https://doi.org/10.17221/84/2025-JFS

Scots Pine (*Pinus sylvestris* L.) establishment success under climate change: Effect of site, stock type and planting time

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Citation: Plačková A., Vacek Z., Vacek S., Cukor J., Gallo J., Černý J. (2025): Scots Pine (*Pinus sylvestris* L.) establishment success under climate change: Effect of site, stock type and planting time. J. For. Sci., 71: 555–564.

Abstract: Scots pine (*Pinus sylvestris* L.) is one of the most widespread and economically important coniferous species in the Northern Hemisphere. However, its regeneration success has recently been increasingly affected by global climate change (GCC), particularly through increasing mortality. This research aimed to evaluate the early establishment success of 30 400 bare-root and containerised Scots pine seedlings and saplings of different height classes, planted at various times on acidic and gleyed sites (479–610 m a.s.l.) across four locations in the Czech Republic. On acidic sites, seedlings exhibited 16% higher height growth and 11% lower mortality compared to gleyed sites. Containerised planting stock achieved significantly ($P < 0.05$) greater height growth (by 83%) and lower mortality (by 36%) than bare-root stock. For containerised material, spring plantings showed superior growth and vitality compared to autumn plantings. Planting stock height class had a stronger influence on height growth than on mortality. Based on the results, planting containerised saplings of 26–35 cm or 36–50 cm height in April is recommended for optimal establishment success of Scots pine under GCC.

Keywords: artificial regeneration; bare-rooted and containerised seedlings/saplings; climate stress; Czech Republic; growth potential; mortality

Scots pine (*Pinus sylvestris* L.) is the most widespread conifer species in the Northern Hemisphere and represents a substantial component of European forests, covering more than one-quarter of the forested area (Krakau et al. 2013; Sharma et al. 2017; Lundqvist et al. 2019). Although it has traditionally been considered relatively tolerant to environmental stress, recent droughts have revealed limits to Scots pine vitality, with increased mortality and reduced regeneration capacity in Central Europe (Špulák, Černý 2023). Therefore, it is increasingly considered sensitive to ongoing global climate change (GCC) (Vacek et al. 2016; Buras et al. 2018; Brichta et al. 2023, 2024). Pine stands suffer considerably from climatic fluctuations manifested by uneven distribution of wet and dry periods

Supported by the Forest Grant Service of the Czech Republic (Project No. 129).

https://doi.org/10.17221/84/2025-JFS

(Gao et al. 2017; Spinoni et al. 2018). This has a direct negative effect on the photosynthetic activity of pines (Reddy et al. 2004), their cambial growth (Vacek et al. 2017), overall resistance to insect pests (Dobbertin et al. 2007), fungal pathogens (Aguadé et al. 2015), and infestation by mistletoe (*Viscum album* L.) (Mutlu et al. 2016). Furthermore, drought periods increase the risk of forest fires in pine forests (Vilà-Cabrera et al. 2013; Vacek et al. 2023). In addition, GCC is expected to exacerbate other threats to pine by weakening tree defences and increasing the frequency and severity of heatwaves, reducing regeneration success through soil desiccation and altered microsite conditions, and promoting range shifts that may leave local populations maladapted to new climatic regimes (Vacek et al. 2023; Bose et al. 2024).

Adaptation to a wide range of natural pine habitats is crucial for mitigating the impacts of GCC on Scots pine and represents a key factor for successful forest regeneration and achieving the full growth potential of restored stands (Albrektson et al. 2012; Vacek et al. 2016). The selection of suitable tree species and the application of appropriate management practices serve as a means of adapting to site conditions (Poleno et al. 2009; Nordin et al. 2023). Adaptation to site conditions often occurs at the site level, although most forest sites exhibit micro-site variability in soil type, moisture, and other key factors (Aleksandrowicz-Trzcińska et al. 2017). Awareness of micro-site adaptation is therefore essential for achieving successful regeneration in forestry practice (Saksa et al. 2021; Persson et al. 2022). The choice of planting site can be understood as micro-site adaptation, where different local characteristics may vary in suitability for planted seedlings (Häggström et al. 2021; Nordin et al. 2023). Open areas expose seedlings to substantial environmental stress (Poleno et al. 2009), emphasising the importance of selecting an appropriate planting position to ensure rapid establishment (Thiffault, Jobidon 2006).

Soil temperature and hydrological conditions differ between elevated and lower planting positions (Sutton 1993). On mounds and raised microsites, porous structures with humus under a mineral soil layer may increase the risk of drying under low precipitation, thus reducing water availability (Luoranen et al. 2018; Häggström et al. 2021). Conversely, lower planting positions in moist environments may increase the risk of oxygen deficiency due to water accumulation but can be advantageous in dry conditions (Örlander et al. 1990; Hansson et al. 2018). Fluctuations in soil moisture within a site can lead to varying growth and mortality outcomes in seedlings and motivate diverse management approaches (Skovsgaard, Vanclay 2013; Holmström et al. 2019).

Among the key factors influencing the success of artificial regeneration are the type of planting material, planting time, and morphological maturity of the seedlings (Poleno et al. 2009). In connection with GCC and increasingly frequent spring droughts, late-summer and autumn planting is becoming more common, allowing seedlings to root before winter and enabling a more even distribution of silvicultural work (Poleno et al. 2009; Barzdajn, Kowalkowski 2016). Containerised pine seedlings generally show higher survival and better early growth due to an intact root system and the possibility of extending the planting period (Barzdajn, Kowalkowski 2016; Aleksandrowicz-Trzcińska et al. 2017). An appropriate combination of optimal planting material, timing, and seedling maturity significantly reduces mortality, enhances resilience to GCC, and promotes faster stabilisation of plantations during the early stages of forest regeneration; however, results are variable, and overall planting success has declined in recent years. This study aims to evaluate the early stages of Scots pine planting stock by examining the effects of planting stock type (bare-rooted vs. containerised) and seedling height classes, in combination with different planting times and contrasting site conditions (acidic and gleyed soils) within the 4–5th forest vegetation zone. The research focuses on quantifying the effect of these factors on initial growth potential and mortality rate to identify conditions and planting strategies that enhance early establishment success. Based on the ecological characteristics of the planting stock and expected site conditions, we formulated two hypotheses. First (H_1), higher mortality and height growth will be observed in bare-root stock compared to containerised stock due to stronger transplant shock, reduced protection of the root system against desiccation, and slower post-planting root regeneration. Second (H_2), autumn planting will result in higher survival and greater height growth than spring planting because seedlings benefit from a longer period for root system regeneration before the onset of the growing season, more favourable soil moisture conditions, and reduced exposure to early-season drought and temperature extremes.

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MATERIAL AND METHODS

Study sites. The study area (Czech Republic, Natural Forest Region 16) includes plantations on two acidic sites at Forest Administration (FA) Nasavrky (49°48'46"N, 15°41'41"E) and FA Ledeč nad Sázavou (49°40'47"N, 15°20'26"E), and on two gleyed sites at FA Třebíč (49°20'23"N, 15°50'56"E) and FA Nasavrky (49°45'35"N, 15°46'51"E), all managed by the state enterprise Forests of the Czech Republic. In terms of typology, the sites are gradually classified as *Abieto-Fagetum acidophilum* (5K), *Fagetum acidophilum* (4K), (*Fageto-*) *Abietum variohumidum mesotrophicum* (5O), and *Abietum piceosum variohumidum acidophilum* (5P) (Viewegh et al. 2003). The elevation of the experimental plots ranges from 479 m a.s.l. to 610 m a.s.l. with a slope of 1–14°. Acidic sites are dominated by cambisols, while gleyed sites have pseudogleys or stagnogleys. According to the Köppen-Geiger classification, the area lies within a temperate oceanic climate (Cfb; Peel et al. 2007), classified regionally as a moderately warm climatic zone, with an average annual temperature of 6.5–7.5 °C and annual precipitation of 650–750 mm. At FA Třebíč and Ledeč nad Sázavou, the sites are one- to two-year-old clear-cuts, whereas at FA Nasavrky, they are older (3–4 years), heavily overgrown post-disturbance clear-cuts. Each of the four study areas consists of three fenced plots of approximately 0.4 ha.

Planting design. A total of 30 400 seedlings/saplings were planted at a spacing of 110 × 110 cm on plots with an area of 15 × 15 m (180 plots in total), with five random-placed replicates for one autumn planting (4th week of November 2024) and three replicates for two spring plantings (2nd week of March 2025 and 1st week of April 2025) within a single fenced plot (Figure 1). The planting variants were as follows: bare-root seedling, bare-root sapling, containerised seedling, containerised sapling, with height classes of 10–14 cm, 15–25 cm, 26–35 cm, and 36–50 cm, respectively. The certified planting material code is CZ-2-2B-BO-00015-16-5-J. Containerised planting material was carried out using an auger with a 120 mm bit (STIHL, Germany), while bare-root material was planted using a flat planter (Interforst, Czech Republic). Mechanical weed control was carried out uniformly across all sites using a brush cutter MS 461 (STIHL, Germany), with the intervention repeated twice during the vegetation period: first in June–July 2025, and again in August–September 2025. Codes and dimensions of the planting material are summarised in Table 1.

Data collection and analysis. For each planting variant, the annual height increment of all individuals in the studied plots was measured at the end of the growing season (September 2025) with an accuracy of 0.1 cm, and the mortality rate of seedlings was also assessed. Statistical analysis of the data for different planting material types, sites, and timing was conducted using basic descriptive and inferential methods in Statistica (Version 14.1, 2023). For testing individual variants, height increment and mortality were first assessed for normality using the Shapiro-Wilk test and for homogeneity of variance using Bartlett's test. When both assumptions were met, differences among the examined parameters were tested using analysis of variance (ANOVA) followed by Tukey's HSD test. If the assumptions of normality and homogeneity of variance were not met, the characteristics were analysed using the non-parametric Kruskal-Wallis test. Significant ($P < 0.05$) differences between variants are denoted by different letters. The average value of the parameters across all variants is marked with a line.

Sapling 36–50 cm	Seedling 10–14 cm	Seedling 15–25 cm	Sapling 15–25 cm	Sapling 26–35 cm
Sapling 15–25 cm	Sapling 26–35 cm	Sapling 36–50 cm	Seedling 10–14 cm	Seedling 15–25 cm
Seedling 10–14 cm	Seedling 15–25 cm	Sapling 15–25 cm	Sapling 26–35 cm	Sapling 36–50 cm

Figure 1. The planting design of Scots pine in the spring planting treatment using containerised stock in experimental plots with an area of 15 × 15 m (the same design was used for bare-root stock)

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Table 1. Standard planting material of Scots pine used in experimental plots

Code	Developmental stage	Stock type	Minimal root collar thickness (mm)	Height classes (cm)
20130	seedling	bare-root	3	10–14
20135	seedling	containerised	3	10–14
20140	seedling	bare-root	4	15–25
20145	seedling	containerised	4	15–25
20240	sapling	bare-root	4	15–25
20245	sapling	containerised	4	15–25
20250	sapling	bare-root	5	26–35
20255	sapling	containerised	5	26–35
20260	sapling	bare-root	6	36–50
20265	sapling	containerised	6	36–50

RESULTS

Growth potential. Significant differences in height increment among the planting variants were observed across all sites ($P < 0.001$; Figure 2). At the acidic sites in Ledeč, no significant difference in height growth was detected between early and late spring plantings. However, at both representing acidic sites, containerised planting material generally exhibited higher growth compared to bare-root material. The highest increment (17.5 cm) in Ledeč was recorded for a container-

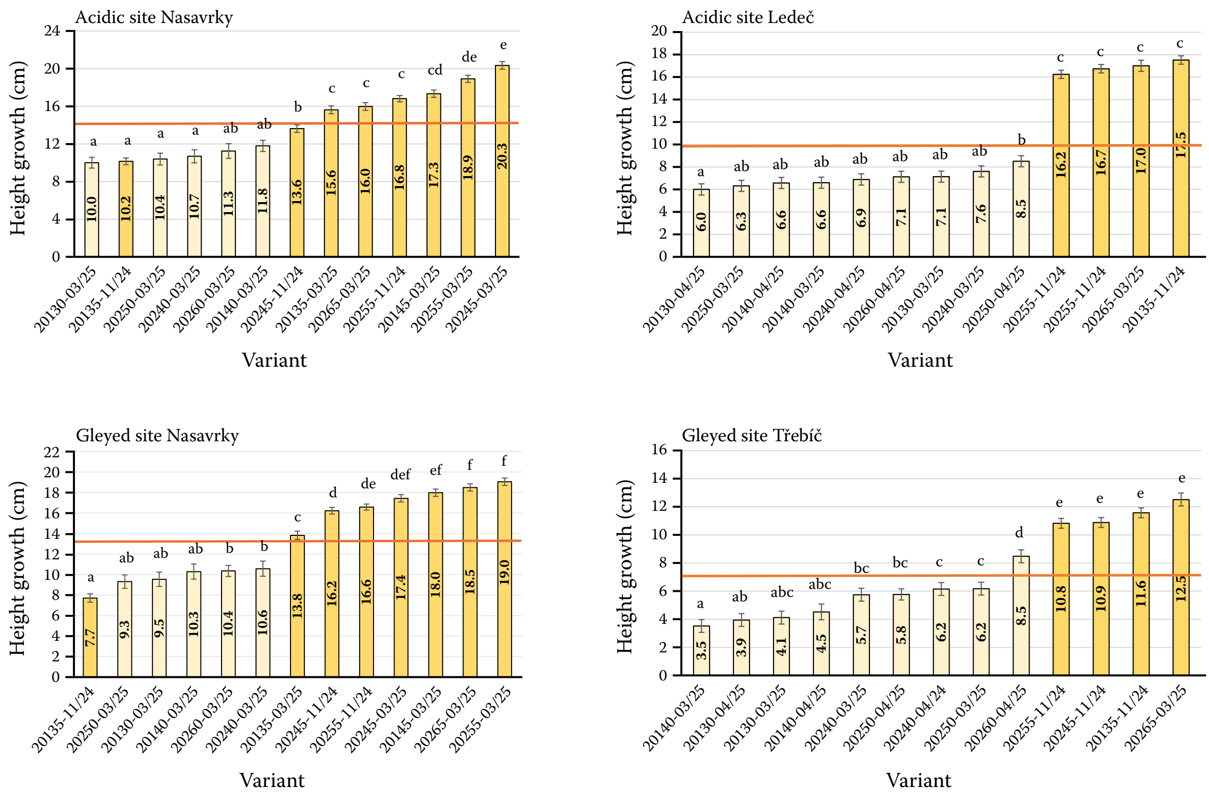

Figure 2. Annual height growth of Scots pine seedlings/saplings differentiated by planting material variant (codes), planting time (11/24, 03/25, 04/25), and site type (acidic, gleyed)

Containerised stocks are indicated by a darker shading compared to bare-root ones; the lines depict the mean values across all treatment variants; significant ($P < 0.05$) differences between variants are denoted by different letters

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ised seedling 10–14 cm from the autumn planting, whereas the lowest increment was observed for a bare-root seedling 10–14 cm from the late spring planting (6.0 cm). At gleyed sites in Nasavrky, the containerised seedling 10–14 cm from the autumn planting showed the opposite trend, with the lowest increment (7.7 cm). At other sites, the highest increments were observed at the acidic site in Nasavrky for variant 20245-03/25 (20.3 cm), at the gleyed site in Třebíč for variant 20265-03/25 (12.5 cm), and at the gleyed site in Nasavrky for variant 20255-03/25 (19.0 cm).

Across all planting material variants, pine exhibited 15.9% higher growth on acidic sites compared to gleyed sites. Containerised material outperformed bare-root plantings, showing an 82.9% higher increment, with containerised seedlings of 26–35 cm and 15–25 cm consistently forming homogeneous groups with the highest height increments. Regarding planting time, containerised material planted in spring achieved higher growth than autumn plantings. For bare-root material, no significant difference was observed between early and late spring plantings on acidic sites; however, on gleyed sites, late spring plantings showed higher growth, likely related to waterlogged conditions.

Mortality. Significant differences in mortality were observed across all sites ($P < 0.001$; Figure 3). The lowest mortality at acidic sites in Ledeč was recorded for variant 20265-03/25 (8.4%), at acidic sites in Nasavrky for variant 20255-03/25 (8.1%), at gleyed sites in Třebíč for variant 20265-03/25 (28.9%), and at gleyed sites in Nasavrky for variant 20145-03/25 (12.6%). Conversely, the highest mortality at acidic sites in Ledeč was observed for variant 20240-03/25 (48.4%), at acidic sites in Nasavrky for variant 20260-03/25 (79.2%), at gleyed sites in Třebíč for variant 20140-03/25 (69.0%), and at gleyed sites in Nasavrky for variant 20140-03/25 (80.1%).

Overall, bare-root planting material exhibited 35.8% higher mortality than containerised material (59.5% vs. 23.8%). Regarding site type,

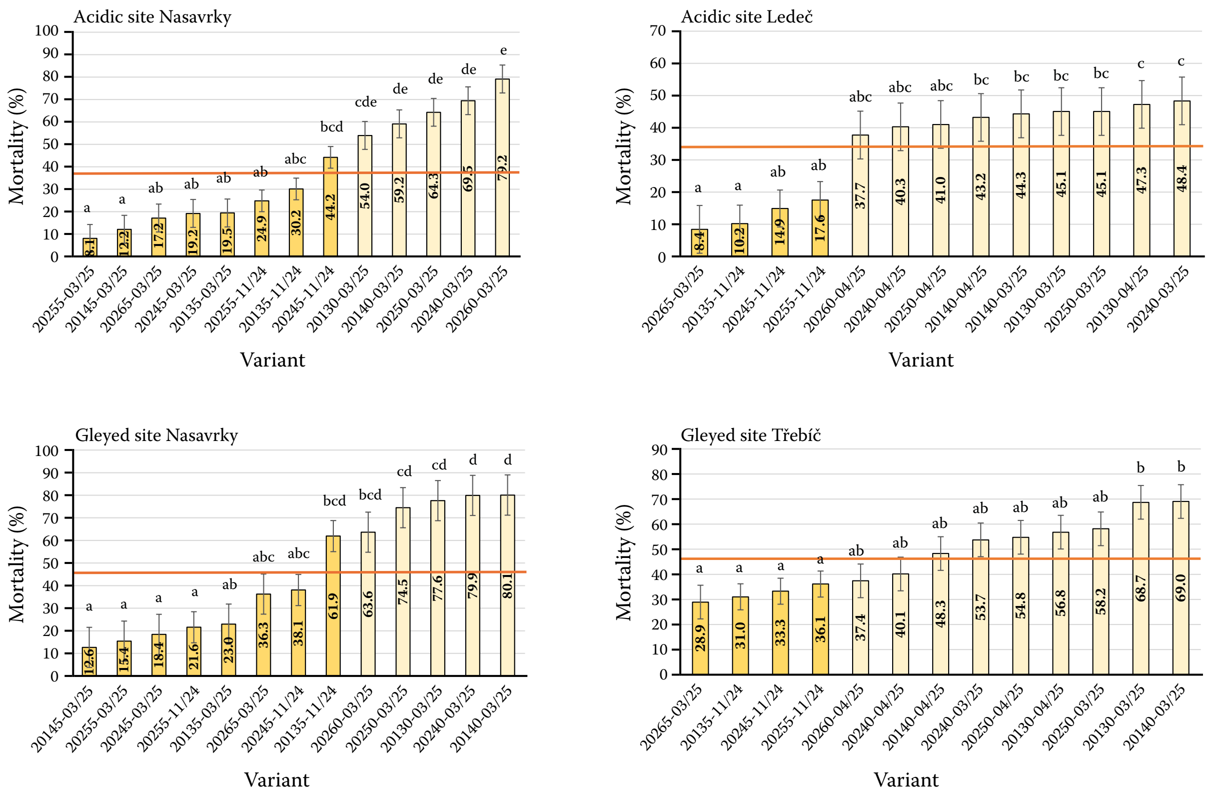

Figure 3. Annual mortality of Scots pine seedlings/saplings differentiated by planting material variant (codes), planting time (11/24, 03/25, 04/25), and site type (acidic, gleyed)

Containerised stocks are indicated by a darker shading compared to bare-root ones; the lines depict the mean values across all treatment variants; significant ($P < 0.05$) differences between variants are denoted by different letters

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mortality was 10.6% higher on gleyed sites compared to acidic sites. The lowest mortality was observed at acidic sites in Ledeč (34.1%), and the highest at gleyed sites in Třebíč (47.4%). Regarding planting time, containerised material planted in spring showed lower mortality compared to autumn plantings. For bare-root material, significantly lower mortality was observed for late spring plantings on both acidic and gleyed sites.

DISCUSSION

Growth potential. In this study, significant differences in height growth were observed among the different variants. Aleksandrowicz-Trzcińska et al. (2017) also reported that planting methods and stock type significantly affect both the biometric parameters and mortality of Scots pine saplings. Generally, more developed saplings (taller and with a thicker root collar) grow faster than smaller ones (Collet, Moguédec 2007). Interestingly, the highest increment (17.5 cm) on an acidic site in Ledeč was recorded for a 10–14 cm containerised seedling from the autumn planting, whereas on gleyed sites in Nasavrky, the same stock type showed the lowest increment (7.7 cm). On other sites, the highest increments were recorded for all containerised seedlings 15–25 cm in March at acidic sites in Nasavrky (20.3 cm), 36–50 cm in March on gleyed sites in Třebíč (12.5 cm), and 26–35 cm in March on gleyed sites in Nasavrky (19.0 cm).

Overall, containerised stock consistently outperformed bare-root stock, with height increments up to 82.9% higher, particularly in the taller classes, suggesting that more developed seedlings better compete for nutrients and other resources. Stronger seedlings can also take greater advantage of improved soil conditions (Heiskanen, Rikala 2006), have better-developed foliage and higher photosynthetic rates (Thiffault et al. 2003), and are less susceptible to late spring frosts or competition from herbaceous vegetation (Bedford, Sutton 2000). However, in some cases, smaller or less developed stock outperformed larger stock in growth on our plots.

Planting methods influence the height and root-collar diameter growth of pine during the first 2–3 years (Bilodeau-Gauthier et al. 2011; Aleksandrowicz-Trzcińska et al. 2017). Rapid early growth is crucial for competing with other vegetation (Löf 1998). According to Aleksandrowicz-Trzcińska et al. (2017), planted pine seedlings were taller than herbaceous vegetation by the third year, whereas seedlings reached similar growth a year later. Planting methods also help suppress herbaceous growth on clear-cuts (Nordborg, Nilsson 2003; Nordborg et al. 2006). Pine generally grows better on mineral soils and elevated mounds with sufficient humus than on waterlogged soils (Häggström et al. 2024), which is consistent with our results, where growth on gleyed sites was 15.9% lower than on acidic sites. Regarding planting time, spring plantings of containerised stock achieved greater growth than autumn plantings, while for bare-root stock, no difference was observed between early and late spring plantings on acidic sites; on gleyed sites, late spring plantings showed higher growth due to waterlogging conditions.

Mortality. Similar to height growth, mortality differed significantly among the stock variants. In our study, the lowest mortality rates were recorded at acidic sites in Nasavrky for variant 20255-03/25 (8.1%), at acidic sites in Ledeč for variant 20265-03/25 (8.4%), at gleyed sites in Nasavrky for variant 20145-03/25 (12.6%), and at gleyed sites in Třebíč for variant 20265-03/25 (28.9%). Conversely, the highest mortality was found for variant 20140-03/25 on gleyed sites in Nasavrky (80.1%), variant 20260-03/25 on acidic sites in Nasavrky (79.2%), variant 20140-03/25 on gleyed sites in Třebíč (69.0%), and variant 20240-03/25 on acidic sites in Ledeč (48.4%). In the study by Häggström et al. (2024), pine mortality ranged between 4–26% three years after planting, with the main cause being damage by the large pine weevil (*Hylobius abietis* L.). Slightly lower mortality of one-year-old pine seedlings (both bare-root and containerised) was reported by Barzdajn (2010), with an average mortality of 11% across 40 sites; only April bare-root plantings showed 57% mortality due to drought during planting.

Because of frequent drought episodes, autumn planting and deeper planting on organic soils are recommended to protect the root collar from frost damage (Barzdajn 2006, 2010; Barzdajn, Kowalkowski 2016). Containerised planting material is generally less sensitive to planting time, whereas for bare-root material, August plantings were too early, with October being the most suitable autumn term. For containerised material, Au-

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gust and March plantings performed best, while September plantings were least successful. Furdyna (2008) also found that pine planted in September showed the highest vitality and growth performance. Barzdajn (2006, 2010) emphasised that late-summer and autumn plantings may perform as well as spring plantings. Similarly, containerised material is not always superior to bare-root ones (Kerr 1994). Planting time should correspond to the root growth rhythm. McKay (1998) reported from England that root growth potential is low in October, increases during winter, and declines sharply before bud break. For two-year-old bare-root seedlings, the optimal planting window for survival, height growth, and vitality ranged from mid-November to mid-March (McKay 1998). Szeligowski (2005) confirmed similar results in Poland, provided the soil was not frozen. Root growth rhythms differ among pine ecotypes as well as among provenances (Bułaj 2006; Hejtmánek et al. 2023).

In our study, bare-root stock exhibited 35.8% higher mortality than containerised material (59.5% vs. 23.8%). Mortality was also 10.6% higher on gleyed sites compared with acidic ones. The lowest overall mortality occurred on acidic sites in Ledeč (34.1%), while the highest was observed on gleyed sites in Třebíč (47.4%). Regarding planting time, containerised stock planted in spring showed lower mortality than autumn plantings. For bare-root stock, significantly lower mortality was found for late spring planting on both site types. By contrast, Barzdajn (2010) reported no significant differences in most cases between bare-root and containerised stock. Nonetheless, strict adherence to planting and handling procedures remains crucial for successful establishment (Jurásek, Mauer 2016; Jurásek et al. 2010).

Our results partially supported the formulated hypotheses. Hypothesis 1 (H_1) was confirmed, as bare-root stock showed higher mortality and lower height growth than containerised stock. Hypothesis 2 (H_2) was rejected, since spring plantings had higher survival and better height growth than autumn plantings. For future plantations, it is important to consider both the choice of stock type and planting timing, as well as the suitability of resistant introduced tree species to ensure long-term viability and production potential (Vacek et al. 2021; Podrázský et al. 2025).

CONSLUSION

On acidic sites, significantly higher height growth was observed (on average by 16%) compared to gleyed sites. Gleyed sites exhibited a higher mortality (by 11%) of artificial pine regeneration than acidic sites. Containerised planting stock achieved significantly greater height increments than bare-root stock – on average up to 83% higher. In terms of health status, bare-root material was markedly less resilient, with mortality 36% higher than that of containerised stock. The type of planting stock has a stronger influence on seedling/sapling mortality than on height growth. Medium-height saplings (26–35 cm) appear to be the most suitable option in terms of economic and growth parameters, while taller classes (36–50 cm) are also favourable due to lower costs of weeding and good growth tendencies. Lower-height seedlings are entirely unsuitable for afforestation due to high mortality, lower growth, and high costs of weed protection. In some cases, smaller seedlings surpassed larger planting stock in growth, highlighting the importance of physiological condition and adaptation to site conditions. The height class of regeneration influences height growth more than mortality. For containerised planting stock, spring plantings showed better results in terms of growth and vitality compared to autumn plantings. For bare-root stock, a later spring planting (April) is recommended over early spring (March), particularly on gleyed sites due to waterlogging, although this depends on moisture conditions. A limitation of this study is that the observed growth and mortality patterns are site-specific and represent only the first year after planting, which may not fully capture longer-term trends under varying stand conditions under GCC.

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Received: November 11, 2025
Accepted: November 19, 2025
Published online: November 28, 2025