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REVIEW ARTICLE

Nurse structures effectively improve the performance of restoration plantings: a systematic review

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Abstract

Introduction: Tree planting for ecosystem restoration often occurs on disturbed, degraded, or former agricultural sites, where seedlings face harsh conditions like sun exposure, drought, wind, frost, and browsing, which can lead to poor performance. To improve survival and growth, nurse structures such as nurse plants, plant residues, or artificial shelters may be used to buffer environmental stress.

Objectives: We aimed to assess how different nurse structures influence the performance of restoration plantings and how this effect varies with climate and environmental stressors, nurse structure type, plantation age, and tree species traits.

Methods: Using descriptive statistics and meta-analyses, we systematically reviewed 82 studies from temperate and boreal forests addressing effects of nurse structures on the performance of planted trees.

Results: Nurse structures improve the performance of planted seedlings or saplings, particularly by enhancing survival and height growth. However, their effects on diameter growth and plant water status tend to be negative. The effects are consistent across tree species types but are stronger in temperate and continental climates, in younger plantations, and when using artificial shelters rather than nurse plants. Nurse structures are most effective at mitigating drought, frost, and browsing, while evidence for impacts on competition or wind is inconclusive.

Conclusions: Survival and growth of planted seedlings are improved through nurse structures. However, their effectiveness is context-dependent, so site-specific conditions should be considered when applying them for restoration purposes.

Implications for Practice: Nurse structures have broad applicability to facilitate establishment of planted trees with different shade tolerance and other functional traits. Furthermore, they are particularly helpful to improve survival and height growth of young trees. Yet, nurse plants that compete with target species for water should be avoided, especially in high-density plantings or in dry environments. In dry regions, well-ventilated shelters are preferable to prevent excessive heat buildup and water stress. Nurse structures, especially artificial ones, are most effective at early establishment stages. Their timely removal should be planned to prevent negative effects, such as spindly growth or suppression of seedlings.

Key words: artificial and natural shelters, climate adaptation, facilitation, restoration, silviculture, tree growth, tree regeneration

Introduction

Reforestation and afforestation are expected to play a major role in mitigating climate change and conserving biodiversity (Griscom & Ashton 2011; Derhé et al. 2016). The global recognition of this role is reflected in multiple large-scale restoration initiatives aimed at increasing the extent of forested land (IUCN 2020; Forest Declaration Assessment 2021; Trillion Trees 2024). Much of this expansion of planted forests is expected to occur on degraded or former agricultural lands, where natural tree regeneration may be insufficient (Holl & Aide 2011; Simonsen 2013). Against this background, promoting regeneration through artificial regeneration (i.e. planting or sowing) remains a primary strategy for achieving successful restoration of forest ecosystems. However, in such environments, planted seedlings are often highly exposed, experiencing stress due to excessive solar radiation, drought, wind, frost, as well as browsing and trampling by livestock or wild herbivores. Consequently, poor seedling survival and subsequent reduced growth in such conditions can significantly delay canopy closure (Bannister et al. 2018; Fargione et al. 2021; Kremer et al. 2021), postponing the onset of meaningful carbon sequestration and biodiversity gains associated with habitat restoration (Bracho et al. 2012). Seedling survival and

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performance become increasingly critical in the context of projected increases in temperatures and frequency of extreme climatic events and disturbances, which are likely to intensify stress on planted seedlings (Machado et al. 2022).

These challenges highlight the importance of developing silvicultural practices that enhance seedling establishment. One option for this is the use of nurse structures or safe sites, commonly defined as structures or objects that reduce environmental stress to seedlings and thus facilitate their establishment (Fowler 1988; Shemesh 2025). For the purposes of this article, nurse structures are classified as either natural or artificial origin. Natural nurse structures comprise nurse plants such as young trees, shrubs, or herbs (Gómez-Aparicio et al. 2004; Padilla & Pugnaire 2006), and plant residues such as deadwood or crown material of felled trees (Castro et al. 2011; Stroheker et al. 2018). These structures may enhance seedling performance by protecting mainly against excessive sun radiation and water stress (Castro et al. 2004; Badano et al. 2015), but also against browsing or trampling (García & Obeso 2003; Maublanc et al. 2022), soil compaction (Gómez-Aparicio et al. 2005), and frost and wind damage (Tulod & Norton 2020). Artificial nurse structures comprise tubes, cloth, or mesh shelters, among others (Abe 2022). Artificial shelters usually form a walled physical barrier around seedlings, and can be made out of synthetic inorganic (e.g. plastic or cloth) or manufactured organic materials. As opposed to nurse shrubs, shelters have historically had a stronger focus on browsing prevention (Marquis 1977; Tuley 1985; Conner & Toliver 1987). However, they have also been shown to buffer both biotic and abiotic stressors by reducing water stress (Kjelgren & Rupp 1997), limiting competition (Ceacero et al. 2014), and decreasing exposure to wind (Sharpe et al. 1999) and low temperatures (Devine & Harrington 2008), among others. These benefits may vary according to the age of the target plants, as their physiological requirements and sensitivity to environmental stressors change during early establishment and subsequent growth stages (Leck et al. 2012). Moreover, the effects of shelters may also be influenced by species-specific traits (e.g. shade-tolerant vs. shade-intolerant or conifer vs. broadleaf), which often determine plant strategies for coping with abiotic stress (Niinemets & Valladares 2006; Robakowski et al. 2020; Brienen et al. 2025).

Despite their expected benefits, nurse plants may compete with planted seedlings for light, water or nutrients, or even suppress them eventually (Franco & Nobel 1988; Galindo et al. 2017). Similarly, artificial nurse structures may have adverse effects on seedlings, such as causing excessive heat buildup (Bergez & Dupraz 2009) or reduced growth due to shading (Jacobs & Steinbeck 2001). Thus, a comprehensive evaluation of the benefits and potential drawbacks of nurse structures under different ecological and operational contexts remains essential to determine when and how they can most effectively support seedling establishment. A previous survey conducted among restoration practitioners within the "SUPERB" project (Systemic Solutions for Upscaling of Urgent Ecosystem Restoration for Forest-related Biodiversity and Ecosystem Services) (SUPERB 2022), spanning 12 large-scale demonstration areas across Europe (i.e. hundreds to thousands of hectares each), confirms this need. Among others, it revealed that the effectiveness of nurse structures to enhance seedling establishment is a frequent knowledge gap for which practical experience and scientific guidance are limited (Supplement S1).

Previous syntheses have addressed the effectiveness of nurse structures in supporting tree regeneration, though typically focusing on certain types of structures or regional contexts. For example, Gómez-Aparicio et al. (2004) conducted a meta-analytical review (i.e. a systematic review based on meta-analyses) on nurse plant effects in experimental reforestations in Spain's Sierra Nevada, and Abe (2022) conducted a meta-analytical review of global scientific literature on artificial nurse structures. A more recent review considered both natural and artificial shelters, yet the evidence was analyzed only qualitatively (Shemesh 2025). The reviews of Gómez-Aparicio et al. (2004) and Abe (2022) report mainly facilitative effects of nurse plants and tree shelters, respectively. However, despite the relevant insights provided by these studies, we perceived the need for an updated and more globally comprehensive synthesis that encompasses a broader range of environmental conditions and techniques, while applying a quantitative analytical approach (i.e. based on a systematic, transparent, and quantitative analyses of empiric data from selected studies).

We conducted a quantitative systematic review to evaluate the effects of nurse structures on the performance of reforestation and afforestation plantings across different contexts. Our objective was to provide a comprehensive synthesis of available evidence by addressing the following key questions: (1) what are the effects of nurse structures on the overall performance of planted tree seedlings?; (2) how do different response variables (survival, height growth, diameter growth, and plant water status) respond to nurse structures?; (3) how do these effects vary depending on climate, type of stressors they are intended to buffer, type of nurse structure (natural vs. artificial), tree species characteristics (shade-tolerant vs. shade-intolerant; conifer vs. broadleaf), and plantation age? We defined overall performance as the synthesized overall response of seedlings to nurse structures, derived from the range of individual performance indicators (e.g. survival, height growth, diameter growth, etc.) assessed across the studies included in the review.

This review offers an updated, comprehensive and systematic evaluation of the influence of nurse structures (both natural and artificial) on seedling performance. Furthermore, to enhance both representativeness and analytical robustness, we addressed our research questions through a dual analytical approach: (1) descriptive trend analyses based on patterns informed by a wide range of studies, regardless of whether they provided the quantitative data required for meta-analysis and (2) statistical meta-analyses based on subset of studies that provided more specific quantitative data. Moreover, we aim to assess not only the response of traditional performance indicators such as survival and growth, but also of physiological indicators such as water potential, one of the most commonly used indicators for water status (De Swaef et al. 2022). When adapted to specific contexts, needs, and site conditions, these results can help inform general recommendations for large-scale forest restoration initiatives.

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This study was conducted within the framework of the SUPERB project, which focused on providing evidence for guiding forest restoration in Europe. Consequently, our synthesis centers on the climate types relevant to the European context (i.e. dry, temperate, continental, and polar) (Peel et al. 2007), which largely include temperate (sensu Adams et al. 2019) and boreal forests (sensu DeAngelis 2008). To ensure more general insights, we focused on evidence from these climate types worldwide, regardless of the specific geographic location of the studies.

Methods

This study was conducted following the Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) guidelines for adequate reporting in systematic reviews (Page et al. 2021), and the extended guidelines of synthesis without meta-analysis (SWiM) to be used in systematic reviews when estimating effect sizes is either not possible or fully adequate (Campbell et al. 2020).

Literature Search

We organized the search string on the basis of the main components of the review question, following a modified version of the PICO framework (population, intervention, comparison, and outcome) (Richardson et al. 1995) (Table 1). Analogue searches were conducted in Web of Sciences (WOS) and Science Direct on 16th of May 2023, using the search fields described in Table 2, and formatted according to the requirements of each search engine (see Table S1 for viewing the actual search strings). To assess the suitability of the search string, we compared the search outcomes against a sample of five pre-selected studies published up to 2023 (Table S2). Specifically, we verified whether these studies, which were selected as representative examples of relevant research, appeared in the search results of at least one of the search engines used. If any relevant study was missing, we refined our search terms by either incorporating overlooked synonyms of key research components or adding wildcards (*) to the existing terms to capture alternative word endings.

Table 1. Components of the research question and their corresponding synonyms or related terms, following a variation of the PICO framework (population, intervention, comparison, outcome) (Richardson et al. 1995). Along the search string, the different components were linked with the Boolean operator "AND," whereas the synonyms of each component were linked with "OR." Wildcards (*) stand for alternative word endings for the corresponding terms. [a]A subject component was added to limit search results to the field of forestry and forest restoration, due to the large number of studies retrieved from both search engines.

Context	*Comparator*	*Outcome*	*Field*[a]
Restor*	Nurse	Survival	Forest
Afforest*	Shelter*	Growth	
Reforest*	Protect*	Performance	
Reafforest*	Assist*	Productivity	
Rehabilit*	Facilit*	Establishment	

Study Selection

After removing duplicates, we screened the complete list of studies by reviewing title and abstract, and discarded those studies that did not address the research questions. Subsequently, we conducted a full-text review of the remaining studies to evaluate the following inclusion criteria: (1) Peer-reviewed article from scientific journal; (2) full-text online availability; (3) written in English, Swedish, German, Spanish, French, Portuguese or Italian (i.e. the languages that the group of authors could cover); (4) based on field experiments; (5) conducted under one of the climate types occurring in Europe according to the Köppen classification (i.e. temperate, continental, dry, and polar) (Peel et al. 2007); (6) addressing a relevant review population sensu Page et al. (2021) (i.e. tree plantations established through reforestation or afforestation at sites without canopy cover); (7) conducting a relevant comparison (i.e. sown or planted tree species with vs. without nurse structures); (8) a relevant outcome was provided (i.e. indicators of survival, height growth, diameter growth, or water potential [leaf or stem]); (9) means and standard deviations of seedling or sapling performance indicators, or results of statistical tests, were provided.

As nurse structures we considered any aboveground structure (either organic or inorganic) whose potential was explored to shelter seedlings or saplings from recurring stressors such as drought or excessive exposure to sun, wind, frost, browsing, or trampling by wild herbivores, or competing vegetation. However, this excluded grass vegetation, which is often investigated for its competitive effects on tree regeneration rather than for facilitative sheltering functions, and thus falls outside the scope of this review focused on facilitation (Hoffmann & Haridasan 2008; Celis & Jose 2011).

Data Extraction

Although the definition of seedlings and saplings varies considerably across studies and contexts, most studies surveyed (95%) included individuals younger than 10 years. Because most studies did not clearly distinguish between seedlings and saplings, and because these categories are often applied subjectively, we hereafter refer to all planted individuals as *seedlings or saplings*, regardless of the specific classifications used in the original studies. Hence, we do not differentiate between the two stages in our analyses.

The selected studies used different response variables to evaluate the effect of nurse structures on the performance of planted individuals. From these, we extracted data on survival, height, height growth (height increment over time), diameter, diameter growth (diameter increment over time), and water potential, as

Table 2. Search fields in which each of the string components were searched for each database, and the corresponding number of records retrieved.

Database	*Search fields*	*Outcome (no. of studies)*
Web of Science	"All fields"	2450
Science Direct	"Title, Abstract"	143

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indicators of performance. Each reported outcome for a given response variable within a study was treated as a separate observation. Based on the data provided, each observation was classified as reporting a significant ($p < 0.05$) or a null effect (i.e. no significant effects), and significant effects were classified as positive or negative. Positive or negative effects were recorded when the use of a nurse structure led to a statistically significant increase or decrease, respectively, in the reported response variable.

Several studies also used multiple response variables as indicators of performance. Thus, a single study could report multiple observations, and as a consequence, the total number of observations was larger than the number of studies included. Additionally, studies often addressed multiple subjects to determine the response of seedlings or saplings to nurse structures (e.g. seedlings or saplings of multiple species or species varieties, different ages, under different additional treatments that were not necessarily relevant for this review, or on different experimental sites), and provided separate results in each case.

For meta-analyses of the effects of nurse structures on the response variables, we extracted the means and standard deviations of the corresponding variable with and without the influence of the nurse structure, as well as the sample sizes involved, whenever this information was available. When only available in graphical format, the means and standard deviations were obtained using WebPlotDigitizer (Rohatgi 2022). When SE values were provided, these were transformed into standard deviation by multiplying them by the square root of the sample size.

Data Analysis

Our study was based on a dual analytical approach that combined trend analyses and meta-analyses. The trend analyses were not intended as inferential statistical tests, but rather as a descriptive synthesis of the direction and frequency of reported effects across the available evidence base, as recommended for SWiM (Campbell et al. 2020). This type of analysis was included to increase the representativeness of the review. Because of their minimal data requirements, trend analyses allow the inclusion of a substantially larger number of studies that address the research question through sound experimental designs and hypothesis testing, but do not report the specific quantitative information required for meta-analysis. In contrast, meta-analyses, while offering stronger inferential power, can usually be conducted only on a subset of the available literature. By integrating both approaches, we aimed to provide a more balanced and informative assessment of the influence of nurse structures that benefits both from the higher inferential strength of meta-analyses and from the broader representativeness and contextual depth of trend analyses.

Our analyses focused on the effects of nurse structures on the response variables survival, height growth, diameter growth, and plant water status. Although growth is ultimately reflected by size variation over time, a substantial proportion of studies used instantaneous size measures as proxies for growth when comparing seedling or sapling performance across treatments. Because our objective was to analyze broad trends rather than responses of highly specific variables, and in order to avoid making our analyses and results overly complex, we grouped height and height growth as indicators of height growth, and diameter and diameter growth as indicators of diameter growth.

Trend Analyses. For each response variable, we quantified the frequency of null, positive, and negative effects of nurse structures and expressed it as proportions of the total number of observations (Page et al. 2021). To prevent biasing the results toward studies evaluating the effect of nurse structures on multiple subjects (and thus, with a higher number of observations), the output or contribution of each observation to the overall frequencies for a specific response variable was weighted by dividing it by the total number of observations addressed in the corresponding study for the corresponding response variable. Finally, when the response variables were measured repeatedly over time, only the last comparison among treatments was considered, unless the measures were repeated over a long time (>10 years). In this case, all measurements were registered and weighted as described above, to capture responses both during and beyond the establishment phase.

To determine the influence of potential effect moderators (i.e. variables potentially affecting the effect of nurse structures on regeneration performance), we compared the overall frequency of positive, negative and null effects on seedling or sapling performance between groups of observations stemming from plantations of different ages (<1 years; > = 1 and < 2 years; > = 2 and <5 years; > = 5 years), climates (temperate; continental; dry; polar), and species types (shade-tolerant vs. shade-intolerant; conifer vs. broadleaf). We also compared outcomes based on the type of shelter used (living plants; plant residues; artificial shelters), and the environmental stressor that nurse structures were aimed to buffer (drought and/or sun exposure; frost; wind; browsing and/or trampling by wild herbivores; competing vegetation). While alternative age classes are possible, our choice of age thresholds aimed to capture ecologically meaningful transitions in early tree development, from which the first year proves particularly critical for survival and establishment (Leck et al. 2012). Furthermore, although seedling recruitment varies widely across species and communities, we considered 5 years to be a meaningful threshold for plantations in open environments of temperate and boreal forests, after which the most sensitive phase of the plant life cycle is overcome (Eriksson & Ehrlén 2012). To determine in which climate type each study was conducted, we used the coordinates provided in the corresponding study, and overlayed them with the world map of the Köppen-Geiger climate classification by Peel et al. (2007). Shade tolerance of tree species was assigned based on descriptions in the original studies, and when absent, we used Google's aritificial intelligence Overview tool to retrieve summaries from authoritative sources.

To examine whether study sample size influenced the likelihood of detecting significant effects, we computed the point-biserial correlation between-study sample sizes and the presence of significant effects. This correlation measures both the

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strength and direction of the association between a binary variable (i.e. whether an effect was significant) and a continuous variable (i.e. study sample size). A positive correlation would indicate that larger studies tend to report more significant effects, potentially reflecting a sample size bias (Tate 1954; Kornbrot 2014).

Meta-analyses. In addition to trend analyses, we performed meta-analyses to quantitatively assess the magnitude and direction of the effects of nurse structures on the response variables. A minimum of five studies per response variable was required to conduct a meta-analysis. These had to report means and standard deviations for the respective response variable, along with the corresponding sample sizes. Employing the "Metafor" R package (Viechtbauer 2010), we used these data to calculate Hedges' *d* (Hedges & Olkin 2014), an effect size metric to compare mean effect sizes obtained with and without nurse structures. As a standardized metric, Hedges' *d* enables the comparison of treatment effects across response variables originally measured in different scales. We used random effects models to estimate the mean effect sizes, in order to account for the within-study variance (i.e. the sampling error) and the between-study variance (Borenstein et al. 2021).

For studies reporting the response of a certain variable in interaction with additional factors (e.g. for plantations of different species, under different fertilizing treatments, or at different locations), we aggregated the reported effect sizes into a single combined effect size per study with the "aggregate" function from the "Metafor" R package. This function summarizes the effect sizes of multiple observations from a single study to prevent biasing meta-analysis results toward studies with multiple observations. In this case, the multiple outcomes from the corresponding study were assumed to be independent from one another (Viechtbauer 2010).

To determine the influence of effect moderators, for each response variable, we conducted separate meta-analyses with studies grouped according to plantation age (<1 years; > = 1 and < 2 years; > = 2 and < 5 years; > = 5 years), climate type (temperate; continental; dry), and target species type (shade-tolerant vs. shade-intolerant; conifer vs. broadleaf), whenever there were at least five observations per response variable within these groups. We also conducted separate meta-analyses based on the type of nurse structure used (natural; artificial), and the type of stressor that nurse structures were expected to mitigate (drought and/or sun exposure; frost; wind; browsing and/or trampling by wild herbivores; competing vegetation). Unlike for the trend analyses, observations assessing the effects of plant residues as nurse structures were merged with those assessing living plants under the category of "natural" nurse structures. This was necessary because fewer than five observations on plant residues provided the quantitative data required for inclusion in the meta-analyses. Similarly, no separate meta-analyses were conducted for the polar climate type, as the total number of studies providing the required data was less than five.

With regards to the comparisons among plantations of species with different levels of shade tolerance, here we did not use aggregated effect sizes by study, since unlike for the other moderators, a large proportion of studies (36%) reported effects of nurse structures for both shade-tolerant and shade-intolerant species. Aggregation would thus have obscured much of the intra-study variability related to this factor. Hence, to compare results among these classes, we treated all observations as independent from one another, regardless of whether they stemmed from the same study or not. Also in this case we applied random effects models to account for inter-study variance (Borenstein et al. 2021).

For all meta-analyses, we considered the effect of nurse structures to be statistically significant when the associated *p* value was below 0.05.

Results

From the 2593 studies obtained from both databases, 103 were discarded as duplicates. Further 2033 were discarded after screening the title and abstract. The remaining 457 studies were subjected to full-text reviewing. Following the inclusion criteria for this stage, 82 studies were finally considered relevant and used for data extraction (Fig. S1; Supplement S2). All these studies were used in the trend analyses, while 52 studies were suitable for meta-analyses.

Overview of the Evidence Base

The studies finally included in this review span from 1998 to 2023. The number of publications per year shows an increasing trend, rising from one study per year in 1998 to six studies per year in 2022 (Fig. S2). Geographically, most studies were conducted in Europe (33), North America (24), and the Southern Cone of South America (12), with the European studies largely concentrated in southern Europe, particularly Spain (23). In contrast, only a few studies stemmed from Oceania (5), Asia (3), and Africa (1) (Fig. 1). The vast majority of studies were carried out in temperate regions (69%), followed by continental (15%) and dry regions (13%), and only a minor percentage (4%) was conducted in polar regions.

In most studies (72%), nurse structures were meant to protect against drought and sun exposure. This was mostly the case for studies in dry regions, all of which regarded drought or excessive exposure to sunlight as a stressor to young trees. Browsing or trampling by wild herbivores was the second most frequently named stressor, followed by competing vegetation, frost, and wind, with 39, 21, 13, and 11% of the included studies mentioning these factors, respectively (Table 3).

Regarding the nature of the nurse structures, 43% of the studies assessed the effects of natural structures, most of them (86%) in the form of nurse plants (trees, shrubs, or herbaceous plants other than grass), and a lower number (14%) originating from plant residues such as deadwood or crown material from felled trees. Meanwhile, 52% of studies focused on artificial structures, including tubes (88%), meshes (9%), and shade cloths (3%). The remaining 5% of studies examined both natural and artificial structures. Among the studies employing tubes, 24% employed vented tubes (i.e. featuring pores or holes), and 76% employed non-vented tubes (Fig. S3).

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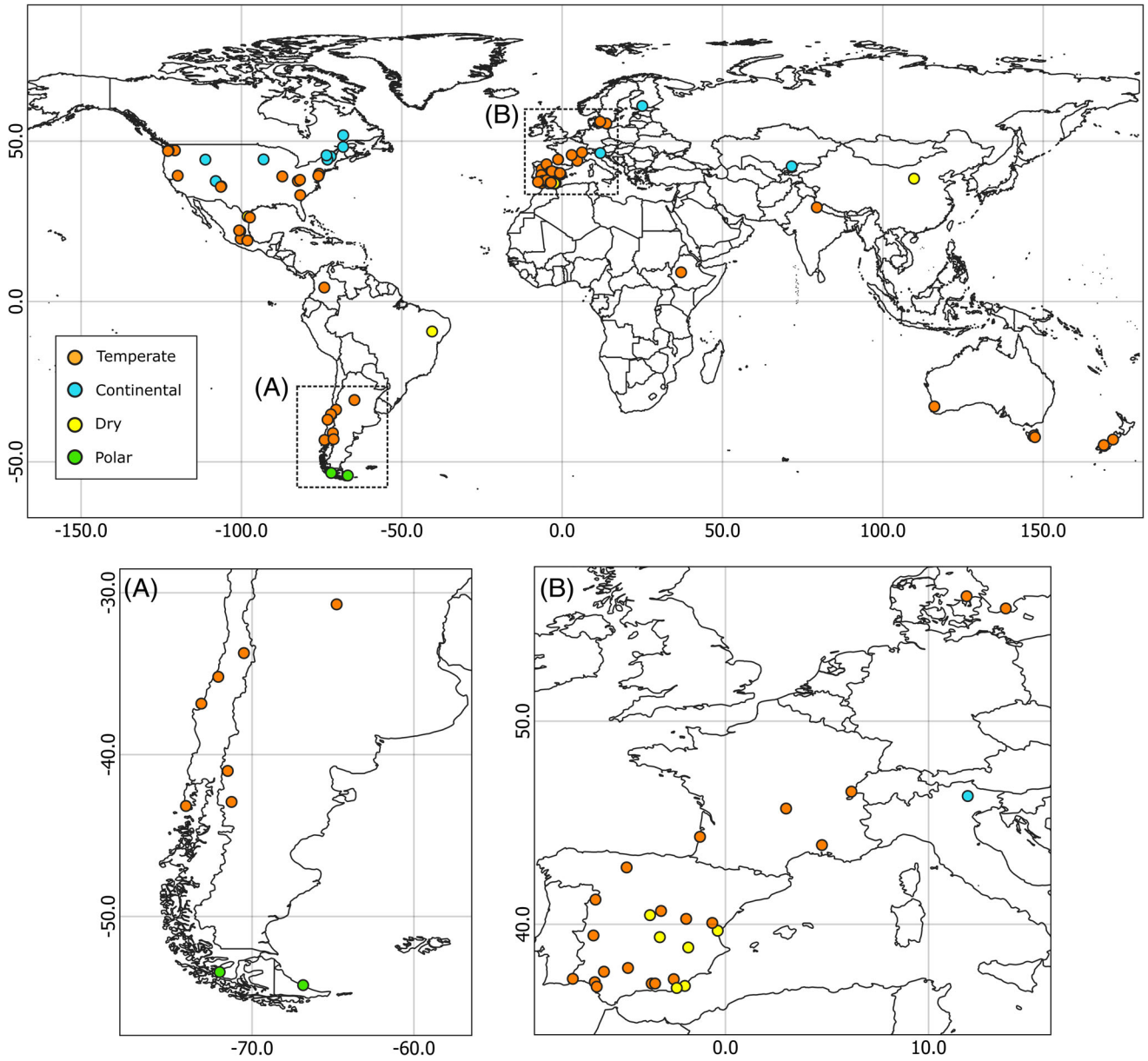

Figure 1. Location of the studies included, classified according to their Köppen climate type (Peel et al. 2007). Due to the high concentration of studies in some specific regions (e.g. Europe, South America, or North America), some points are not visible.

Most studies examined the effects of nurse structures on broadleaved species (63%), while fewer studies focused on conifers (23%) or both types (13%). 45% of the studies focused on shade-tolerant species, 23% on shade-intolerant species, and 32% included both types. Finally, the maximum tree age at which measurements were recorded ranged between 2 months and 20 years, with an average of 3.2 years (standard deviation = 3.0). Regarding the pre-defined age classes described above, 9% of the studies reported results for plantations younger than 1 year, 24% for plantations aged 1–2 years, 48% for plantations aged 2–5 years, and 20% for those older than 5 years. Only two studies (2%) evaluated sowed seedlings or saplings, while all the evaluated planted individuals.

Response Variables

In total, 162 observations were obtained on the effects of nurse structures on artificial regeneration, which were used in the trend analysis. The main response variables comprised survival (69 observations), followed by height growth (50 observations), diameter growth (35 observations), and water potential (8 observations) (Fig. 2).

Effects of Nurse Structures on Performance

Trend Analyses. The overall trend analysis revealed significant effects of nurse structures on seedling or sapling performance in 54% of cases, with 45% cases showing positive effects and 9%

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Table 3. Frequency of the most common stressors that nurse structures were meant to buffer, expressed as the percentage of studies in which each stressor was described as relevant, within each of the different climate types.

		Frequency (%)				
Climate type	*No. of studies*	*Drought or sun exposure*	*Browsing or trampling by wild herbivores*	*Frost or low temperatures*	*Wind*	*Competing vegetation*
Dry	11	100	18	0	18	0
Temperate	56	71	41	14	5	18
Continental	12	58	50	17	25	50
Polar	3	33	33	33	33	33
Total	82	72	39	13	11	21

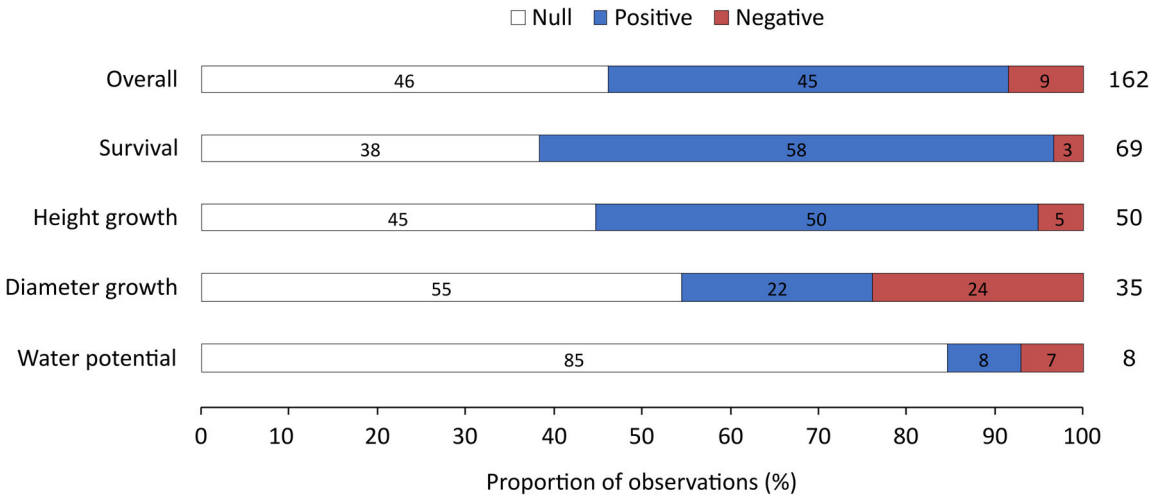

Figure 2. Frequency of observations indicating positive, negative, and null effects of nurse structures on seedling performance, for the different types of indices reported. Values within the bars indicate the frequency (%) of each effect type. Values on the right indicate the number of observations in each case. Percentages were calculated from either whole or weighted observations, depending on whether the studies reported outputs for multiple subjects.

negative effects. However, these values varied considerably across response variables. The highest proportion of significant effects was observed for survival (61%), followed by height growth (55%), diameter growth (45%), and water potential (15%). There were hardly any negative effects of nurse structures on survival and height growth (3% and 5% of total observations, respectively). Yet, more than half of the significant effects on diameter growth (52%), and nearly half of those on diameter growth (47%) are negative (Fig. 2).

When comparing the overall effects of nurse structures across different moderator variables (climate type, nurse structure type, environmental stressor, plantation age, target species shade tolerance, and target species type), the frequency of significant effects generally shows small variations relative to the overall trend. The largest variations were observed across climate types, environmental stressors, and plantation ages. Studies conducted in dry and especially in polar climates show a lower frequency of significant effects (40 and 27%, respectively) compared to the overall trend and to studies in temperate or continental climate types (58 and 53%, respectively). Regarding environmental stressors, significant effects of nurse structures are most frequent when mitigating competition (63%) and least frequent when protecting against wind damage (40%). With respect to plantation age, the highest frequency of significant effects was observed in plantations older than 5 years (64%), whereas frequencies in younger plantations ranged from 45 to 52%.

In contrast to climate types, environmental stressors, and plantation age, the overall frequency of significant effects varies little with nurse structure type, target species shade tolerance, or whether the target tree species are conifers or broadleaves. Differences among the classes of these moderators are also small. Similarly, the proportion of significant negative effects shows little variation among moderator classes, with the exception of plantation age. In this case, the proportion varies from 5% of observations in plantings between 1 and 5 years old to 15% in those less than a year old, and 20% in those older than 5 years. For all other moderator classes, the proportion of significant negative effects remained between 0 and 11%. Notably, none of the studies addressing shade-tolerant species reported negative effects of nurse structures, whereas 7% of studies addressing shade-intolerant species did (Fig. 3).

The point-biserial correlation between the sample size of the studies and the frequency of significant results was 0.16 ($p < 0.001$), indicating a weak positive association between these two variables.

Meta-analyses. ***Effects on Overall Performance.*** According to the meta-analyses, nurse structures have a significant positive effect on the overall performance of planted seedlings and saplings. This positive trend is consistent across climate types,

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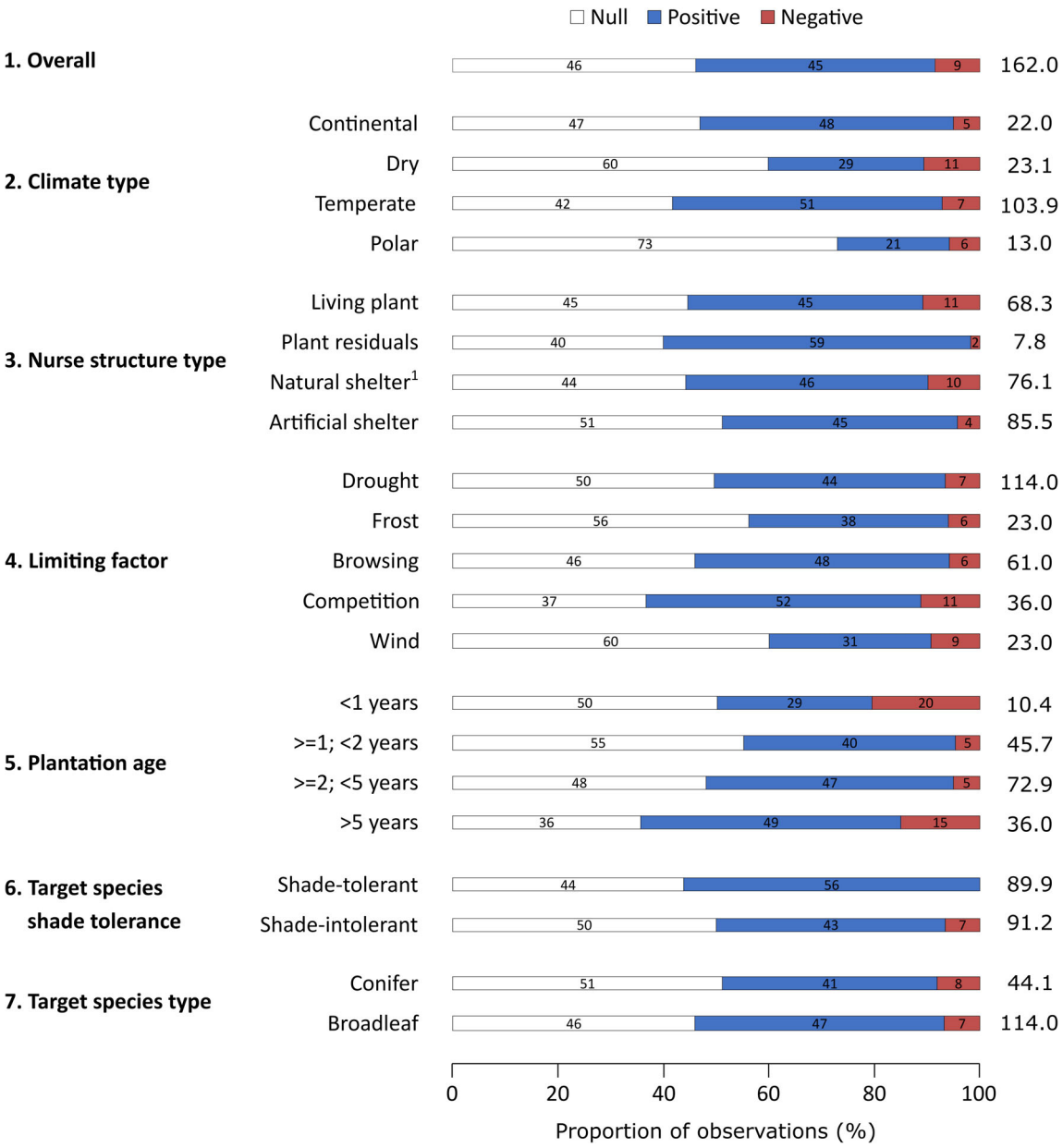

Figure 3. Frequency of observations indicating positive, negative, and null effects of nurse structures on the performance of plantations or planted individuals. Values within the bars indicate the frequency (%) of each effect type, while values outside the bars indicate the number of observations per moderator class. Decimal values result from weighting the outputs of observations based on the total number of observations per study, to avoid over-representing studies with multiple observations. [1]The moderator class "natural shelters" represents both plant residuals and living plants combined.

age classes, nurse structure types, target species types, shade-tolerance types, and the different types of environmental stressors. However, the positive effect is not statistically significant for studies in dry regions, planted trees older than 5 years, when using natural nurse structures, or when targeting the mitigation of competition and wind effects (Fig. 4).

Effects on Specific Response Variables. Nurse structures show a significant positive effect on both survival and height growth. These effects are consistent across all moderator classes, with only a few exceptions. In the case of survival, positive effects are not significant under dry climate. For the continental climate type, there were not enough studies to perform a specific meta-analysis on this response variable. In the case of height growth, positive effects are non-significant only for studies conducted in dry regions, for plantations older than 5 years, when using natural nurse structures, and when aiming to protect from competition (Fig. 4). The positive effects on height growth are particularly strong in studies involving shade-intolerant species, which show a substantially higher effect size (standardized mean difference [SMD] = 2.86) compared to those involving shade-tolerant species (SMD = 1.12).

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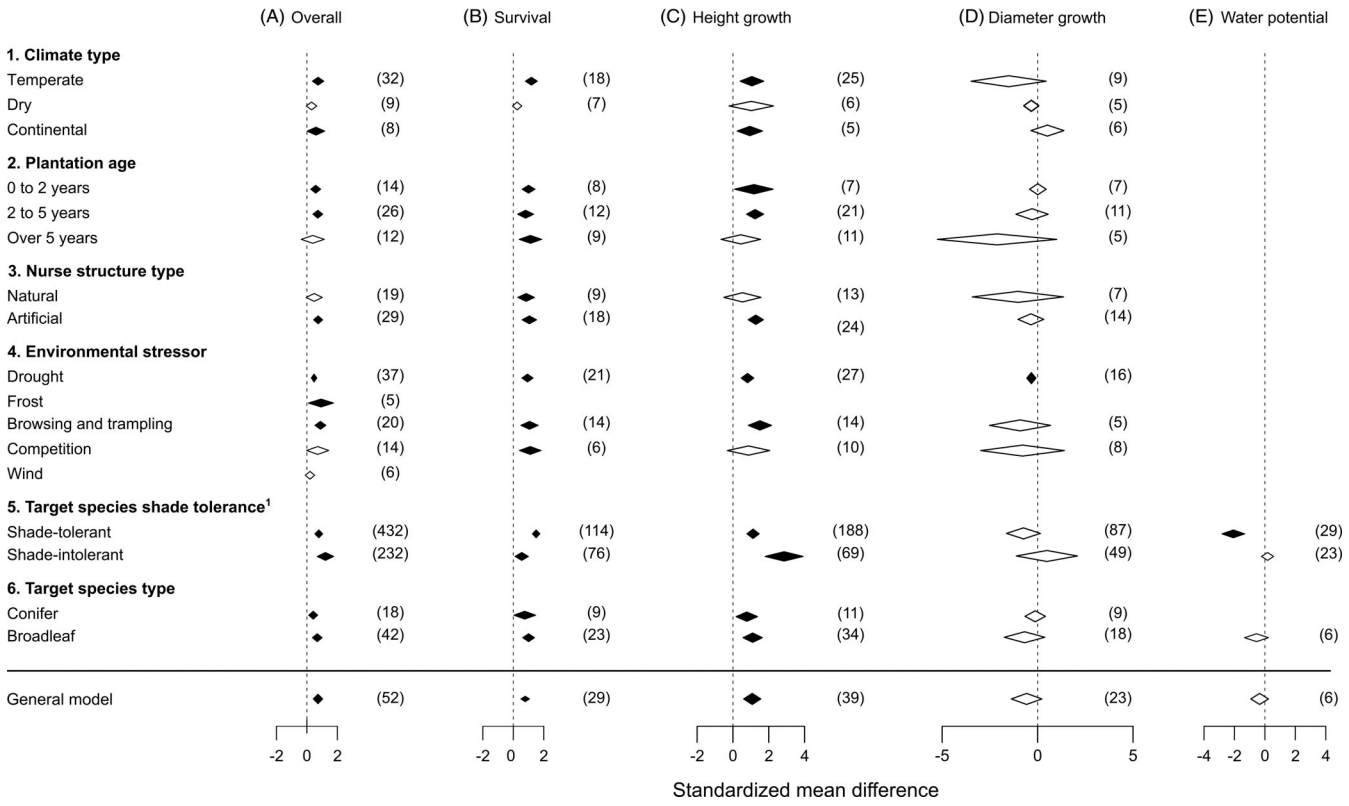

Figure 4. Forest plots of the meta-analyses on the effect of nurse structures (A) Overall, (B) on survival, (C) on height growth, (D) on diameter growth, and (E) on water potential of planted individuals. The figure shows the effect of presence versus absence of nurse structures, based on a random effects model, and expressed as standardized mean difference (SMD) (i.e. the difference between the means with and without nurse structures in standard deviation units). The centroids of the polygons indicate the point estimate of the combined SMD for each group of studies or observations, while their outer edges indicate the 95% CIs limits. Polygons not intersecting the null effect axis (depicted in black) indicate an overall significant effect of nurse structures. Polygons on the right side of the corresponding null effect axis indicate a positive effect, while those on the left side indicate a negative effect (Viechtbauer 2010). Moderator levels with fewer than five studies or observations were excluded. Numbers in brackets indicate the number of studies or observations in each case. Details on the studies employed in these analyses are provided in Supplement S2. [1]For comparisons among plantations of species with different shade tolerance, effect sizes were not aggregated by study, and observations were treated as independent from one another, regardless of whether they stemmed from the same study or not. As a result, the sum of observations for this moderator exceeds the total number of observations used in the overall meta-analysis.

In contrast to survival and height growth, both diameter growth and plant water potential show negative responses to the use of nurse structures, although these effects are not statistically significant, either overall or across most moderator classes. Exceptions include a significant negative effect on water potential for shade-tolerant species (unlike for shade-intolerant species), and a significant negative effect on diameter growth in studies addressing drought mitigation. For water potential, the number of studies or observations was particularly limited, allowing separate meta-analyses only for studies focused on broadleaf species, and both for those focused on shade-tolerant and shade-intolerant species (Fig. 4). The negative effects observed on diameter growth and water potential are less pronounced in studies with shade-intolerant species (SMD = 0.66 and SMD = 0.17, respectively) than those with shade-tolerant species (SMD = −1.98 and SMD = −2.08, respectively) (Fig. 4).

For the stressors frost and wind, the number of available studies was insufficient to perform meta-analyses for specific response variables (Fig. 4).

Discussion

General Patterns of Influences of Nurse Structures

Both the trend analyses and meta-analyses consistently indicate that nurse structures have predominantly positive effects on the performance of planted seedlings or saplings, in case significant effects occur. However, the trend analyses also show that in most cases, nurse structures have little or no impact, while in a lower number of cases the significant effects are actually negative. The weak correlation between sample sizes and occurrence of significant effects suggests that some of the non-significant effects may originate from studies with small sample sizes (type II errors), which may partly hide the true effect of nurse structures. Yet, the fact that the proportion of significant effects is fairly constant across moderator classes suggests that nurse structures can be applied under a variety of conditions with a high probability of facilitating regeneration and a low risk of adverse effects. When examining specific response variables, both the trend analyses and the meta-analyses indicate that nurse structures are most effective in enhancing seedling or sapling survival and height growth. By contrast, diameter

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growth and water potential are less responsive to nurse structures. Moreover, these two variables most frequently show negative responses, accounting for a substantial share (64%) of the overall negative effects informed by the general trend analyses.

Furthermore, our findings are consistent with theories on biomass and carbon allocation hierarchies in trees, where respiration and metabolism are prioritized to ensure survival and plant functioning. Within this hierarchy, allocation to plant organs that facilitate acquisition of limiting resources is typically prioritized. Under shaded conditions such as those potentially caused by nurse structures, height growth is prioritized over diameter growth (Oliver & Larson 1996). This is particularly the case for shade-intolerant tree species, for which the prioritization of height growth at the expense of diameter growth may even negatively affect the latter (Giertych et al. 2015; Kang et al. 2021). Accordingly, nurse structures should have particularly strong positive effects on height growth and negative effects on diameter growth of shade-intolerant species. This is partly supported by our meta-analyses: shade-intolerant species show higher effect sizes of nurse structures on height growth. However, they do not show lower effect sizes on diameter growth than shade-tolerant species, as would be expected.

Meanwhile, the lower and partly negative influence of nurse structures on water potential may be related to the type of nurse structures used. Most of the observations reporting negative effects on water potential (81%) stemmed from studies focusing on living plants as nurse structures. When using nurse plants to protect seedlings or saplings from wind, sun, or frost exposure, the nurse plants may eventually compete with the target tree species for belowground resources, thereby constraining water availability. This may be particularly the case under drought-prone conditions or in the presence of a dense nurse vegetation (Franco & Nobel 1988; Al-Namazi et al. 2017). The other 19% of observations reporting negative effects of nurse structures on water potential focused on the effects of transparent tube shelters on oak species regeneration in Mediterranean Spain (Oliet et al. 2021). Artificial shelters, especially when made of transparent materials and with lack of ventilation, may trap solar radiation, leading to a build-up of heat and to plant desiccation (Bergez & Dupraz 2009). While it may seem surprising that the meta-analyses show significant negative effects particularly for shade-tolerant species, this pattern may reflect their comparatively low tolerance to heat and water stress (e.g. owing to traits such as thin leaves or shallow root systems), which can make them more susceptible to heat buildup in shelters or to belowground competition with nurse plants (Gale & Grigal 1987).

It could be argued that differences in regeneration stage between direct sowing and tree planting may contribute to variation in responses to nurse structures, as direct sowing includes the germination and early establishment stages, which are particularly vulnerable to environmental stressors (Leck et al. 2012). Nevertheless, because only two of the selected studies evaluated direct sowing, this factor likely had only a limited influence on the overall patterns identified in this review.

Influence of Moderators on the Effects of Nurse Structures

According to the trend analyses, the overall response of seedlings and saplings to the presence of nurse structures is fairly constant across nurse structure types, shade-tolerance levels of the planted species, and types of species (conifers or broadleaves). In contrast, the response differs more notably among climate types, environmental stressors that nurse structures aim to mitigate, and plantation age classes.

Influence of Climate Type. The lower response to nurse structures in dry regions is consistent with the lack of significance in the positive trend informed by the meta-analyses in dry regions. This pattern, which holds for response variables survival and height growth, was rather unexpected. In accordance with the stress-gradient hypothesis, nurse structures should be most effective under extreme conditions (Bertness & Callaway 1994), as was also found in experimental reforestations in southeast Spain (Gómez-Aparicio et al. 2004), indicating stronger effects of nurse shrubs under drier conditions. The fact that we did not observe this pattern in our results might be explained by an overriding role of water limitation in arid environments when comparing studies or observations across a broader regional scale, which may outweigh the benefit of shading and wind protection provided by nurse structures (Carvajal et al. 2014; Kremer et al. 2019). Also, some artificial shelters might create unfavorable microclimates through buildup of heat (Bergez & Dupraz 2009), while nurse plants may directly compete with the target species for water and nutrients. This may be particularly the case in dry environments (Hunter 1989; Holmgren et al. 1997). Furthermore, many drought-adapted tree species from dry regions are also shade-intolerant, leading to reduced photosynthetic activity under the shade of nurse structures (Niinemets & Valladares 2006).

Influence of Plantation Age. The meta-analyses indicated that the positive effects of nurse structures are strongest at younger plantation ages, particularly within the first 5 years. Shortly after establishment, seedlings and saplings are most vulnerable to environmental stressors and can most strongly benefit from protection against harsh abiotic conditions (Margolis & Brand 1990; Leck et al. 2012). This might seem to contradict the results of the trend analyses, according to which positive significant effects are most frequent in older plantations (>5 years). However, this age class simultaneously shows the second highest frequency of significant negative effects, likely as a result of the onset of competitive interactions with nurse structures (Miriti 2006; West 2014). The higher frequency of both positive and negative effects in this age class might actually explain that the meta-analyses do not detect a clear significant positive effect for this age class, as meta-analyses evaluate net effect direction.

Influence of the Nurse Structure Type. The positive trend in survival and growth responses to both natural and artificial nurse structures is consistent with previous syntheses of the effects of nurse plant (Gómez-Aparicio et al. 2004) and artificial shelters (Abe 2022). Specifically, the significant positive effects of artificial shelters on survival rates and height growth, together with the absence of significant effects on diameter growth, align with the findings of Abe (2022). In contrast, the lack of statistical significance informed by our meta-analyses in the positive

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response of overall performance to natural nurse structures suggests that these may be less effective than artificial structures in enhancing seedling or sapling performance. As indicated by the trend analyses, this pattern is most likely driven by the higher frequency of negative effects associated with (living) nurse plants, since negative effects linked to plant residues were very rare. This supports the idea of competitive interactions between the nurse and the target plants (Franco & Nobel 1988; Al-Namazi et al. 2017). However, the separate meta-analyses for individual response variables indicate that this does not hold for survival, which benefits significantly from both natural and artificial structures. Thus, the lack of overall significance is most likely given by the negative trend and higher variability of the effect size observed for both height and diameter growth.

Effects of Nurse Structures According to the Environmental Stressor. According to the meta-analyses, nurse structures are largely effective when aiming to protect against drought, frost, and browsing or trampling damage, which is most evident in the response of survival. The lack of significant effects of nurse structures when aiming to protect young trees from wind is consistent with the trend analyses, according to which nurse structures are least effective in protecting against this factor. However, this may result from the limited number of studies focused on wind as an environmental stressor, leading to low statistical power. In fact, the small number of studies addressing wind protection prevented further inferences regarding the response of individual performance variables. Eventually, some shelters, particularly artificial ones, may not be designed specifically to block wind, especially due to their porosity and/or limited height (Taylor et al. 2009; Urretavizcaya & Defosse 2013). In addition, wind effects are more difficult to measure in relation to nurse structures when compared to factors such as light, soil moisture, or frost (Heisler & DeWalle 1988). As a result, wind is often not monitored directly, and any presumed benefits for seedlings tend to be based on assumptions rather than empirical data.

The lack of significant effects of nurse structures in mitigating competition informed by the meta-analyses is largely explained by the high variability in the effect sizes on both height and diameter growth. In contrast to survival, these growth metrics exhibit non-significant responses to nurse structures. This might partly be due to the complexity of quantifying competition. It is worth noticing that 71% of studies aiming to reduce competition employed artificial shelters. These structures can help secure aboveground growing space for seedlings and minimize branch interference from neighboring vegetation, but may still permit belowground competition, particularly with herbaceous plants or grasses (Dick et al. 2016; van Galen et al. 2023).

Influence of the Target Species Functional Type. According to our results, nurse structures significantly enhance the performance of regenerating tree species of different functional types, regardless of whether they are conifers or broadleaves, shade-tolerant or shade-intolerant. While specific physiological or ecological traits may influence the strength of the response, they do not substantially alter the overall positive trend. This highlights the broad applicability of nurse structures as a facilitative tool in forest regeneration across species with contrasting characteristics.

Knowledge Gaps and Future Research

Beyond providing an overall response on the effectiveness of the use of nurse structures, the broader scope of this review enabled a synthesis and comparison of findings of studies across different contexts and nurse structure types with a transparent analytical approach. Its results provide evidence to inform case-specific decision-making across a range of conditions, while also allowing guidance for future research priorities.

Specifically, our review has identified several important knowledge gaps. Geographically, it reflects an unequal distribution of evidence across climate types, with most studies stemming from temperate regions, which highlights the importance of further research in dry, continental, and polar regions, especially on the effectiveness of nurse structures for mitigating the specific environmental stressors from those regions. In particular, the lower relative abundance of studies in dry regions may seem contradictory to previous reviews on the effects of nurse structures such as Shemesh (2025), in which the majority of studies stemmed from such climate types. However, the more specific inclusion criteria we used for a quantitative analysis, as well as the inclusion of artificial shelters and living plants in our review, may explain the differences.

Furthermore, the low number of studies on plant water status, compared with the predominance of studies assessing survival and growth, suggests that there may be a lack of studies addressing functional aspects, which may in fact help explain the patterns observed for these variables. This limitation becomes particularly evident in view of the low number of studies on plant water status as influenced by nurse structures. Aside from light and water availability, little is known about how nurse structures influence broader microsite and ecological conditions, such as air temperature, wind, and overall competition pressure. Consequently, it is difficult to determine against which specific environmental stressors nurse structures provide protection, beyond the assumptions made in the original studies.

When aiming to enhance seedling performance, practitioners need clearer guidance for selecting the most suitable types of nurse structures, and to determine which structural features are best suited to specific site conditions or stressors. Research should therefore focus on determining how nurse structures specifically mitigate specific environmental stressors. However, studies rarely compare different types of nurse structures directly, and the results obtained here rely largely on cross-study comparisons, which are inherently influenced by inter-study variability. Thus, future research should prioritize experimental designs that directly compare different nurse structure types within consistent ecological contexts, while broadening the range of response variables and microsite conditions assessed. This would help clarify which features are most effective under which conditions, enhancing the practical utility of nurse structures in forest regeneration.

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Supporting Information

The following information may be found in the online version of this article:

Supplement S1. Surveys to stakeholders of the SUPERB Project.
Supplement S2. List of included studies and associated data.
Table S1. Search strings used in each of the different search engines.
Table S2. List of pre-selected studies against which the search results were compared to verify the inclusion of relevant articles.
Figure S1. Flow diagram of the study selection process.
Figure S2. Number of included studies per year addressing the effects of nurse structures on the performance of reforestation and afforestation plantings in temperate and boreal forests.
Figure S3. Number of studies per type of nurse structure.

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