

Effects of Herbicide-Based Weed Control and Fertilization on Nutrient Status and Growth in Maritime Pine (*Pinus pinaster* Aiton) Plantation

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ABSTRACT

To meet the industrial demand for wood raw material, Türkiye initiated provenance trials of fast-growing exotic tree species after the 1960s. Among these, the Corsican origin of maritime pine (*Pinus pinaster*) has gained prominence. To maximize industrial wood production and ensure sustainability, silvicultural treatments such as weed control and fertilization are of critical importance. This study investigates the two-year effects of herbicide application (3% glyphosate) for weed control and NP fertilization (180 g or 360 g NP fertilizer per tree) on the growth performance of six-year-old maritime pine plantations. For this purpose, experimental plots were established in a maritime pine plantation in Düzce, following a randomized block design with split plots and three replications. Measurements of diameter at breast height (D) and total height (H) were conducted before treatment and over the subsequent two years. Herbicide application significantly increased both D and H growth in the first year, and its cumulative positive effect persisted over two years, although it was reduced in the second year. NP360 fertilization improved D and H growth only in the first year, with no effect observed in the second year or over the total two-year period. No significant interaction was found between herbicide and fertilization, indicating their effects were independent. Needle analysis revealed that phosphorus was near the lower critical threshold and thus the primary limiting nutrient, while other macronutrients were sufficient. These results suggest that early weed control and phosphorus fertilization independently enhance initial D and H growth in maritime pine plantations, but the benefits of single-event fertilization are temporary and highly dependent on environmental conditions such as water availability. For sustained growth, regular weed control until canopy closure and phosphorus (P) fertilization to maintain adequate needle P concentrations are recommended, along with consideration of repeated fertilization and sufficient water supply for long-term productivity.

Keywords:

fertilization, glyphosate, herbicide, macronutrients, Türkiye

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INTRODUCTION

It is not considered feasible to meet Türkiye's increasing demand for industrial wood in the near future solely through production from natural forests, as is currently the case (Birler 2009). Globally, a growing emphasis on conservation has increasingly limited wood production from natural forests. The General Directorate of Forestry aims to maximize wood yield per unit area using fast-growing tree species through industrial plantations, thereby alleviating the pressure on natural forests caused by the ever-increasing and diversifying demand for timber (OGM 2013).

To this end, trials with fast-growing exotic species have been initiated in Türkiye since the 1960s, with species such as *Pinus taeda* L., *Pinus radiata* D. Don, *Pseudotsuga menziesii* (Mirb.) Franco, *Eucalyptus camaldulensis* Dehnh., and *Pinus pinaster* Aiton being investigated (Çalışkan 1998). Maritime pine (*Pinus pinaster*) was first introduced to Türkiye in 1880 and was used for the stabilization of the Terkos dunes in Istanbul. Subsequently, in the 1950s, seeds from four different provenances (Corsica, Spain, Gironde, and Toulon) were planted in regions such as Burunsuz (Istanbul-Bahçeköy), Kalabaklı (Çanakkale), and Taşdelen (Istanbul-Alemdağ) (Akalp 2002). After it was determined that the species displayed rapid growth in the Black Sea region, provenance trials commenced between 1974 and 1979. Due to the susceptibility of provenances, except Corsica, to snow breakage and snow damage (Toplu and Bozkuş 1988) from 1983 onwards, Corsican provenances have been predominantly used in maritime pine afforestation efforts (Toplu et al. 2002). As of 2019, approximately 58,000 hectares of industrial plantations have been established with maritime pine in Türkiye, 2% of which are located in the Aegean and Mediterranean regions, 15% in the Black Sea, and 83% in the Marmara Region (Güner et al. 2019). Within the boundaries of the Düzce Forest Enterprise, 144.36 ha of the 460.3 ha of maritime pine plantations are managed as industrial plantations (OGM 2019).

Intensive silvicultural practices (soil preparation, fertilization, weed control, thinning, and pruning) in industrial plantations are critical for enhancing wood production, preserving ecosystem services, and ensuring sustainability (Savill et al. 1997, Boydak and Çalışkan 2014). In plantations, crops compete with other species for space, light, water, and nutrients (Hytönen et al. 2017). The morphological diversity of these competing species, combined with various forms of competition, results in spatial and temporal variations in resource competition. The impact of competition on tree growth is generally greater at higher quality sites (Rolando and Little 2009). Studies conducted in Europe on the early years of afforestation have revealed the effects of weed competition on plantation establishment and seedling growth (Willoughby et al. 2009), indicating that weed control can increase stand volume by 30–500% (Wagner et al. 2005). In maritime pine plantations in the Izmit region, it was reported that glyphosate application after site preparation and a single hoeing one year after planting were the most effective and economical methods for seedling growth and soil productivity (Fidan et al. 2022).

It has been indicated that the most effective time for fertilization in industrial plantations is before canopy closure and towards the end of the rotation period (Savill et al.

1997). In the United States, the positive effect of standard weed control on total stand volume in *Pinus taeda* plantations was around 37.5 tons/ha, whereas the effect with advanced chemical control increased to 95 tons/ha (Fox et al. 2004). Measures such as site preparation, fertilization, weed control, thinning, pruning, and the use of genetically improved planting stock have been shown to substantially increase total stand volume and significantly shorten rotation periods in industrial plantations (Rubilar et al. 2018). For instance, nitrogen and phosphorus (P) fertilization in *Pinus taeda* plantations resulted in up to a fivefold increase in volume depending on site factors and fertilizer dose, and intensive silvicultural practices potentially reduced the rotation periods from 50 years to less than 20 years (Fox et al. 2004).

In most maritime pine plantations, phosphorus (P) is the main limiting nutrient; nitrogen addition generally promotes significant growth only when combined with P (Warren and Adams 2002, Dumbrell and McGrath 2003, Ali et al. 2014). Typically, 50–125 kg/ha of P fertilizer is recommended for industrial plantations (Savill et al. 1997). However, the effect of fertilization alone may be limited, and growth can be enhanced when combined with weed control (Pires and Xavier 2010, Xavier et al. 2010). Furthermore, the positive effect of a single application of fertilizer may diminish or disappear over time (Eşen and Özbayram 2016). Thus, periodic fertilization is recommended for sustained rapid growth (Bergh et al. 2014, Loewe-Muñoz et al. 2020).

Although some silvicultural studies have been conducted on maritime pine plantations that are well adapted to Türkiye's ecological conditions and established over extensive areas (Ayberk 1996, Şener 2004, Güney et al. 2014, Balekoğlu and Ertaş 2016, Kahyaoğlu and Güvendi 2020, Demir and Eşen 2025), research focusing on intensive silvicultural practices such as weed control and fertilization is quite limited (Tolay et al. 1988, Fidan et al. 2022). The aim of this study is to investigate the two-year effects of herbicide-based weed control and NP fertilization on the growth of maritime pine in industrial plantations in the Düzce region, Türkiye. It is hypothesized that the applied weed control and fertilization will increase diameter and height growth of maritime pine over the two-year period.

MATERIALS AND METHODS

Study Site

This experiment was conducted within a maritime pine plantation located in the Düzce Forest Enterprise under the jurisdiction of the Düzce Forest District Directorate in the Western Black Sea Region (40° 47.769' N, 31° 16.077' E; 305 m elevation). The site is classified as site class II, with a slope ranging from 10% to 30% and a western exposure. According to the long-term average (1959–2022), the area receives an average annual precipitation of 834 mm and has a mean annual temperature of 13.1 °C. However, the total annual precipitation in the first (2019) and second (2020) years of the experiment was 921 mm and 699 mm, respectively, while the mean annual temperatures were 14.8 °C and 15.0 °C, respectively (MGM 2023). Soil profile analysis indicated that the absolute soil depth exceeds 120 cm, with a physiological depth of approximately 90 cm. The soil has a clay

loam texture (30% sand, 32% clay, and 38% silt), a pH ranging from 4.0 to 5.1, low salinity (57.1 ± 13.5 uS/cm), very low lime content ($0.04 \pm 0.001\%$), and low organic matter content ($1.83 \pm 0.76\%$).

The first maritime pine plantation at the research site was established in 1976. Prior to clear-cutting in 2013, the stand had a timber volume of $173.59 \text{ m}^3/\text{ha}$ and an annual increment of $12.87 \text{ m}^3/\text{ha}$ (Anonymous 2015). Following clear-cutting in 2013, the area underwent mechanical site preparation using a rake and roter attached to a crawler tractor, followed by subsoiling with a triple ripper and heavy disk harrowing. After soil preparation, 1 + 0 containerized maritime pine seedlings of Kefken origin raised in the Düzce Gümüşpınar nursery were planted in 2014 at a spacing of 3×3 meters using the pit planting method (Anonymous 2015). Mechanical weed control was implemented for two years following planting. The site currently contains a dense understory of species such as oak (*Quercus* sp.), phillyrea (*Phillyrea* sp.), blackberry (*Rubus* sp.), and heather (*Erica* sp.).

Experimental Design and Treatments

The experimental site was established in November 2018 using a randomized block split-plot design with three replications to minimize spatial variability across the site. Blocks were arranged based on topographical characteristics to ensure homogeneity within each block. There were two main plots in each block: one treated with herbicide (HA) and one without herbicide (NoHA). Main plots were further subdivided into three subplots, randomly assigned to one of three fertilizer treatments: control (no fertilizer, NP0), low dose (NP180), and high dose (NP360). Each subplot measured $25 \text{ m} \times 25 \text{ m}$ (625 m^2), with data collection restricted to the central $20 \text{ m} \times 20 \text{ m}$ (400 m^2) to minimize edge effects, while the surrounding area served as a buffer zone. Treatment assignments within blocks and subplots were randomized using a random number generator. In total, the experiment comprised 3 blocks $\times$ 2 main plots $\times$ 3 subplots = 18 experimental units.

Herbicide application was performed twice (early May and late June 2019) using a 3% glyphosate solution [N-(Phosphonomethyl) glycine, NuFarm KLINIC (4800 g/L)] applied with a backpack sprayer to the understory vegetation in one main plot of each block. Given the generally low P levels in the site soil and in maritime pine plantations overall (Eimil-Fraga et al. 2014, Martins et al. 2009), fertilizer doses were determined based on P content. In this experiment, 180 g (15.7 g pure P and 36 g pure N per tree) and 360 g (31.4 g pure P and 72 g pure N per tree) of 20:20:0 NP fertilizer were spread on the soil within a 50 cm diameter circle around each tree under the crowns of trees in randomly chosen NP180 and NP360 subplots in April 2019.

Soil and Needle Sampling and Analysis

Soil samples were collected from the topsoil (0–20 cm depth) around three trees located near the center of each plot. The soil samples were air-dried and then put through a 2-mm sieve in the lab to get them ready for analysis. Additionally, in July of both the first and second years of the experiment, five needles were collected from the terminal shoots of five randomly selected trees near the center of each plot (25

needles $\times$ 18 subplots = a total of 450 needles per year). In the laboratory, the needle samples were dried in an oven at 65°C and then ground to prepare them for analysis.

Nutrient analyses of needle and soil samples were carried out at the Düzce University Scientific and Technological Research Application and Research Center (DÜBİT). Total nitrogen (N) in the soil was determined using the Kjeldahl method (Bremner 1960). Available phosphorus (P) was measured in soil samples using the Olsen method with a spectrophotometer (Silva et al. 2015). Potassium (K) was analyzed in ammonium acetate extracts using Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES). Concentrations of calcium (Ca), magnesium (Mg), sodium (Na), iron (Fe), copper (Cu), zinc (Zn), and manganese (Mn) in soil samples were determined after wet digestion, also using ICP-OES (Krogstad and Zivanovic 2022).

For needle (foliar) nutrient analyses, samples were first subjected to wet digestion using a mixture of concentrated acids (Barros et al. 2015), after which the concentrations of Ca, Mg, Na, Fe, Cu, Zn, and Mn were determined by ICP-OES (Barros et al. 2015). Total N in needle samples was measured by the Kjeldahl method (Amin and Flowers 2004), while total P was determined spectrophotometrically in the digested extracts using the molybdenum blue method. K content was also analyzed by ICP-OES following digestion (Ivanova et al. 2001, Lee et al. 2017).

Measurements of Diameter and Height Growth

Immediately following the establishment of the experimental design (November 2018), the diameter at breast height at 1.30 m above ground level (D) and the total height (H) of 20 selected individuals at the center of each subplot were measured. These individuals were marked at breast height with oil paint to ensure repeated measurements on the same trees in subsequent years. Measurements of D and H were repeated in November 2019 and 2020 for the marked trees. Annual and biennial increments in diameter (Di) and height (Hi) were calculated as the differences between the respective measurements.

Statistical Analysis

In this study, a randomized block split-plot design with three blocks was employed, with herbicide application serving as the main plot factor and NP fertilizer dose as the subplot factor. Each treatment was replicated one time within each block, resulting in a total of 18 experimental units. Prior to the main analyses, data were checked for normality using the Shapiro–Wilk test and for homogeneity of variances using Levene's test. A two-way analysis of variance (ANOVA) was used to see how herbicide application and NP fertilization affected the soil and needle nutrient concentration, as well as the growth of maritime pine. In the analysis, herbicide application and NP fertilizer dose were included as fixed factors, while block was treated as a random factor. When significant differences were detected ($p < 0.05$), Duncan's multiple range test was used for post hoc comparisons of means. All statistical analyses were performed using IBM SPSS Statistics for Windows, Version 21.0 (IBM Corp., Armonk, NY, USA). The results are presented as means $\pm$ standard deviation.

RESULTS

Nutrient Status in Soil and Needles

The effects of herbicide and fertilization treatments, as well as herbicide $\times$ fertilization treatment interaction on soil and needle nutrient concentrations, were not significant, with the exception of soil P concentrations in the first (2019)

experimental year (Table 1). The concentration of all nutrients in soil (except P concentration in the soil of 2019), as well as in needles, was similar in all fertilization treatments for both experimental years (2019 and 2020). The soil P concentration of 2019 in the NP0 and NP180 treatments was similar and significantly lower than in the NP360 treatment.

Table 1 Mean concentration of nutrients in soil and needles in the first (2019) and second (2020) experimental year for the control fertilization treatment (NP0), as well as for fertilization treatments with an NP fertilizer dose of 180 g (NP180) and 360 g (NP360). The statistically significant differences between treatments at $p < 0.05$ are shown in bold with different lowercase letters. Values in parentheses indicate standard deviations.

Nutrients	2019			2020		
	NP0	NP180	NP360	NP0	NP180	NP360
Soil	Total N (mg/g)	1.02 (0.42)	0.84 (0.27)	0.91 (0.28)	1.09 (0.45)	0.78 (0.39)
	Available P (mg/kg)	0.57 (0.27) a	0.45 (0.19) a	1.10 (0.59) b	1.07 (0.49)	0.90 (0.74)
	K (mg/kg)	54.99 (26.62)	49.8 (15.56)	41.1 (9.92)	58.13 (21.25)	50.49 (7.91)
	Ca (mg/kg)	471.71 (256.18)	375.17 (61.86)	287.59 (72.04)	456.17 (226.63)	462.67 (135.54)
	Mg (mg/kg)	185.55 (171.55)	163.95 (136.59)	117.35 (90.26)	189.79 (164.06)	157.65 (79.39)
	Na (mg/kg)	13.21 (2.54)	12.61 (2.70)	13.10 (3.20)	12.72 (0.78)	12.36 (1.67)
	Fe (mg/kg)	41.38 (19.32)	27.08 (4.88)	29.49 (10.49)	44.71 (15.79)	36.17 (14.42)
	Zn (mg/kg)	0.46 (0.11)	0.4 (0.11)	0.36 (0.07)	0.44 (0.11)	0.44 (0.15)
	Cu (mg/kg)	0.49 (0.31)	0.53 (0.19)	0.43 (0.16)	0.48 (0.29)	0.45 (0.13)
	Mn(mg/kg)	39.01 (47.66)	68.06 (74.86)	49.92 (46.16)	37.23 (31.65)	47.65 (42.51)
Needles	N (mg/g)	32.84 (14.38)	32.82 (11.95)	30.75 (9.12)	35.89 (10.66)	38.7 (4.82)
	P (mg/g)	0.65 (0.11)	0.75 (0.09)	0.75 (0.13)	0.67 (0.11)	0.72 (0.1)
	K (mg/g)	2.70 (0.70)	2.99 (0.72)	2.94 (0.55)	2.75 (0.66)	3.09 (1.06)
	Ca (mg/g)	4.07 (0.77)	4.24 (0.65)	4.34 (0.98)	4.17 (1.40)	5.29 (1.03)
	Mg (mg/g)	1.22 (0.21)	1.40 (0.43)	1.32 (0.50)	1.14 (0.26)	1.67 (0.58)
	Na (mg/kg)	1416.34 (517.16)	1422.34 (675.82)	1281.84 (497.85)	2059.34 (774.46)	1928.5 (1021.83)
	Fe (mg/kg)	149.84 (26.02)	159.17 (28.82)	140.84 (29.52)	153.5 (37.53)	128 (28.31)
	Cu (mg/kg)	2.56 (0.35)	3.13 (0.51)	2.92 (0.36)	2.47 (0.19)	2.80 (0.72)
	Zn (mg/kg)	21.12 (5.49)	31.91 (9.7)	27.19 (10.06)	17.54 (8.35)	21.39 (8.85)
	Mn (mg/kg)	409.00(118.48)	609.34 (148.61)	621.84 (171.03)	400.0 (104.85)	689.0 (167.43)

Diameter Increment (Di)

The initial mean diameter measured in 2018 before the start of the experiment was 31.9 ± 3.9 mm, with no significant differences observed between the main plots (two-way ANOVA; $F = 11.071$, $p = 0.080$) or between the subplots (two-way ANOVA; $F = 0.121$, $p = 0.887$), that is, among the future treatment groups.

The effect of herbicide application on Di was statistically significant in the first experimental year and in the combined analysis of both years, but it was not significant in the

second year. In the first year, herbicide application increased Di by 14% compared to NoHA (Figure 1A), but this effect disappeared in the second year (Figure 1D). Over the two-year experimental period, herbicide application resulted in Di values that were approximately 8% higher than those of NoHA (Figure 1G).

The effect of fertilizer applications on Di was statistically significant only in the first experimental year; no significant effect was observed in the second year or in the combined analysis of both years (Figure 1B, E, and H). In the first year,

both NP180 and NP360 fertilizer applications had similar effects on Di, and both treatments increased Di by about 19% compared to NP0 (Figure 1B).

The interaction effect of herbicide and fertilizer applications on Di was not statistically significant in either year or in the combined analysis of both years (Figure 1C, F, and I).

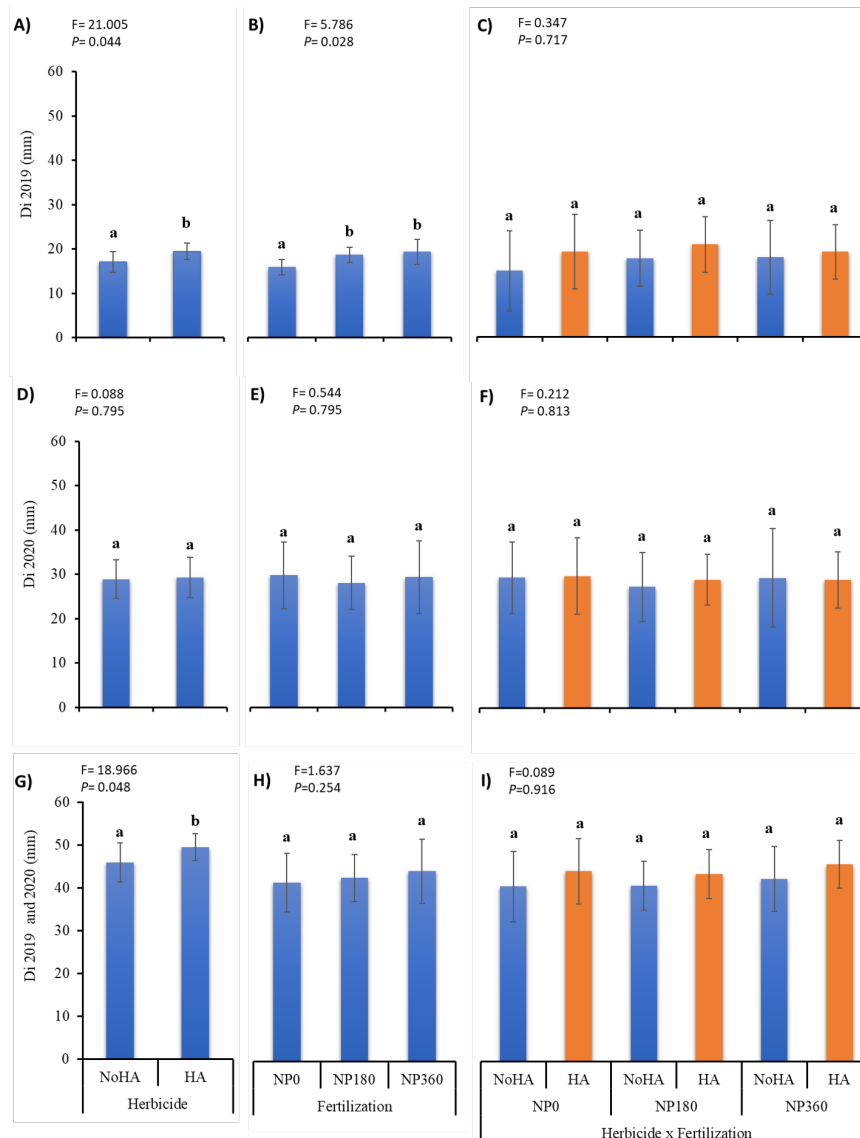


Figure 1 Mean diameter increment (Di) in the first (2019), second (2020), and both (2019 and 2020) experimental years under the effects of no herbicide application (NoHA) and herbicide application (HA) treatments (A, D, G), under the effects of control fertilization treatment (NP0) and fertilization treatments with NP fertilizer doses of 180 g (NP180) and 360 g (NP360) (B, E, H), as well as under the effects of NoHA (blue bars) and HA (orange bars) considering fertilization treatments (C, F, I). The figures show F and p values that indicate the significance of investigated treatment effects on Di as calculated by two-way ANOVA. Different lowercase letters indicate significant differences between herbicide application treatments, as well as among fertilization treatments. Error bars indicate standard deviations.

Height increment (Hi)

The initial mean total height recorded in 2018 prior to the experiment was 156.0 ± 25.1 cm, with no significant differences detected between the main plots (two-way ANOVA; $F = 8.631$, $p = 0.099$) or the subplots (two-way ANOVA; $F = 0.159$, $p = 0.856$), indicating uniformity among the prospective treatment groups.

The impact of herbicide application on Hi was statistically significant in the initial experimental year (2019) and in the combined analysis of both years (2019 and 2020), but it was not significant in the subsequent year. In the initial year, herbicide treatment elevated Hi by 18% relative to NoHA (Figure 2A); however, this impact dissipated in the subse-

quent year (Figure 2D). During the two-year study period, herbicide application yielded Hi values approximately 6% higher than those of NoHA (Figure 2G).

The impact of fertilizer treatment on Hi was statistically significant solely in the initial experimental year; no significant impacts were seen in the subsequent year or in the aggregate analysis of both years (Figures 2B, E, and H). During the initial year, the impacts of NP0 and NP180 applications on Hi were comparable, but the NP360 treatment elevated Hi by 25% relative to both NP0 and NP180 (Figure 2B).

The interplay between herbicide and fertilizer administrations had no statistically significant impact on Hi in any of the experimental years (Figures 2C, F, and I).

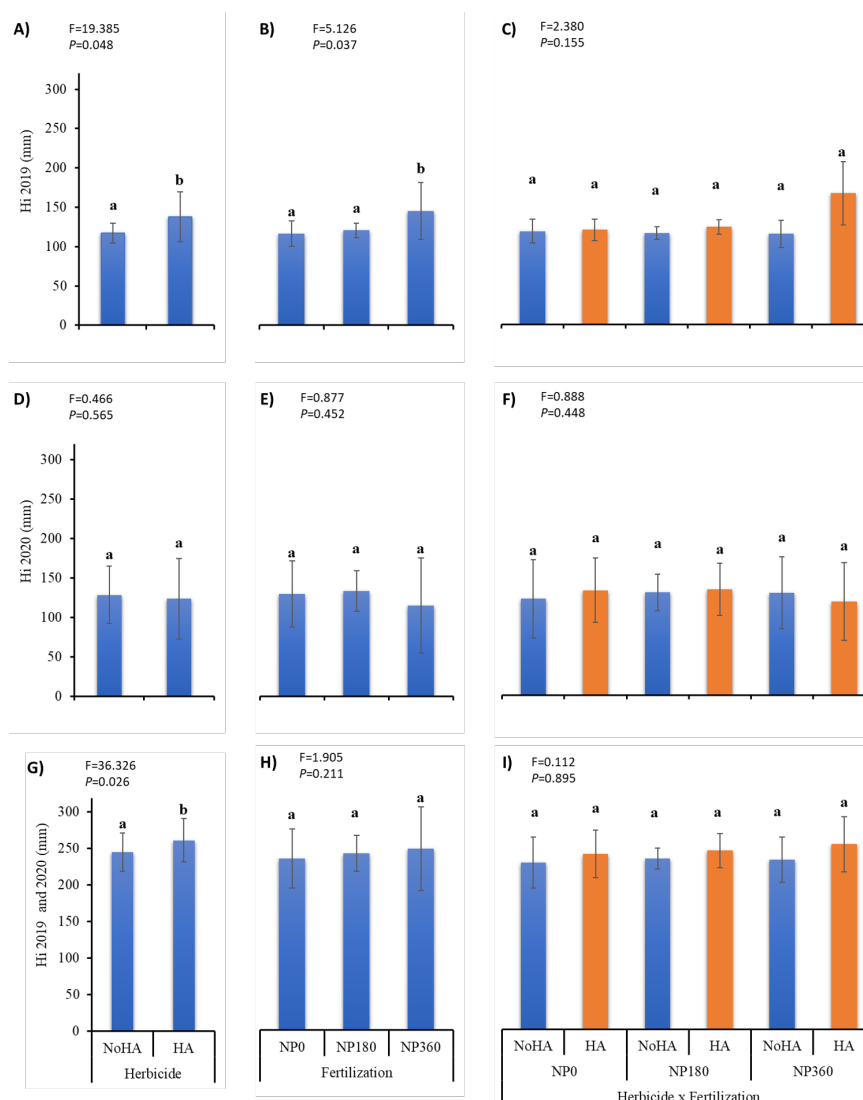


Figure 2 Mean height increment (Hi) in the first (2019), second (2020), and both (2019 and 2020) experimental years under the effects of no herbicide application (NoHA) and herbicide application (HA) treatments (A, D, G), under the effects of control fertilization treatment (NP0) and fertilization treatments with NP fertilizer doses of 180 g (NP180) and 360 g (NP360) (B, E, H), as well as under the effects of NoHA (blue bars) and HA (orange bars) considering fertilization treatments (C, F, I). The figures show F and p values that indicate the significance of investigated treatment effects on Hi as calculated by two-way ANOVA. Different lowercase letters indicate significant differences between herbicide application treatments, as well as among fertilization treatments. Error bars indicate standard deviations.

DISCUSSION

Soil and Needle Nutrient Concentration

Maritime pine naturally grows in nutrient-poor, acidic, sandy soils and often experiences deficiencies in P, as well as, often, Mg and Ca (Dumbrell and McGrath 2003, Martins et al. 2009). Although maritime pine can morphologically adapt to a wide acidic pH range (3.5–6.5) (Arduini et al. 1998), optimal root development and growth are achieved in moderately acidic soils (pH ~4.0–5.0) (Bakker et al. 2006, Ali et al. 2009, Fraga 2016, Kahyaoglu and Guvendi 2020). Accordingly, the soil pH (4.1–5.0) of our study site is within the optimal range for maritime pine development. The soil's organic matter and N content are at moderate levels, while Mg, Fe, Cu, and Mn concentrations are sufficient. However, K, Ca, and Zn are low, and available P and Na are very low (Ülgen and Ateşalp 1972, Sillanpää 1990). Since high sodium (salinity) is generally more problematic than sodium deficiency for plants (Roy and Chowdhury 2020), the limiting nutrient for growth

and development at the study site is the low available P content in the soil (Dumbrell and McGrath 2003, Martins et al. 2009, Augusto et al. 2022). The low levels of macronutrients such as P, K, and Mg in the soil may be attributed to intensive site preparation prior to planting. In a nearby maritime pine plantation in İzmit, intensive site preparation was reported to reduce soil P, K, and Mg contents by up to 50% compared to basic preparation (Fidan et al. 2022). Moreover, in eastern beech stands in Düzce, areas subjected to mechanical site preparation showed significant reductions in soil organic matter, nutrients, and bulk density compared to areas with hoeing (Yildiz et al. 2007, 2009).

Fertilization interventions are aimed at maintaining the nutrient content in the soil and leaves/needles at target concentrations. In this study, NP360 fertilization resulted in a clear increase in available P in the soil during the first year, while no significant differences were detected for total nitrogen (N) or other nutrients in either year (Table 1). This result aligns with previous research in pine plantations,

which has found that short-term or single applications of nitrogen fertilizer rarely lead to a measurable increase in total N in the soil. Rather, substantial increases typically require long-term and repeated applications (Maimone et al. 1991, Magill et al. 2000, Yang et al. 2023). Recent studies have further emphasized that total soil N may remain unchanged after N fertilization, primarily due to rapid plant uptake, leaching, volatilization, or microbial immobilization (Tian et al. 2020, Yang et al. 2023). In general, fertilization tends to provide only short-term increases for limiting elements such as P, while effects on other nutrients are often limited and temporary (Subedi et al. 2015). The lack of a significant fertilization effect on available soil P in the second year may be attributed to the gradual fixation of P in the soil, which reduces its availability to plants and diminishes the effectiveness of applied P over time (Hinsinger 2001, Ali et al. 2014).

In terms of needle nutrient content, different fertilizer doses did not alter the N and P concentrations in the needles. Single-dose fertilization does not always cause a clear change in needle nutrient content in pine species. Studies have indicated that nutrients (especially N and P) are translocated from older needles to new shoots, which can mask the effect of external fertilization on leaf nutrient status (Sheriff et al. 1986, Albaugh et al. 2012).

Generally, the most frequently deficient nutrients in maritime pine are, in order of importance, P, K, Mg, Ca, and N (Eimil-Fraga et al. 2014). N is one of the most important nutrients for plant growth, as it significantly affects water uptake and photosynthetic activity (Sever et al. 2023). The average needle N concentration in this study ranged from 32.1 mg/g to 39.2 mg/g over two years, which is sufficient for optimal growth. Several studies have reported needle N content in maritime pine ranging from 7.0 mg/g to 20.0 mg/g (Donald and Glen 1974, Warren 2006, Augusto et al. 2008, Trichet et al. 2008, Martins et al. 2009, Gómez-Rey et al. 2021), and the minimum threshold for N deficiency in maritime pine plants is reported as 9.8 mg/g (Eimil-Fraga et al. 2015).

Among nutrients, P is the most commonly deficient element in maritime pine plantations (Martins et al. 2009, Eimil-Fraga et al. 2014), making it a key growth-limiting nutrient. In this study, the needle P concentration was measured between 0.70 and 0.90 mg/g. The literature reports P concentrations in maritime pine needles generally ranging from 0.60 to 1.60 mg/g (Warren et al. 2005, Augusto et al. 2008, Trichet et al. 2008, Gómez-Rey et al. 2021). The optimal growth in maritime pine is observed at needle P concentrations of 1.20 mg/g, and regular P fertilization is recommended to maintain this level (Trichet et al. 2008). Photosynthesis may begin to slow down when needle P drops below 0.80 mg/g (Loustau et al. 1999, Kulmann et al. 2024). Furthermore, N:P ratios in needles are considered indicators of N or P limitation for plant growth. Reich and Oleksyn (2004) classified N or P limitation globally as $N:P < 14$ or > 16 , respectively, in plant leaves. Needle N:P ratios for maritime pine that grows in Mediterranean and Atlantic climates are usually between 10 and 15 (Eimil-Fraga et al. 2015, Vallicrosa et al. 2022). An N:P ratio above 16 indicates P limitation and may cause growth reduction (Wang et al. 2021, Guo et al. 2023). In the study, the needle N:P ratio was found to be 40, which, according to the literature, clearly demonstrates a

severe phosphorus deficiency and a significant limitation on growth. Additionally, the obtained needle P concentration is considerably below the recommended 1.20 mg/g for optimal growth. This situation indicates the necessity of regular and adequate phosphorus fertilization in plantations.

The K, Ca, Mg, Na, Fe, Cu, Zn, and Mn concentrations in the maritime pine needles at the plantation were generally within normal ranges reported in the literature: K, 3.0–5.0 mg/g (Tausz et al. 2004); Ca, 1.60–2.70 mg/g (Tausz et al. 2004); Mg, 0.50–2.00 mg/g; Cu, 2–9 mg/kg (Saur 1989, Tausz et al. 2004, Gómez-Rey et al. 2021); Zn, 16–65 mg/kg (Saur 1989, Tausz et al. 2004, Gómez-Rey et al. 2021); and Mn, 40–400 mg/kg (Saur 1989, Gómez-Rey et al. 2021). However, Fe and Na concentrations in the needles were observed to be somewhat higher than those reported in the literature (Saur 1989, Gómez-Rey et al. 2021).

Effect of Herbicide-Based Weed Control and Fertilization on Growth

Weed control and fertilization are among the most important silvicultural practices in afforestation areas. Weed control reduces competition for water, nutrients, and light, resulting in lower seedling mortality and improved early tree growth (Hytönen et al. 2017). The importance of weed control is even greater for improving early-stage tree growth (Mason and Milne 1999, Albaugh et al. 2004, Fidan et al. 2022). In the present study, herbicide-based weed control significantly accelerated both Di and Hi of maritime pine individuals in the first year following intervention. Similarly, herbicide-based weed control has been reported to significantly increase Di and Hi in *Pinus radiata* (Albaugh et al. 2004, Stokes and Willoughby 2014). This can be attributed to the redirection of limited site resources to crop trees as competition from weed vegetation is reduced. However, in the second year after intervention, the positive effects of the initial herbicide application on both Di and Hi diminished and were no longer statistically significant. This may be explained by the re-establishment of weed vegetation sharing the limited resources in the second year. Although herbicide application had no significant effect on Di and Hi in the second year, its cumulative positive impact persisted over the two-year period, resulting in approximately 8% greater Di and 6% greater Hi compared to untreated plots.

NP360 fertilization increased Di and Hi compared to the control in the first year after application. However, the positive effects of fertilization on Di and Hi observed in the first year disappeared in the second year and over the total two-year period. Xavier et al. (2010) reported that fertilization increased growth in maritime pine during the first two years, but its effect disappeared in subsequent years. In Spanish maritime pine plantations, fertilization was found to increase diameter and height growth compared to the control, but the second-year growth was not as pronounced as in the first year (Zas et al. 2006). Our results further support the notion that single-event fertilization effects are often temporary and can be strongly affected by site-specific factors such as precipitation or drought events. Although previous studies have reported that the effects of fertilization persist in the second year, albeit to a lesser extent, this effect disappeared in the second year of our study, most likely due to the drought stress experienced in

2020. Indeed, the annual precipitation in 2020 decreased by 24% compared to 2019. This suggests that environmental stress factors such as water limitation may suppress the positive effects of fertilization on growth. Sever et al. (2023) noted that the contribution of nitrogen to growth declines during drought periods and that water scarcity becomes the primary limiting factor. In addition, it has been emphasized that P fertilization increases yield in nutrient-limited *Pinus pinaster* stands, but the effect is strong in more humid areas and weak in drier areas (Trichet et al. 2009). Therefore, ensuring an adequate water supply is essential for the sustainable effect of fertilization. Additionally, researchers have emphasized the need for continued fertilization in subsequent years to maintain its effect on growth (Trichet et al. 2009, Bergh et al. 2014, Eşen and Özbayram 2016, Loewe-Muñoz et al. 2020, Loewe-Muñoz et al. 2025).

Moreover, no statistically significant interaction was found between herbicide and fertilization for either Di or Hi. This indicates that the positive effects of these applications are independent and do not provide an additional benefit when combined, which is consistent with previous studies (Ferreira et al. 2020, Zhang et al. 2022, Moore et al. 2023). This finding suggests that, although both practices are important for early growth, their combined application does not yield greater improvements than each treatment applied separately.

On the other hand, fertilizer composition can affect growth in maritime pine in different ways. For example, in a study in Lebanon where different combinations of N, P, and K fertilizers were tested in maritime pine plantations, only P fertilization increased height growth by 10% compared to the control in the first year, and its effect on third-year height growth continued at a rate of 4% (Donald and Glen 1974). In a fertilization experiment in Western Australia, Warren et al. (2005) reported that only P fertilization increased the average height growth by 55–137 cm two years after application, while N and K fertilization had no effect on height. These findings underscore the frequent occurrence of P deficiency in maritime pine stands and, hence, the potential for P fertilization to increase height growth (Warren et al. 2005, Martins et al. 2009).

CONCLUSIONS

Silvicultural maintenance practices in industrial plantations are indispensable for ensuring healthy seedling development, accelerating growth, and increasing production efficiency. This study demonstrated that early cultural interventions, particularly weed control and phosphorus (P) fertilization, play a critical role in the initial growth of maritime pine plantations. Weed control using herbicides significantly enhanced Di and Hi during the first year, and its cumulative positive effect on growth persisted over the two-year period, although the effect diminished in the second year due to the re-establishment of weed vegetation. In contrast, NP360 fertilization promoted growth in the first year, but this positive effect was not sustained in the second year or over the total two-year period, likely due to environmental stresses such as drought and rapid nutrient uptake or loss. Needle analyses indicated that P concentrations were at the lower threshold for optimal growth, confirming that phosphorus is the primary nutrient limiting growth at the site. Other

nutrient elements were found to be at sufficient levels.

These results indicate that the benefits of single-event fertilization are often temporary and highly dependent on site-specific factors, especially water availability. No synergistic effect was observed between weed control and fertilization, suggesting that their positive impacts on growth are independent rather than additive. The findings suggest that targeted P fertilization and early weed control each contribute to faster canopy closure and greater production efficiency, but their combined application does not provide additional benefits beyond their individual effects. However, for sustained growth and yield, it is crucial to ensure an adequate water supply and to consider repeated or long-term fertilization strategies if nutrient limitations persist.

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