NYU: natural young unthinned; NYN: natural young normally thinned; NYH: natural young heavily thinned; PMU, planted middle-aged unthinned; PMN, planted middle-aged normally thinned; PMH, planted middle-aged heavily thinned; POU, planted old unthinned; PON, planted old normally thinned; POH, planted old heavily thinned; numbers indicate replication).

Stand	Age (Year)	Plantation Area (ha)	Age at Thinning (year)	Thinning Intensity (%) of Basal Area	No. of Plot	Total Plot Area (ha)	Sampling Intensity (%)
NYU1	17	3.1	-	-	5	0.3125	10.1
NYU2	17	2.4	-	-	4	0.25	10.4
NYU3	17	2.1	-	-	3	0.1875	8.9
NYN1	15	2.0	7	15	3	0.1875	9.4
NYN2	15	2.0	7	15	3	0.1875	9.4
NYN3	15	2.1	7	15	3	0.1875	8.9
NYH1	16	2.2	7	35	3	0.1875	8.5
NYH2	16	2.1	7	35	2	0.125	6.0
NYH3	16	2.0	7	35	2	0.125	6.3
PMU1	34	4.8	-	-	7	0.4375	9.1
PMU2	34	5.2	-	-	8	0.5	9.6
PMU3	34	6.2	-	-	10	0.625	10.1
PMN1	32	4.2	17	15	6	0.375	8.9
PMN2	32	4.2	17	15	6	0.375	8.9
PMN3	32	4.3	17	15	7	0.4375	10.2
PMH1	30	3.3	17	35	5	0.3125	9.5
PMH2	30	3.0	17	35	5	0.3125	10.4
PMH3	30	3.4	17	35	5	0.3125	9.2

Table 1. *Cont.*

Stand	Age (Year)	Plantation Area (ha)	Age at Thinning (year)	Thinning Intensity (%) of Basal Area	No. of Plot	Total Plot Area (ha)	Sampling Intensity (%)
POU1	48	2.1	-	-	3	0.1875	8.9
POU2	48	2.6	-	-	4	0.25	9.6
POU3	48	2.1	-	-	3	0.1875	8.9
PON1	52	3.1	33	15	5	0.3125	10.1
PON2	52	2.6	33	15	4	0.25	9.6
PON3	52	3.1	33	15	5	0.3125	10.1
POH1	50	4.2	33	35	6	0.375	8.9
POH2	50	4.2	33	35	6	0.375	8.9
POH3	50	4.4	33	35	7	0.4375	9.9
Total	-	87.0			130		-
Average	-	-	-	-	-		9.3

2.3. Data Analysis

After checking the normality (Kolmogorov-Smirnov test) and homogeneity of variance (Levene's test), one-way ANOVA and Duncan's test were applied to analyze the effects of thinning treatments on the stand dendrometric characteristics and also on snow and wind damage on stand trees. Independent samples t-test was applied to compare snow and wind damage in each stand. Frequency of damage types were compared by ANOVA and Duncan's test in the stands. Regression analysis was applied to test the relationships between damage frequencies and stand dendrometric characteristics. All analyses were performed using SPSS 19 software (IBM, New York, NY, USA).

3. Results

Results of ANOVA indicated that thinning operations had a significant effect ($p < 0.01$) on all stand dendrometric characteristics (except tree height) in naturally regenerated young (NY), planted middle-aged (PM), and planted old (PO) stands (Table 2). Heavily thinned stands (NYH, PMH, and POH) showed significantly higher DBH value ($p < 0.05$) than unthinned ones (NYU, PMU, and POU). The normally thinned stands (NYN, PMN, and PON) presented significantly higher DBH value ($p < 0.05$) than unthinned planted ones (PMU and POU), while DBH value in the naturally regenerated young normally thinned stand (NYN) (13.4 cm) did not show any significant differences ($p > 0.05$) in comparison to naturally regenerated young unthinned stand (NYU) (11.7 cm). Tree density was significantly reduced ($p < 0.05$) by thinning operations in all the stands. Basal area of heavily thinned stands was significantly ($p < 0.05$) higher than normally thinned and unthinned stands. Basal area of normally thinned stand was significantly higher than that of planted unthinned stands, while values of basal area in the naturally regenerated young normally thinned stand (NYN) (21.60 m^2 ha^{-1}) had no significant difference in comparison to naturally regenerated young unthinned stand (NYU) (19.58 m^2 ha^{-1}). Stand volume in the heavily thinned stands was significantly ($p < 0.05$) higher than the normally thinned stands, and in normally thinned stands it was significantly ($p < 0.05$) higher than in unthinned stands.

Results of ANOVA tests indicated that thinning intensity (unthinned, normally thinned, and heavily thinned) had a significant effect on the frequency of trees damaged by snow and wind, and total damage in all the three age classes of loblolly pine plantations (Table 3).

The results indicated that 10.3% of trees were damaged, of which 7.8% were damaged by snow, and 2.5% by wind in all studied stands (Table 4). In fact, about 75.7% of the total damage was caused by snow and 24.3% by wind. Results of *t*-tests indicated mean of damaged trees frequency caused by snow were significantly higher than those values that caused by wind in all the studied stands. The highest snow damage and wind damage were observed in the NYU stands. In three stands (PMN, PON, and POH), damage caused by wind was not observed.

Table 2. Dendrometric characteristics (mean ± SD) of studied loblolly pine stands (Year: 2020), and results of ANOVA and Duncan's test for the thinning effects on stand characteristics (DBH: average diameter at breast height; N, first: naturally regenerated; P: planted; Y: young; M: middle-aged; O: old; U: unthinned; N, end: normally thinned; H: heavily thinned).

Stand	Average DBH (cm)	Average Tree Height (m)	Density (Stem ha^{-1})	Basal Area (m^2 ha^{-1})	Stand Volume (m^3 ha^{-1})
NYU	11.7 ± 2.1b	13.1 ± 2.2c	1832 ± 21a	19.58 ± 2.11b	168.0 ± 15.8c
NYN	13.4 ± 1.7ab	12.0 ± 2.0c	1536 ± 20b	21.60 ± 1.95ab	196.3 ± 17.0b
NYH	15.4 ± 2.0a	12.3 ± 2.1c	1329 ± 23c	24.85 ± 2.14a	223.5 ± 24.4a
F-value	8.95 **	1.57 ^{ns}	29.08 **	10.62 **	39.50 **
PMU	23.0 ± 1.6c	19.3 ± 2.5b	551 ± 19a	22.84 ± 1.06c	301.5 ± 26.2c
PMN	28.3 ± 1.7b	19.9 ± 2.4b	488 ± 14b	28.15 ± 1.80b	339.1 ± 25.8b
PMH	34.9 ± 3.1a	20.1 ± 2.6b	387 ± 18c	37.02 ± 2.30a	433.0 ± 30.8a
F-value	41.50 **	1.45 ^{ns}	37.24 **	21.68 **	62.60 **
POU	36.7 ± 2.8c	28.3 ± 2.7a	515 ± 15a	54.39 ± 3.17c	1044.2 ± 42.6c
PON	42.0 ± 2.8b	28.1 ± 1.9a	429 ± 13b	59.47 ± 3.01b	1113.4 ± 50.4b
POH	48.4 ± 2.5a	28.3 ± 1.5a	357±15c	65.42 ± 3.44a	1223.0 ± 50.6a
F-value	25.47 **	1.28 ^{ns} N.S.	18.47 **	27.40 **	35.61 **

Note: * $p < 0.05$; ** $p < 0.01$; ^{ns} not significant. Different letters by column indicate significant differences by Duncan's test at $\alpha = 0.05$.

Table 3. Results of one-way ANOVA (*F*-values) of thinning intensity effect on frequency of damaged trees by snow and wind in loblolly pine plantations.

Cause of Damage	Young Stand (Naturally Regenerated)		Middle-Aged Stand (Planted)		Old Stand (Planted)	
	Den DF	*F*-Value	Den DF	*F*-Value	Den DF	*F*-Value
Snow	2	21.138	2	15.305	2	11.704
Wind	2	25.070	2	46.245	2	27.320
Total damage	2	32.560	2	30.491	2	17.844

Note: Den DF is denominator degrees of freedom, all values in ANOVA were significant ($p < 0.01$).

Table 4. Frequency (mean ± SD) of damaged trees by snow and wind, and results of two-tailed *t*-test.

Stand	Damage by Snow (%)	Damage by Wind (%)	*t*-Value	*p*-Value
NYU	21.4 ± 3.4	9.3 ± 0.9	10.324	0.0001
NYN	11.8 ± 1.5	3.6 ± 0.6	14.802	0.0001
NYH	5.0 ± 0.9	0.4 ± 0.1	15.707	<0.0001
PMU	8.2 ± 1.1	5.3 ± 0.6	8.060	0.0013
PMN	6.6 ± 1.0	0	-	-
PMH	9.1 ± 1.4	2.1 ± 0.4	16.142	<0.0001
POU	4.8 ± 0.6	2.2 ± 0.4	11.347	0.0001
PON	1.3 ± 0.2	0	-	-
POH	1.8 ± 0.3	0	-	-
All stands	7.8 ± 3.1	2.5 ± 1.3	6.659	0.00

Results showed that the frequency of snow, wind, and overall-damaged trees in the thinned stands (NYN, NYH, PMN, PMH, PON, and POH) are lower ($p < 0.05$) than in the unthinned ones (NYU, PMU, and POU) in each age class, and decreased by increasing stand age (Figure 1). Snow damage was observed in every stand, while wind damage was not observed in PMN, PON, and POH stands.

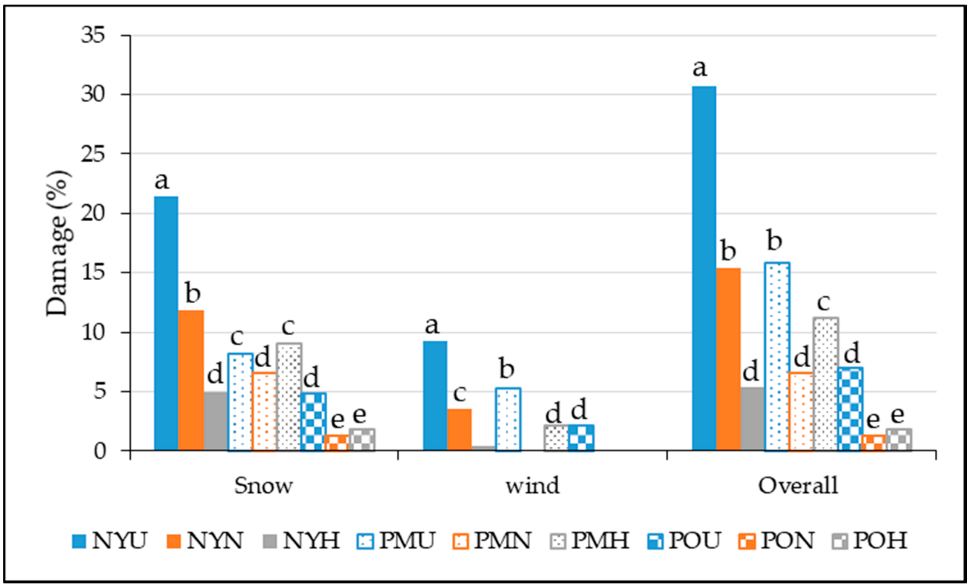

Figure 1. Damage percentage by snow and wind in loblolly pine plantations, (PMU, planted middle-aged unthinned; PMN, planted middle-aged normally thinned; PMH, planted middle-aged heavily thinned; POU, planted old unthinned; PON, planted old normally thinned; POH, planted old heavily thinned; NYU: natural young unthinned; NYN: natural young normally thinned; NYH: natural young heavily thinned). Different letter in each case of damage or overall damage indicate significant differences by Duncan's test at $\alpha = 0.05$.

ANOVA results indicated the frequency of snow-damaged trees between stands had significant differences ($F = 108.27$, $p < 0.01$). The maximum frequency of snow damaged trees was observed in the naturally regenerated young unthinned (NYU) stand by 21.4% which was significantly higher ($p < 0.05$) than in the other stands.

Moreover, ANOVA results indicated that the frequency of wind damaged trees between stands had significant differences ($F = 48.30$, $p < 0.01$). The highest frequency of wind-damaged trees was observed in the naturally regenerated young unthinned (NYU) stand by 9.3%, which was significantly higher ($p < 0.05$) than in the other stands.

ANOVA results indicated also that the frequency of snow and wind (overall) damaged trees between stands had significant differences ($F = 64.76$, $p < 0.01$). The highest frequency of snow and wind damaged trees (overall-damaged trees) was observed in the naturally regenerated young unthinned (NYU) stand by 30.7%, which was significantly higher ($p < 0.05$) than in the other stands.

In the young-age stands the frequency of snow, wind, and overall-damaged trees in the heavily thinned stand (NYH) (5%, 0.4%, and 5.4% respectively) was significantly ($p < 0.05$) lower than those in the normally thinned stand (NYN) (11.8%, 3.6%, and 15.4% respectively). Meanwhile, in the middle-aged stands, heavy thinning increased snow damage, wind damage, and overall damage compared with normal thinning, so the frequency of snow, wind and overall-damaged trees in the PMN stand was 6.6%, 0%, and 6.6%, respectively, while in the PMH stand it was 9.1%, 2.1%, and 11.2%, respectively. Also, in the old stands the heavy thinning operation increased damage frequency compared with normal thinning operation, so the frequency of snow, wind and overall-damaged trees in the PON stand was 1.3%, 0%, and 1.3%, respectively, while in the POH stand was 1.8%, 0%, and 1.8%, respectively.

Results of ANOVA tests indicated that the damage agent (snow or wind) had a significant effect on the frequency of damage types in all the stands, except in PON and POH stands, where only branch breakage was observed (Figure 2). The bended trees had the highest frequency in the young stands (15%, 8.2%, and 3.3% in the NYU, NYN, and NYH, respectively) (Figure 2). However, the highest frequency of damage type was uprooted (5.3%) in the unthinned middle-aged stand (PMU), branch breakage in the normally and heavily thinned middle-aged stands (4.2% and 4.7%, respectively), and also branch breakage in the unthinned, normally thinned, and heavily thinned old stands (4.4%, 1.3%, and 1.8%, respectively). In the normally and heavily thinned old stands (PON, and POH, respectively) observed damage type was only branch breakage. According to Figure 2, every one of the four damage types decreased by increasing thinning intensity in the young stands, but in the middle-aged stands uprooted trees was 0% in the normally thinned stands, while it was 2.1% in the heavily thinned stands. Also, stem breakage, branch breakage, and bending increased by increasing thinning intensity in the middle-aged stands.

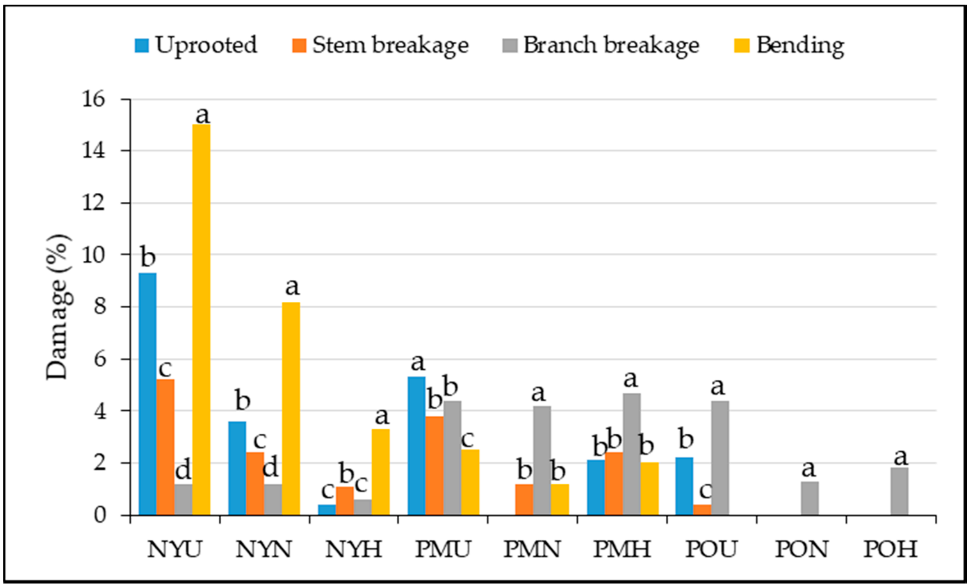

Figure 2. Percentage of damage types by snow and wind in the loblolly pine stand. Results of one-way ANOVA: $F = 35.08$, $p < 0.01$ in NYU; $F = 33.50$, $p < 0.01$ in NYN; $F = 15.17$, $p < 0.05$ in NYH; $F = 16.29$, $p < 0.01$ in PMU; $F = 9.34$, $p < 0.05$ in PMN; $F = 11.60$, $p < 0.01$ in PMH; $F = 14.22$, $p < 0.01$ in POU. Results with same letters are not significantly different (Duncan's test, error rate of $\alpha = 0.05$).

In the old stands, the damage types of uprooted, stem breakage, and branch breakage decreased by thinning operation, but branch breakage increased by increasing thinning intensity (from 1.3% in PON to 1.8% in POH).

The results of regression analysis indicated that the overall damage was significantly correlated with both tree and stand dendrometric characteristics ($R^2 > 0.70$, $p < 0.01$), so the damage percentage decreased by increasing trees DBH, height of trees, stand basal area, and stand volume, while it increased by increasing slenderness coefficient of trees (H/D) and tree density (Figure 3).

Results of ANOVA and Duncan's test showed the values of slenderness coefficient (H/D), the relative crown width (CD/CL), and the relative crown length (CL/H) of overall-damaged trees were significantly ($p < 0.05$) higher than the undamaged trees in each stand (Table 5). Also, results of ANOVA and Duncan's test indicated that the values of slenderness coefficient (H/D) of trees in thinned stands were significantly ($p < 0.05$) lower than the unthinned stands, while the values of the relative crown width (CD/CL) and the relative crown length (CL/H) in the thinned stands were significantly ($p < 0.05$) higher than the unthinned stands.

Table 5. Tree form values (mean ± SD) in the snow and wind-damaged and undamaged loblolly pine trees. H/D: stem slenderness coefficient, where H is tree height, and D is diameter at breast height (DBH); CL: crown length; CD: crown diameter; CD/CL: crown widening coefficient; CL/H: crown length coefficient.

Stand	Tree Uprooted	Stem Breakage	Branch Breakage	Tree Bent	Overall Damage	Undamaged
			Stem Slenderness Coefficient (H/D)			
NYU	119.4 ± 6.0a	115.6 ± 7.0ab	110.6 ± 9.2b	119.3 ± 7.5a	118.2 ± 9.0a	110.0 ± 9.2b
NYN	115.0 ± 9.8a	110.6 ± 6.8ab	108.5 ± 7.7b	113.4 ± 9.2a	113.1 ± 7.2a	92.0 ± 7.4c
NYH	114.7 ± 9.0a	114.3 ± 5.9a	103.4 ± 5.4b	110.5 ± 6.0a	106.0 ± 7.4b	83.4 ± 7.2c
PMU	98.3 ± 3.3b	96.5 ± 3.7b	89.5 ± 6.3c	102.0 ± 4.5a	96.5 ± 4.1b	86.6 ± 5.3c
PMN	-	92.3 ± 7.1a	88.5 ± 6.6a	88.0 ± 6.2a	89.3 ± 6.3a	73.3 ± 6.5b
PMH	85.2 ± 4.7ab	88.1 ± 5.2a	80.7 ± 5.4b	84.8 ± 9.2ab	84.5 ± 6.0ab	56.2 ± 4.5c
POU	88.2 ± 6.9a	85.4 ± 3.7a	79.6 ± 6.3b	-	81.5 ± 7.1b	70.3 ± 6.4c
PON	-	-	70.3 ± 6.4a	-	70.3 ± 6.4a	68.2 ± 5.5b
POH	-	-	76.3 ± 5.5a	-	76.3 ± 5.5a	64.9 ± 7.3b
			Relative Crown Wide (CD/CL)			
NYU	0.39 ± 0.08a	0.38 ± 0.07a	0.39 ± 0.07a	0.35 ± 0.05a	0.33 ± 0.05a	0.26 ± 0.04b
NYN	0.38 ± 0.05a	0.37 ± 0.06a	0.38 ± 0.10a	0.39 ± 0.07a	0.39 ± 0.05a	0.29 ± 0.05b
NYH	0.41 ± 0.07a	0.40 ± 0.07a	0.39 ± 0.05a	0.38 ± 0.04a	0.39 ± 0.03a	0.33 ± 0.05b
PMU	0.50 ± 0.08a	0.52 ± 0.05a	0.55 ± 0.06a	0.51 ± 0.10a	0.54 ± 0.06a	0.35 ± 0.10a
PMN	0.50 ± 0.05a	0.52 ± 0.08a	0.55 ± 0.07a	0.53 ± 0.05a	0.53 ± 0.06a	0.42 ± 0.08a
PMH	0.49 ± 0.07a	0.50 ± 0.08a	0.53 ± 0.09a	0.49 ± 0.06a	0.50 ± 0.07a	0.44 ± 0.06a
POU	0.51 ± 0.04a	0.53 ± 0.05a	0.52 ± 0.04a	-	0.53 ± 0.06a	0.33 ± 0.05b
PON	-	-	0.62 ± 0.08a	-	0.62 ± 0.08a	0.45 ± 0.05b
POH	-	-	0.73 ± 0.07a	-	0.73 ± 0.07a	0.51 ± 0.08b
			Relative Crown Length (CL/H)			
NYU	0.24 ± 0.05a	0.24 ± 0.04a	0.27 ± 0.05a	0.25 ± 0.04a	0.25 ± 0.05a	0.15 ± 0.04b
NYN	0.30 ± 0.05a	0.26 ± 0.07a	0.31 ± 0.07a	0.29 ± 0.07a	0.29 ± 0.07a	0.18 ± 0.03b
NYH	0.30 ± 0.07a	0.34 ± 0.056a	0.29 ± 0.07a	0.32 ± 0.07a	0.32 ± 0.07a	0.22 ± 0.05b
PMU	0.34 ± 0.08a	0.27 ± 0.07a	0.35 ± 0.09a	0.32 ± 0.07a	0.32 ± 0.08a	0.17 ± 0.07b
PMN	0.30 ± 0.09a	0.30 ± 0.09a	0.29 ± 0.09a	0.30 ± 0.08a	0.30 ± 0.07a	0.20 ± 0.08b
PMH	0.31 ± 0.09a	0.32 ± 0.06a	0.34 ± 0.08a	0.32 ± 0.09a	0.32 ± 0.08a	0.25 ± 0.09b
POU	0.29 ± 0.07a	0.26 ± 0.07a	0.28 ± 0.07a	0.26 ± 0.06a	0.28 ± 0.09a	0.19 ± 0.07b
PON	-	-	0.33 ± 0.09a	-	0.33 ± 0.09a	0.22 ± 0.06b
POH	-	-	0.32 ± 0.09a	-	0.32 ± 0.09a	0.24 ± 0.05b

Note: Different letter in each row indicate significant differences by Duncan's test at $\alpha = 0.05$.

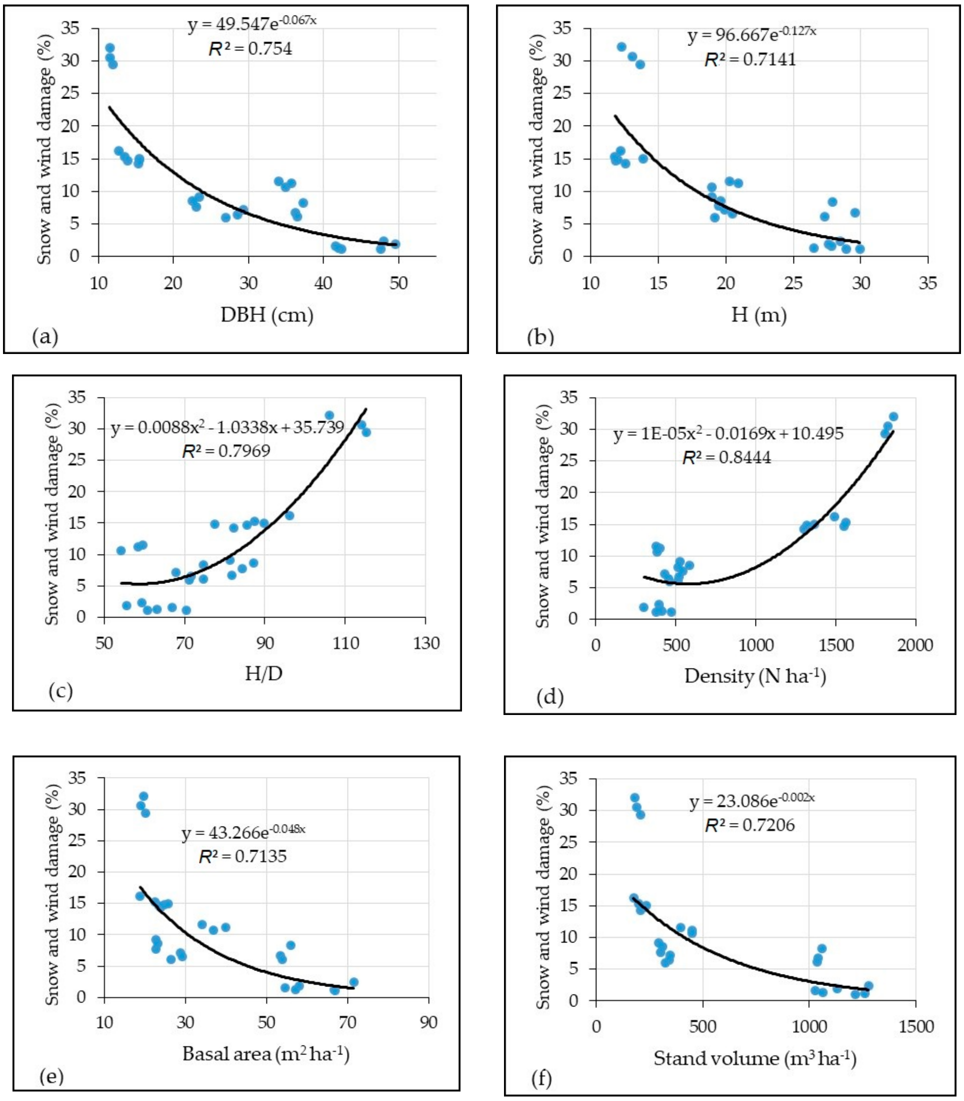

Figure 3. Snow and wind damage to trees in relation with stand DBH (**a**), tree height (**b**), slenderness coefficient (**c**), stem density (**d**), basal area (**e**), and volume (**f**). For each graph, the regression equation and the coefficient of determination (R^2) are given. Note: all the regression were significant ($p < 0.01$).

4. Discussion

A worldwide increase in the severity and frequency of drought, windstorms, fires, and insect outbreaks is predicted under climate change [28,29]. However, daily wind gusts or peak winds, which are considerably weaker than discrete windstorm events, cause damage to forests year-round. Knowledge about the effects of stand density on volume production and risks of both biotic and abiotic damage are essential for the formulation of appropriate thinning guidelines [30].

The results of the present study showed that the total damage on loblolly pine trees by snow and wind (overall damage) varies from 1.3% to 30.7% in different stands in the study area. Our results indicated that the frequency of snow damage (7.8% of trees) was about three times higher than wind damage (2.5% of trees) in each of the studied stands. Whereas, in causing severe damage in the young stands, the share of snow damage was more than the wind, but the share of wind was more than snow in the old stands. In line with the current study results, Kuboyama and Oka [31] reported that the risk of snow damage is higher than the wind one in young stands or dense ones with high stock.

Our results indicated that the snow, wind, overall damages, and damage type (i.e., uprooted, bended, stem breakage, and branch breakage) were affected by stand age, thinning operations, and thinning intensity. The results of this study showed that the frequency of both snow damages and wind ones decreased by increasing stand age. These results are consistent with previous studies [12,32].

Our results indicated the snow and wind damages decreased by increasing tree DBH, height, stand basal area, and stand volume. These results supported previous studies showing that younger stands are likely to be damaged by snow due to slightly tapering stems [15,33]. According to this, the soil and root systems of trees are, of course, important for their stability [9,34], but their diameter, height, stem form, and relative crown length may also affect them [35].

Results showed that the snow and wind damages increased by increasing tree density and slenderness coefficient. The height-to-diameter ratio (h/d ratio or slenderness coefficient) has been used in numerous studies to characterize stability at stand level [8,9,36–38], and it has been proposed that mean h/d ratios above 100 indicate low stand stability and ratios of 80 value should be targeted to minimize risks of damage due to strong winds and snow [32,35]. However, Gardiner and Quin [13] and Wonn and O'Hara [36] have argued that the h/d ratio is a suitable indicator of the likelihood of stem breakage, but not for uprooting. It is important to take into account that stand density and the slenderness coefficient are closely related to stand development and silviculture management practices [37,39]. Accordingly, Martín-Alcón et al. [40] showed that the proportion of snow and wind damaged trees in a stand decreased strongly at higher stand basal area for a given slenderness coefficient of dominant trees. Moreover, Cucchi and Bert [41] reported that, in a maritime pine (*Pinus pinaster* Aiton) stand, the higher firmness is showed by stands where the height, circumference, and crown length are homogeneous [41].

Our results showed that both normal thinning and heavy thinning decreased both snow and wind damages in the young stands. Consistent with the current study, the research by Valinger and Pettersson [25] in *Picea abies* plantations in southern Sweden reported that, for treatments with high basal area removal, the highest relative number of damaged individuals by wind occurred during the first period after thinning. The densest stands (i.e., unthinned controls and stands thinned from above) showed a high proportion of snow damage throughout the observation period.

Our results showed that the normal thinning decreased both snow and wind damages, heavy thinning increased both snow and wind damages in the middle-aged stands, and both normal thinning and heavy thinning decreased both snow and wind damages in the old stands. In contrast, Pellikka and Järvenpää [18] reported that if thinning is delayed until tree height reaches 20 m, the risk for snow damage increases.

Results of the study indicated that bending was the main damage type in unthinned, normally thinned, and heavily thinned young stands; tree bending, uprooting, and stem breakage were not observed in the planted old normally thinned and planted old heavily thinned stands. In line with the current results, Sampson and Wurtz [42] stated that younger trees are more prone to bending. On the other hand, results indicated that uprooted was the main damage type in the middle-aged unthinned stands.

Our results indicated that the frequency of stem breakage was greatly reduced by thinning operations, especially with high intensity thinning in all the stands. In line with our results, Päätalo [43] reported that unmanaged pine stands are more susceptible to break and uproot by snow and wind than managed stands. However, forest management can also increase susceptibility to such kinds of damage.

Similarly, Wallentin and Nilsson [27] detected a strong linear relationship between thinning intensity and the frequency of damage caused by storms and snow in a Norway spruce (*Picea abies* (L.) Karst) plantation in southern Sweden. The avoidance of early thinning resulted in a stand structure characterized by low tree vitality and unfavorable shape of trees, which showed higher susceptibility to the influence of windstorms. Moreover, in even-aged forests at high risk for snow and wind damage, early and frequent selective thinning, starting with low heavy thinning in early ages and reducing the thinning intensity with age, seems the best forest management strategy for maximizing stand-level and single tree stability [44–49].

Future development of the present work could be the development of predictive models, taking into account the current knowledge on the topic and integrating this with GIS (Geographic Information Systems) as described in a recent review [50], in order to provide forest managers with a handy tool to assess the possible wind and snow damages.

5. Conclusions

Our results showed that stand characteristics and thinning operations play a key role in snow and wind damage in loblolly pine plantations. From the results of this study, it can be concluded that in order to reduce snow and wind damage, thinning operations should be planned and focused on reducing the risk of snow in young stands, the risk of both snow and wind in middle-aged stands and the risk of wind in old stands. For this purpose, we recommend high intensity thinning (35% of basal area) in young stands, normal thinning (15% of basal area) in middle-aged stands, and light thinning (15% of basal area) in old stands. According to the results of the present study (minimum snow and wind damaged stands) the suitable basal area (mean ± SE) for minimizing risk of snow and wind damages in young (DBH: 10–20 cm), middle-aged (DBH: 20–35), and old (DBH: 35–50 cm) stands were 25 ± 1.2, 37 ± 1.0, and 60 ± 1.3 m^2 ha^{-1}, respectively, in coastal loblolly pine plantations. The main highlights of this research are:

- Amount and type of snow damage was different from wind damage.
- Amount of snow and wind damage decreased by increasing stand age.
- Thinning can reduce or increase snow and wind damage depending on the time of heavy snowfall and strong winds and the intensity of thinning.
- However, heavy thinning reduced the risk of snow damage, but it may increase the risk of wind damage.
- Young dense stands were more susceptible to snow damage, while old stands were more susceptible to wind damage.

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