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Influence of façade orientation, floor height, substrate pH, and microbial inoculation on woody plants' performance in vegetated façades in Southern Finland

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A R T I C L E I N F O

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A B S T R A C T

Urban densification has led to the adoption of vegetated façades as a nature-based strategy to increase urban green spaces and enhance urban living conditions. However, limited knowledge regarding suitable plants for vegetated façades can impede the process. In this field experiment conducted in Southern Finland, we investigated the performance of 12 potential plant taxa for a vegetated façade by assessing their visual appearance and sizes in relation to façade orientation, floor height, substrate pH, and mycorrhizal inoculation. The 12 plant taxa were categorized into 4 growth forms according to their morphologies: spreading conifers, dwarf conifers, creeping conifers, and climbers. We aimed to evaluate plant performance during the initial two growing seasons, which is critical for the successful establishment of these plants in vegetated façades. Eight of the twelve plant taxa exhibited relatively high performance in terms of visual appearance and size. Notably, creeping conifers outperformed other growth forms in visual appearance, which was most likely due to their close-to-ground morphology. Façade orientation and substrate pH were the most influential predictor variables. Façade orientation affected both plant visual appearance and size, while substrate pH primarily affected plant visual appearance. The east-facing façade (less exposure to sun and wind) and mildly acid substrate (pH 6–6.5) were more conducive to most of the plant taxa. Certain species and cultivars, such as *Juniperus communis* 'Lalli', maintained constant plant visual appearance and size regardless of façade orientation and substrate pH, suggesting their adaptability and stability across various conditions. Floor height and mycorrhizal inoculation only displayed marginal and taxon-specific impacts. Given that some plants in our vegetated façade exhibited optimal performance different from those in their reported natural habitats, we encourage conducting long-term, on-site experiments to identify suitable plants for vegetated façades to ensure successful vegetated façade implementation.

1. Introduction

Green infrastructure incorporating diverse forms of urban greenery is an important consideration to mitigate several environmental problems exacerbated by urbanization (Aronson et al., 2017; Miroshnyk et al., 2022). Urban densification has resulted in sparse, uneven, and fragmented green infrastructure, which negatively affects the ecosystem services delivered by them across the globe (Francis and Lorimer, 2011;

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Haaland and van den Bosch, 2015; Wang et al., 2022). Yet, there is a high demand for ecosystem services in urban areas (Almenar et al., 2021; Shu et al., 2022). To meet this challenge, vertical greenery systems (VGSs) (Safikhani et al., 2014) have been prescribed by researchers and designers (Francis and Lorimer, 2011; Pérez-Urrestarazu et al., 2015). By providing permanent and diverse vegetation on vertical building surfaces, VGSs could substantially supplement ground-level green spaces (Sadeghian, 2016; Xie, 2020; Xie et al., 2022a; Shu et al., 2023). Based on the types of supporting structures and different plant species, VGSs are generally classified into two groups: vegetated façades (also known as green façades) and living walls (Fernández-Cañero et al., 2018; Pérez et al., 2014).

Similar to vegetated roofs (VRs), VGSs could also provide multiple ecosystem services, including preserving energy via insulation, improving air quality, managing stormwater, alleviating the urban heat island effect, increasing urban greening and aesthetic values, and improving urban biodiversity (Pérez-Urrestarazu et al., 2015). Naturally, the key to the successful provision of ecosystem services via VGS is plant performance, including plant size (canopy width and height/-length), visual appearance (damage level), and diversity. Therefore, efforts are made to improve plant performance in VGSs and VRs. For example, Chung et al. (2021) experimented with substrate properties (composition and depth) and vegetation container design (size and geometry) to increase the plant-rooting volume that in turn significantly influenced the growth and cover of climbing plants during the early establishment of a green façade. Our previous research suggests that plant size could be enhanced by applying plant growth-promoting microbes in VRs and VGSs (Xie et al., 2018, 2020, 2022b). Another way to enhance plant performance at the community level is by incorporating diverse plant species in VRs and VGSs. Findings from a study by Lundholm et al. (2010) demonstrated that plant communities comprising a variety of species are more resilient to disturbances and environmental stressors, resulting in increased plant coverage and biomass and ultimately leading to enhanced ecosystem services of VRs. The relationships among plant diversity, vegetation structural complexity, and performance of VRs have been elucidated by Cook-Patton and Bauerle (2012).

Although research on VRs has accelerated during the past two decades, such knowledge cannot simply be generalized to VGSs, as growing conditions differ from those on rooftops. Therefore, experiments specifically conducted in VGSs are indispensable to provide empirical evidence for wide application of VGSs (Xie et al., 2022a; Shu et al., 2023). Furthermore, although researchers have stressed the importance of maintaining high plant species diversity in VRs and VGSs, the plant taxa hitherto identified as suitable for VRs and VGSs remain limited (Lausen et al., 2020). Sedums, mosses, grasses, and climbers dominate the plant list. Despite evidence supporting the use of woody plants in urban greening for human well-being (Shackleton et al., 2015), little is known about whether woody plants, such as conifers, could survive in VRs and VGSs (Wang et al., 2020). Incorporating evergreen conifers into VGSs not only offers a range of benefits that other plant types cannot replicate but also guarantees year-round coverage, ensuring uninterrupted ecosystem services and aesthetic appeal (Clapp et al., 2014). Also, while numerous studies have explored the impact of abiotic factors on plant development (Chaudhry and Sidhu, 2022), limited research has been conducted on the influence of growing conditions on building façades, for which the most obvious proxies are façade orientation and floor height. These proxies can be used to explore the impact of different growing conditions due to, e.g., temperature fluctuations, wind exposure, and solar radiation, which affect plant performance in VGSs. Lastly, it is beneficial to explore plant survival during the early stages of VGSs as plant mortality of woody plants is highest during the establishment phase in urban greening, which can lead to increased maintenance costs, including removing and replacing dead plants (Wattenhofer and Johnson, 2021). Hence, conducting VGS experiments that consider both biotic and abiotic factors is essential for gaining insights into growing and maintaining young woody plants and improving the future success of VGSs (Wattenhofer and Johnson, 2021).

In the present study, we evaluated the performance of 12 plant taxa in vegetated façade containers in a block of flats in Helsinki, representing four distinct plant growth forms: spreading conifers, dwarf conifers, creeping conifers, and climbers. We hypothesize that 1) plant visual appearance and size are affected by façade orientation, floor height, substrate pH, and mycorrhizal inoculation; 2) the visual appearance and size of different growth forms respond to these environmental variables differently, yet taxon-specific responses are also expected; 3) creeping conifers might be especially resilient due to their growth form close to the substrate that allows them to endure harsh conditions, such as wind.

2. Materials and methods

2.1. Study site and experimental design

Our research was carried out at a residential complex (Greenest of the Green, https://oppla.eu/casestudy/18875), which is part of the City of Helsinki Developing Apartment Building Program (in Finnish: Kehittyvä kerrostalo -ohjelma). This residential complex, located in Jätkäsaari in the City of Helsinki, Southern Finland (60°09’19.0"N, 24°54’56.6"E), aims to offer residents a green and biodiverse living environment via VRs and vegetated façades (Appendix Fig. A1). Here, we focus on vegetated façades, i.e., the vegetation containers illustrated in Fig. 1. Completed in October 2017, the vegetated façades consist of 112 vegetation containers, each measuring 138.5 cm × 124.5 cm × 70 cm in size. The vegetation containers are distributed on three building façades at seven different floor heights, with 35 containers facing south (azimuth angle $\gamma = 8.6°$), 38 facing west (azimuth angle $\gamma = 72.2°$), and 39 facing east (azimuth angle $\gamma = 280.0°$). Each vegetation container was constructed with nine components, including a substrate layer, an irrigation system, and a drainage system (Fig. 1). When we conducted the inventories, there were no buildings in any of the three orientations, preventing the likelihood of being shaded by nearby structures. This ensured full exposure of each façade to unobstructed wind and sunlight.

The selection of the 12 plant taxa for our experiment was driven by the role that vegetated façades play in supporting local urban biodiversity and providing habitats for other flora and fauna (Aronen et al., 2009; Madre et al., 2015). Based on the NOBANIS database (https://www.nobanis.org/) (Table 1), none of the selected species were invasive or potentially invasive in the Baltic region, and they are commonly used in Finnish landscape design. The idea was that the 8 evergreen conifers could provide continuous coverage even during cold winters, and that the 4 deciduous climbers could quickly cover the vertical façades every growing season and provide aesthetic value. According to their growth forms, the 12 plant taxa were divided into 4 groups: 1) spreading conifers featuring vertical growth in a vase-shape form, 2) dwarf conifers featuring a globose shape with a flat top, 3) creeping conifers featuring horizontal growth covering the ground, and 4) climbers. The categorization of conifer growth forms is based on the literature (Relf & Appleton, 2000) and information provided by Finnish nurseries. Before installing the plants, the mean heights of creeping conifers were below 14 cm, while the mean heights of spreading and dwarf conifers were above 15 cm. Five to 11 individuals were planted in each vegetation container, including conifer and climber species. In total, 797 individuals were planted. The size of the individuals varied considerably at the time of planting as plants with uniform sizes were not available in sufficient amounts. To correctly identify the 797 individual plants, each plant was given a unique ID number.

According to a literature review, conifer species (*Picea* and *Juniperus*) grow best in substrates with pH 3.7–6.0 (Fejér et al., 2018; Parzych et al., 2018), while *Clematis* and *Humulus* species with pH 6.5–7.0 (Relf and Appleton, 2001; Nath et al., 2022). Therefore, we studied the effects of substrate pH on plant size and visual appearance in our vegetated

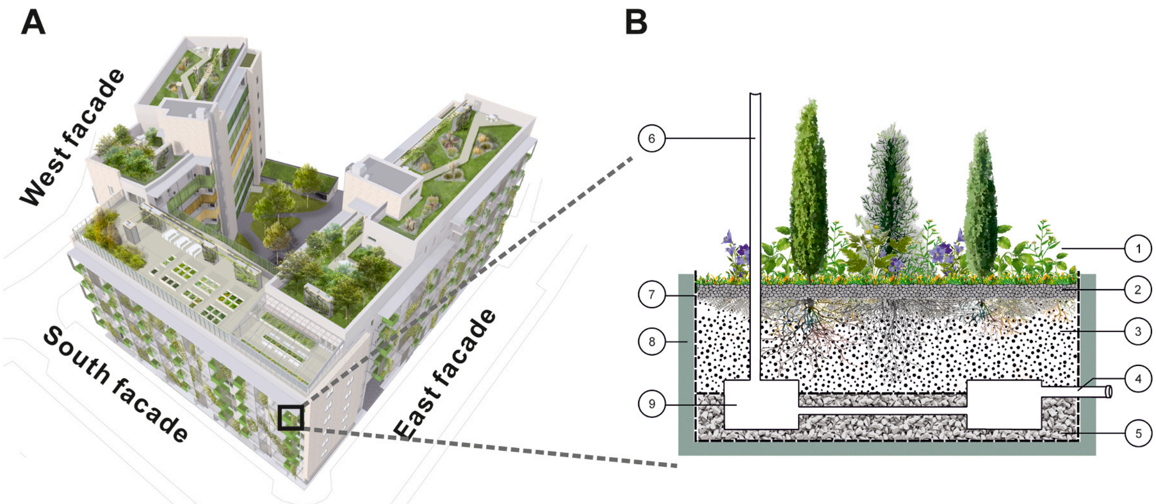

Fig. 1. Experimental layout of the vegetated façade: a 3D model of the building with vegetated façades (A) by Talli Oy; and a cross-section of a vegetation container (B). Each vegetation container consisted of the following components: ① plants; ② 5 cm cover layer with gravel; ③ 40 cm substrate; ④ water outlet; ⑤ 10 cm gravel drainage layer; ⑥ watering pipe linked to water tanks; ⑦ insulation and waterproofing layer; ⑧ container; ⑨ two connected water storage tanks, each with a capacity of holding 24 l of water.

Table 1
The 12 plant taxa selected and their abbreviations, growth forms, quantities per taxon, and quantities per growth form.

Abbreviation *	Plant taxa	Number	Growth form	Total
Jcl	*Juniperus communis* 'Lalli'	26	Spreading conifers	193
Jcls	*Juniperus communis* 'Lotta Svard'	112		
Jcsd	*Juniperus communis* 'Sven Dufva'	55		
Pae	*Picea abies* 'Echiniformis'	54	Dwarf conifers	108
Pan	*Picea abies* 'Nidiformis'	54		
Jca	*Juniperus communis* 'Åland'	54	Creeping conifers	160
Jcx	*Juniperus communis* '110'	54		
Jcxx	*Juniperus communis* '115'	52		
Cs	*Clematis sibirica*	83	Climbers	336
Ha	*Hydrangea anomala* subsp. *petiolaris*	35		
Hl	*Humulus lupulus*	109		
Pq	*Parthenocissus quinquefolia*	109		

* Abbreviations are referred to in tables, figures, and the appendix.

façades by including two pH levels: 5–5.5 and 6–6.5, covering suitable substrate pH for most selected plant taxa. We also introduced mycorrhizal fungi, a group of plant growth-promoting microbes (Bonfante & Anca, 2009), by adding forest humus in the treated containers (Parke et al., 1983). In the end, we produced a two-factor design for the crushed-brick substrates based on pH levels (substrate A, pH 5–5.5; substrate B, pH 6–6.5) and mycorrhizal inoculation (with and without). Consequently, we had four substrate treatments: substrate A, substrate B, substrate A + mycorrhiza, and substrate B + mycorrhiza. The difference in pH levels was obtained by adding lime to substrate A. Biochar was amended to both substrates at a rate of 70 l m^{-3} to achieve high water retention capacity (Razzaghi et al., 2020). Biochar was supplied by Barbetec Oü (Pärnu, Estonia) and produced via slowly pyrolyzing hardwood mixture (mainly aspen, alder, and birch) at 450 °C. The substrate properties are presented in Appendix Table A2, following FLL (2018) guideline. 10 l of forest humus was mixed in 1 m^3 substrate to introduce mycorrhizal species. The substrates and forest humus were supplied by Hyvinkään Tieluiska Oy (Hyvinkää, Finland).

A combination of substrate pH, mycorrhizal inoculation, and 5–11 individual plants was assigned to each container following a stratified random design to ensure that every orientation and floor height would include all substrate pH levels, mycorrhizal inoculation treatments, and plant taxa. The containers were not fertilized during the study and were weeded twice a year. When necessary, professional gardeners were responsible for irrigation by filling the tanks via the watering pipes (Fig. 1). Water in the tanks then becomes available to the plants via capillary action.

In high latitude areas in the northern hemisphere, south-facing façades receive the highest solar radiation, while west-facing façades receive relatively hot afternoon sunshine (Formolli et al., 2023). South- and west-facing façades are also the windiest (Finnish Meteorological Institute, 2015), making the east-facing façade a proxy for the mildest weather conditions for our study site. As the building is close to the seashore and situated in a newly constructed residential district lacking high and established trees at the time of the research, the plants were exposed to sun and strong southwesterly winds from the sea. According to meteorological data obtained from the Kaisaniemi weather station (60°10′ N, 24°56′ E, 2.7 km to the northeast of our study site), daily mean air temperature during the inventory periods was 1.7 °C higher in 2018 (17.1 °C) than in 2019 (15.4 °C). Meanwhile, accumulated precipitation amounts during the inventory periods were similar: 48.0 mm in 2018 and 48.5 mm in 2019, respectively (Appendix Fig. A3).

2.2. Data collection

We conducted four inventories across the 112 containers: twice in 2018 (19–20 June and 29–31 August) and twice in 2019 (7–14 June and 7–9 September) to evaluate plant performance, namely visual appearance and size, of the 797 individual plants. According to the methodology described by Hermans et al. (2003) and Bock et al. (2010), plant visual appearance based on leaf discoloration, leaf withering, dead branches, and defoliation was visually evaluated and classified into six categories: V1 (dead), V2 (100–75% damaged), V3 (50–75% damaged), V4 (25–50% damaged), V5 (0–25% damaged), and V6 (no damage), making visual appearance an ordinal variable (Appendix Table A4 & Fig. A5). We regard V1 to V3 as poor visual appearance and V4 to V6 as good visual appearance. To minimize subjectivity, we used intersubjective consensus values, i.e., the mean values of two to three independent co-authors' estimations. Regarding plant size, we measured the height (distance from the highest point perpendicular to the substrate surface) and width (distance between the widest points of the canopy and parallel to the substrate surface) for conifers, and the length of the longest shoot (distance from the base to the last living bud along the shoot) for climbers. Because it was impossible to measure the exact length of all climbers on the façades, we classified length into four categories: L1 (< 0.5 m), L2 (0.5–1 m), L3 (1–2 m), and L4 (> 2 m). Conifer height and width were continuous variables, and the length of climbers was an ordinal variable. In total, we obtained 3188 records: 772 for spreading conifers, 432 for dwarf conifers, 640 for creeping conifers, and 1344 for climbers.

2.3. Statistical analyses

To examine the impact of façade orientation, floor height, substrate pH, and mycorrhizal inoculation on the visual appearance and size of plants, we included them as predictor variables and conducted four inventories to track changes over time (Table 2). Then we employed multilevel extension models, specifically cumulative link mixed models (CLMM) and linear mixed models (LMM), which are well-suited for the analysis of our repeated-measures data (Christensen, 2018). CLMM is an extension of the cumulative link model (CLM), which is an ordinal regression, and LMM is a parametric linear model that quantifies the relationship between a continuous response variable and various predictor variables (Bates et al., 2015). The IDs of individual plants were included in the models as a random effect to account for repeated measures (marked as "ID" in the models). All predictor variables used in the statistical analysis are categorical, with their levels shown in Table 2.

For the visual appearance analyses, we first built a global CLMM to test the impact of the predictor variables on visual appearance across the four growth forms (Appendix Table A6, Model 1). Then, four CLMMs were built separately for each growth form (Appendix Table A6, models 2–5), including taxon as a predictor variable to reveal any generalities among predictor variables within each group. Lastly, we constructed 12 CLMMs (Appendix Table A6, models 6–17) to identify taxon-specific effects of the predictor variables. All CLMMs of visual appearance included the dead plant individuals.

For the plant size analyses, we excluded all dead plant individuals to determine how size developed in those individuals that were alive. Here, we used the sum of height and width (h+w) as response variable in the conifer size models, and length as response variable in the climber size models. Due to two types of response variables (continuous for conifers vs. ordinal for climbers), it was not possible to build a global model that included all size data. Therefore, the size analyses included 4 group models and 12 taxon-specific models (Appendix Table A7). We used LMMs for all conifers and CLMMs for climbers, totaling 16 models.

To simplify the models, we adopted a stepwise selection procedure to delete non-significant predictor variables, one at a time, starting from the variable with the greatest p-value and continuing until all predictor variables were retained with p-values < 0.05. Only the final models are presented here. All analyses were performed in R version 4.0.4 (R Core Team, 2023). For CLMMs, we used the "clmm" function in the ordinal package (Christensen, 2018). For LMMs, we used the "lmer" function in the "lms4" package (Bates et al., 2015). Because the data of *Picea abies* 'Echiniformis', *J. communis* 'Lotta Svard', *J. communis* 'Åland' and *J. Communis* '110' did not comply with the assumptions of normality, we used robust linear mixed models and chose the "rlmer" function in the "robustlmm" package to build these models (Koller, 2016). The threshold coefficients in CLMMs are equivalent to the intercept in LMMs. We performed post-hoc tests ("emmeans" function) for multiple comparisons among the different levels of each predictor variable (Lenth, 2023).

3. Results and discussions

3.1. Plant visual appearance and size

In the last inventory, 8 out of 12 plant taxa examined consistently exhibited better visual appearance, with over 70% of their individual plants falling within categories V4 to V6. The weakest dwarf conifer was *P. abies* 'Echiniformis', with 66.7% of its population consisting of individuals with poor visual appearance and 43.5% dead. Although 59.6% of *J. communis* '115' individuals fell into categories V4 to V6, it is still considered the weakest among creeping conifers, losing 39.4% of individuals. *P. quinquefolia* was the weakest climber, as 61.9% of individual plants were poor in visual appearance and 41.5% were dead (Fig. 2A). In terms of size, all conifers generally developed in width rather than height, with dwarf and creeping conifers having higher width/height ratios than spreading conifers (Fig. 2B). *C. sibirica* and *H. anomala* subsp. *petiolaris* plants exhibited uniform growth, typically reaching lengths of 0.5–1 m two years after establishment. In contrast, *H. lupulus* and *P. quinquefolia* plants varied in their lengths (Fig. 2C).

According to our statistical models, visual appearance decreased in general for all growth form groups. Creeping conifers exhibited the best visual appearance of all, followed by spreading conifers. Climbers and dwarf conifers had the poorest visual appearance with no significant differences between them (Appendix Table A6, Model 1; Fig. 3A). Yet, 11 of the 12 plant taxa grew significantly bigger in the last inventory than the first, with the exception being *C. sibirica*, which decreased significantly in size (Appendix Table A7, models 22–33; Fig. 3B).

Our results highlight the importance of plant selection for vegetated façades. Generally, coniferous plants thrived during the establishment stage on building façades, whereas climbers, although commonly used in vertical greening in other regions, did not perform as expected in the Nordic climate. For instance, *P. quinquefolia* has traditionally been recognized as a fast grower, extending 3–6 m in length per year in Eastern North America (Edwards, 2007). On the contrary, over 80% of *P. quinquefolia* plants in our study failed to surpass 2 m in length after growing for two years, significantly slower than reported. Furthermore, as pointed out by Wattenhofer and Johnson (2021), the highest plant

Table 2
Predictor variables and their levels used in the data analyses. Numbers in parentheses indicate the number of individual plants at each level of the predictor variable.

Predictor variables and their levels
4 inventories:
June 2018; August 2018; June 2019; September 2019
4 growth forms:
spreading conifers (193); dwarf conifers (108); creeping conifers (160); climbers (336)
12 plant taxa
(see Table 1)
3 façade orientations:
west (276); east (265); south (256)
3 floor categories:
floors 2–3 (256); floors 4–5 (297); floors 6–8 (262)
2 levels of substrate pH:
pH 5–5.5 (402); pH 6–6.5 (395)
2 levels of mycorrhizal inoculation:
inoculated (397); control (400)

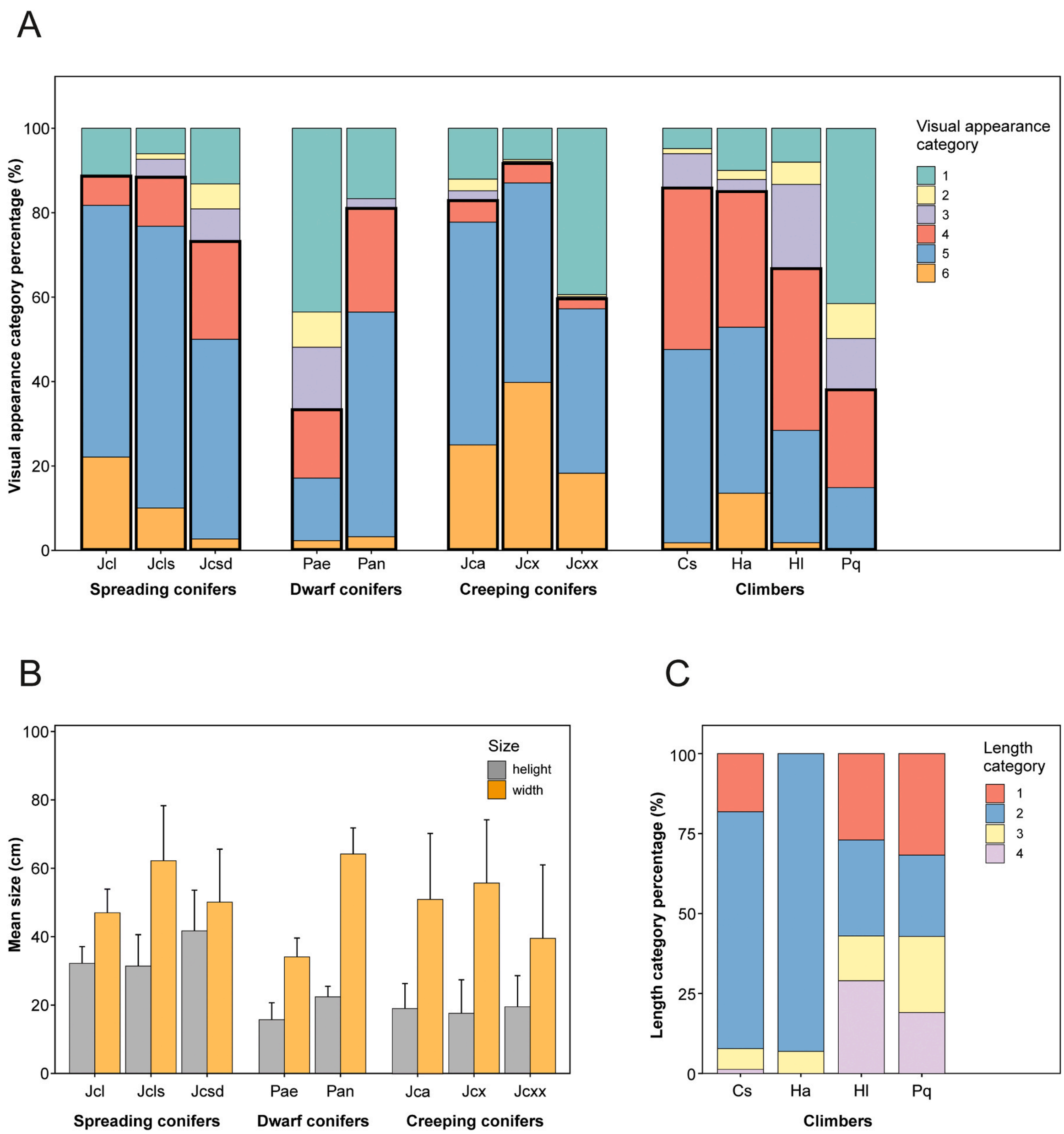

Fig. 2. Descriptive statistics on visual appearance and size of the 12 plant taxa in the last inventory (September 2019). The upper panel shows plant visual appearance, with good visual appearance (4–6) rates of each plant taxa being encapsulated by black frames (A). Visual appearance category refers to plants that were dead (V1), 100–75% damaged (V2), 50–75% damaged (V3), 25–50% damaged (V4), 0–25% damaged (V5), and no damage (V6). The lower left panel shows the size, both in terms of height and width, of the conifers (B). The lower right panel shows the length category percentages of climbers (C). The length category refers to climbers that were < 0.5 m (L1), 0.5–1 m (L2), 1–2 m (L3), and > 2 m (L4) in length.

mortality often occurs within the first few years after planting. Replacing dead plants with new ones to maintain the landscape's aesthetic value will increase maintenance input. Our study suggests that including *J. communis* '115', *P. quinquefolia* and *P. abies* 'Echiniformis' on the plant list for vegetated façades in the Nordic region may increase maintenance costs through replacements of dead plants.

We also noticed that visual appearance and size did not always show the same tendency, meaning good visual appearance did not guarantee bigger size, and vice versa. For instance, *J. communis* '110' and 'Lotta Svärd' grew well and showed good visual appearance, while *J. communis* 'Sven Dufva' and *H. lupulus* grew well despite deteriorating visual appearance. This phenomenon may indicate a potential trade-off between plant visual appearance and size development, which necessitates a less rigid and less conservative approach to visual evaluation in favor of rapid growth (Nagase and Dunnett, 2011). The quest for new aesthetic and functional perspectives in urban green spaces is supported by a growing body of research (Hauru et al., 2012; Mesimäki et al., 2017; Subiza-Pérez et al., 2019). Essentially, the pursuit of rapid growth must be balanced by a careful assessment of long-term visual appearance. In our case, although *P. abies* 'Echiniformis' and *P. quinquefolia* exhibited the poorest visual appearance, their surviving individuals kept growing and did not decrease in visual assessment. Therefore, we need long-term monitoring to verify if they can outperform other plant taxa in the future.

Our results suggest that plant growth form may, to some degree, be informative for selecting plants for vegetated façades, yet there was high taxon-specific variation within the growth form groups. In our data, spreading and creeping conifers showed the best visual appearance and steady size development. We assume that these two growth forms may be resilient to wind, which can be harsh on vertical façades, striking

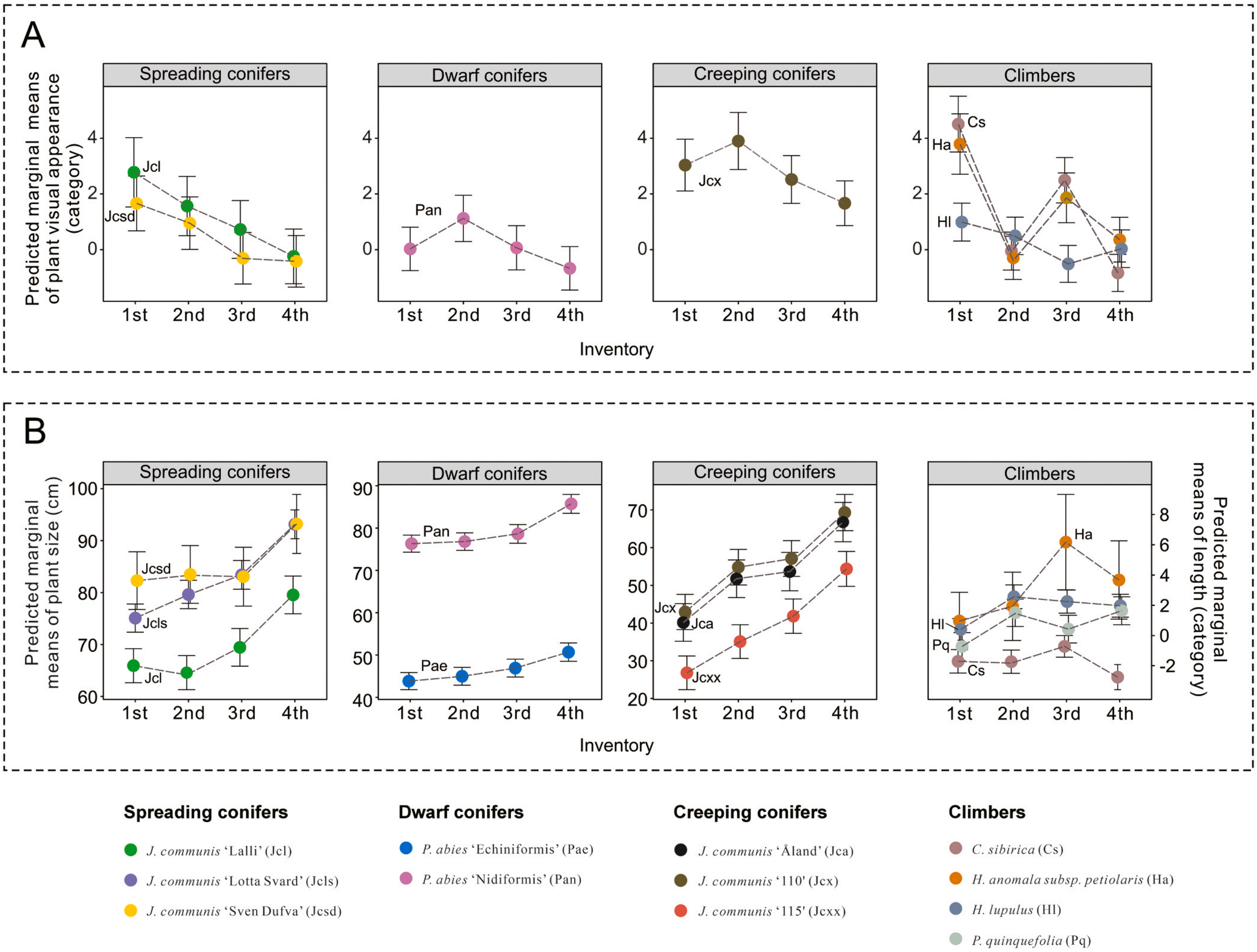

Fig. 3. Predicted marginal means were computed for four inventories from the CLMMs and LMMs. Upper panels show the visual appearance values for 7 plant taxa (A), and lower panels show changes in size of the 12 plant taxa (B). The figure only presents data that show statistical significance. For detailed results of the analyses, see Appendix Tables A6 and A7.

plant canopies and damaging root systems (Moore et al., 2018). However, because all the climbers we tested were broad-leaved and all the conifers were needle-leaved, we cannot differentiate the impact of leaf morphology from that of plant growth form on plant performance on façades.

Lastly, our research suggests a shift in approaching plant selection for vegetated façades, advocating for the inclusion of coniferous species, and harnessing their potential to enhance plant diversity. According to Aronen et al. (2009), there is a longstanding tradition of cultivating conifers in Nordic urban settings, spanning from breeding techniques to landscape management practices. Furthermore, as suggested by Clapp et al. (2014) and Shackleton et al. (2015), woody plants offer a unique set of benefits that are challenging to produce by other plant types. For instance, the use of woody plants can significantly increase variation in vegetation heights (Martins et al., 2017), thereby enhancing structural diversity in vegetated façades. Additionally, by forming dense, year-round vegetation cover, evergreen conifers can provide physical barrier against erosion by wind, rain, snow, and other environmental variables and ensure uninterrupted provision of ecosystem services (Relf and Appleton, 2000; Lundholm et al., 2014). While concerns exist about integrating woody plants into VGSs and VRs due to load-bearing constraints, selecting compact cultivars with slower growth rates provides a feasible solution to address structural concerns.

3.2. The impact of façade orientation and floor height on plant performance

Our global model, the three conifer growth form models, and the taxon-specific models reveal that plants on the east-facing façade showed the best visual appearance, followed by the south- and then the west-facing façades (Appendix Table A6). In terms of specific taxa, 6 of the 12 visual appearance models retained façade orientation as a predictor variable, which almost followed the same pattern as the global model. The only exception was *P. quinquefolia*, which had its best visual appearance on the south-facing façade (Fig. 4A). According to the size analyses, creeping conifers and climbers grew biggest on the east-facing façades (Fig. 4A; Appendix Table A7). Nine out of 12 plant taxa retained façade orientation as a predictor variable in the taxon-specific analyses (Fig. 4B). While we did not detect significant effects of floor height on visual appearance and size in either global or growth form models, a few plant taxa retained floor height as a significant predictor variable in taxon-specific models (Fig. 4C & 4D).

The amount of sunlight and heat a building receives is primarily determined by its orientation relative to the sun's path, leading to microclimatic variation among façade orientations (Obrecht et al., 2019). Thus, plant visual appearance and size can be significantly influenced by the microclimate unique to façade orientation, as shown by our results. The impacts of microclimate on plant development and

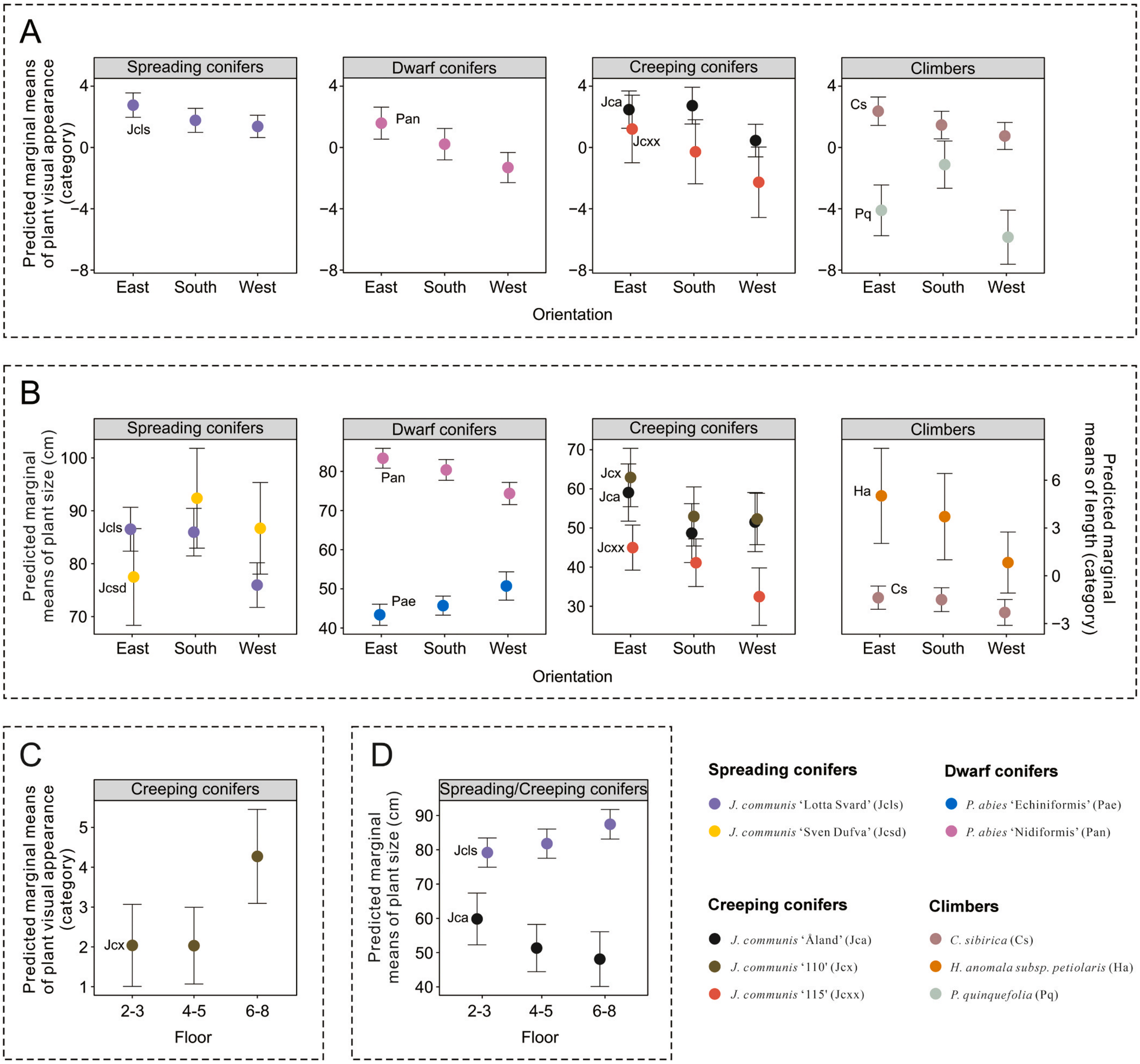

Fig. 4. Predicted marginal means of plant visual appearance and size showing taxon-specific responses to façade orientation and floor height. Panel A shows plant visual appearance in response to façade orientation. Panel B shows plant size in response to façade orientation. Panel C shows plant visual appearance in response to floor height. Panel D shows plant size in response to floor height. The predicted marginal means were computed based on models 6–17 in the visual appearance analysis (Appendix Table A6) and models 22–33 in the size analysis (Appendix Table A7).

performance have also been demonstrated in various cultivation systems (Hatfield and Prueger, 2015; Nassar et al., 2018). Moreover, because the solar energy budget needed for plant development varies by species (Gauslaa, 1984), it is evident why the selected plant taxa responded differently to façade orientation. In contrast, floor height within the 8-storey building appeared to have only marginal effects on plant performance, suggesting that for relatively low buildings, plant performance is predominantly dictated by façade orientation rather than height. In the Finnish context, this means that façade orientation is the critical variable, given that 99.6% of residential buildings in Finland have less than 10 floors (Tulonen et al., 2021).

Our results align with the review by Wahid et al. (2007), which indicates that excessive wind and solar exposure harms plant visual appearance and size. In our study, the majority of models suggest bigger plant size on the east-facing façade that is sheltered from the prevailing wind direction and the hottest afternoon sun. Wahid et al. (2007) also specified symptoms induced by elevated temperatures, including sunburn, premature leaf senescence, growth retardation, and discoloration in fruits and leaves, which corresponded to poor visual appearance in our study. Yet, Finland's geographical location has led to the incorporation of both passive and active solar designs in architectural projects, resulting in overheating challenges in south- and west-facing façades (Sukanen et al., 2023). Therefore, identifying plant taxa capable of thriving on south- and west-facing façades under Nordic climatic and geographical conditions becomes paramount to enhance their diverse ecosystem services. In our study, several taxa demonstrated similar visual appearance (*J. communis* 'Lalli', *J. communis* 'Sven Dufva', *P. abies* 'Echiniformis', *J. communis* '110', *H. anomala*, and *H. lupulus*) or equal size development (*J. communis* 'Lalli', *H. lupulus*, and *P. quinquefolia*), regardless of façade orientation.

3.3. The impact of substrate pH and mycorrhizal inoculation on plant performance

Substrate pH had a more significant effect on plant visual appearance than on plant size. Seven of the 12 plants retained substrate pH as a predictor variable, and 6 of them recorded better visual appearance in substrate B with pH 6–6.5 than in substrate A with pH 5–5.5. Only *H. lupulus* exhibited better visual appearance in the lower pH substrate. *H. lupulus* is also the only plant whose size was affected by substrate pH: it grew bigger at lower pH (5–5.5) (Fig. 5A). However, mycorrhizal inoculation did not appear to exert any clear effect. Across all models, only three plant species retained mycorrhizal inoculation as a predictor variable for visual appearance, each showing different responses (Fig. 5B).

Theoretically, plant size responds to substrate pH, which is mainly influenced by the availability of various nutrients under different pH levels (Gentili et al., 2018). However, in our study, substrate pH affected plant visual appearance more clearly than plant size. One reason why we did not detect a statistically significant change in conifer size could be their relatively slow growth rate. Additionally, our results highlight the importance of field experiments with vegetated façades, as suitable substrate pH levels may change for the same plant species under different growing conditions. For instance, while Parzych et al. (2018) reported *P. abies* to grow best in substrates with pH 5.4–6.0, we found the visual appearance of our *P. abies* taxa to be higher in pH 6–6.5 than in pH 5–5.5. Fejér et al. (2018) stated that *J. communis* normally grows in substrates with pH 3.7–5.7, which also contradicts our result. Nath et al. (2022) pointed out that *H. lupulus* struggles to thrive in acidic substrates, and Sirrine (2010) also reported that when substrate pH decreases below 5.7, manganese levels can become toxic to *H. lupulus*. However, we found that *H. lupulus* performed better in the substrate with a pH of 5–5.5 rather than the one with 6–6.5. These contradictory findings between studies of others and ours suggest that substrate pH for vegetated façade plants should be investigated and optimized under specific growing conditions (Jauni et al., 2020), rather than following guidelines indiscriminately.

According to the literature, *Juniperus* and *Picea* are hosts for both arbuscular mycorrhizal and ectomycorrhizal fungi, and they can benefit from this symbiosis (Korkama et al., 2007; Veldhuis et al., 2022). However, mycorrhizal symbioses with the selected climbers remain almost unexplored. Only the *Clematis* genus and *H. lupulus* are reported to host arbuscular mycorrhizal fungi (Davis et al., 1984; Liu et al., 2020; Zhang et al., 2022). Nevertheless, no plant size difference was detected between mycorrhizal inoculated and uninoculated groups. Since

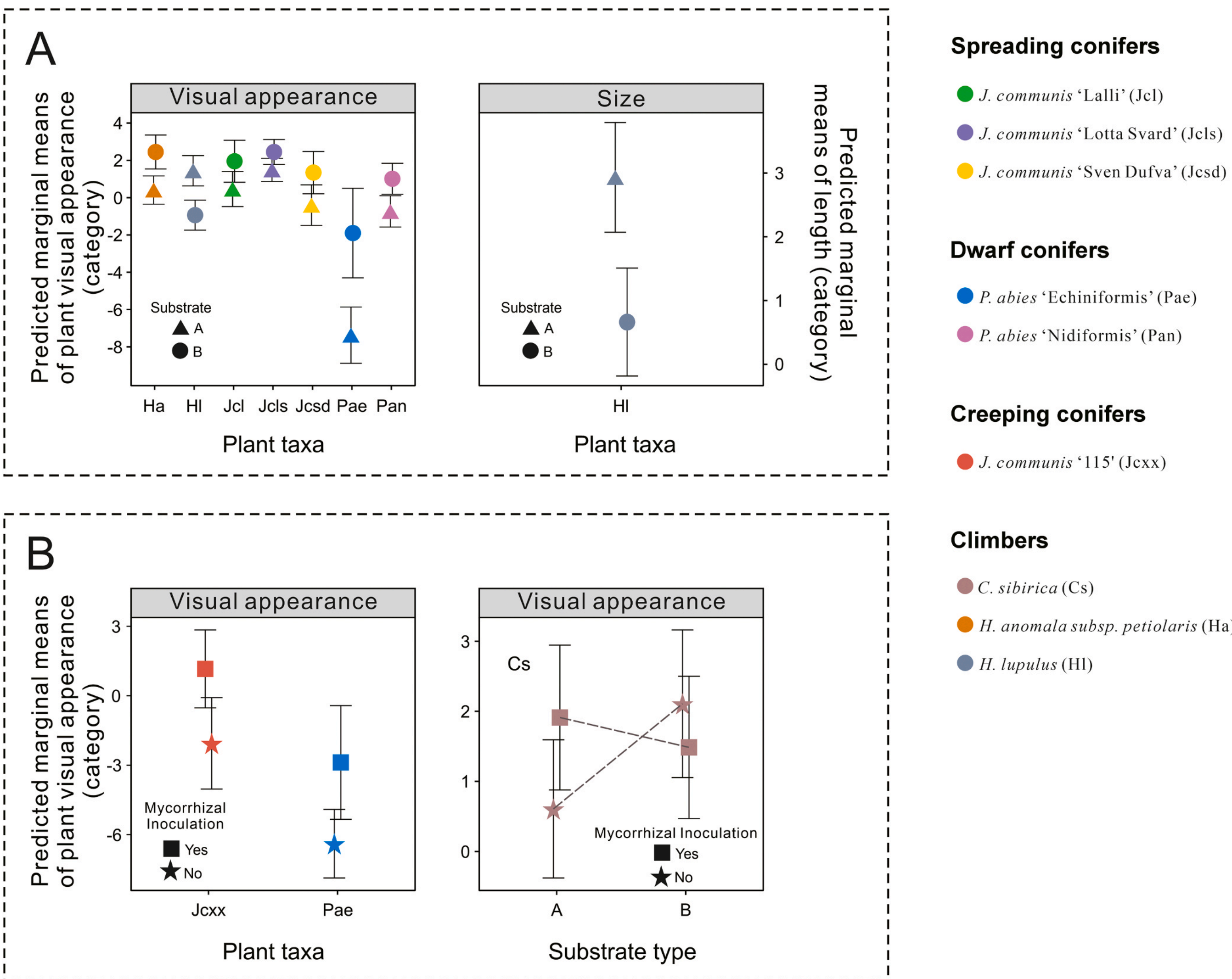

Fig. 5. Predicted marginal means of plant visual appearance and size showing taxon-specific responses to substrate pH and mycorrhizal inoculation. Panel A shows plant visual appearance and size in response to substrate pH. Panel B shows plant visual appearance in response to mycorrhizal inoculation and the interaction between substrate pH and mycorrhizal inoculation. Substrate type A and B refer to pH levels 5–5.5 and 6–6.5, respectively. The predicted marginal means were computed based on models 6–17 in the visual appearance analysis (Appendix Table A6) and models 22–33 in the size analysis (Appendix Table A7).

mycorrhizal colonization level could not be monitored in this study, we cannot say if it was caused by low colonization levels or no colonization at all.

On the other hand, mycorrhizal inoculation appears to influence plant visual appearance, but with mixed impacts: improving the visual appearance of *P. abies* 'Echiniformis' while impairing that of *J. communis* '115'. It suggests that mycorrhizal inoculation does not always produce a positive effect, which also applies to vegetated façade conditions. Our finding is in line with a meta-analysis of nearly 2000 studies on plant responses to arbuscular mycorrhizal and ectomycorrhizal inoculation. In the analysis, positive effects of mycorrhizal inoculation are confirmed for most plant species, yet a few negative cases are also recorded (Hoeksema et al., 2010). Furthermore, the positive, negative, or neutral effect of mycorrhizal inoculation is context dependent (Jonsson et al., 2001). For instance, in our study, the visual appearance of *C. sibirica* was enhanced by mycorrhizal inoculation in the pH 5–5.5 substrate but reduced in the pH 6–6.5 one. Although small in number, a few researchers have reached similar conclusions. Jonsson et al. (2001) reported that soil fertility plays a crucial role in determining the effect of the ectomycorrhizal community on seedling productivity of two tree species, ranging from mutualistic to parasitic. In a study investigating the impact of soil salinity and mycorrhizal inoculation on herbivore parasitism, Moon et al. (2013) found that mycorrhizal inoculation reduced parasitism (leaf miners *Amauromyza maculosa* and *Liriomyza trifolii*) with decreasing soil salinity but increased it with increasing soil salinity. This serves as another example suggesting that the effect of mycorrhizal inoculation is context dependent.

It is also worth noting that plant size and biomass did not respond to mycorrhizal inoculation the way plant physiological traits and visual appearance did. A similar phenomenon was reported in a study using *Hypericum perforatum* L. as the host and a mix of *Rhizophagus intraradices* and *Funneliformis mosseae* as inocula. The authors found that a mixture of the mycorrhizal fungi significantly improved the photosynthetic performance index while showing no effect on shoot biomass (Zubek et al., 2012). In another study, Corrêa et al. (2008) noticed that plant growth did not correlate with photosynthetic performance under mycorrhizal inoculation. A possible explanation would be that plant physiological performances and visual appearance respond to microbial symbiosis more quickly than plant size and biomass.

To conclude, our study suggests that the effect of mycorrhizal inoculation is taxon and context dependent. To argue for the plant growth-promoting effects of mycorrhiza in vegetated façades, one cannot simply apply findings from laboratories or conventional agricultural fields to these façades.

3.4. Limitations

Our observation period was relatively short, and longer-term plant performance in vegetated façades may differ from observations made during the initial two-year establishment period (Wattenhofer and Johnson, 2021). Additionally, our original research plan intended to include 6–7 plant individuals per container, each representing a different taxon. However, due to plant availability and human error, we included between 5 and 11 individual plants per container. Results could be distorted as more plants in one container can provide support and shade for each other against wind and sun (Weiner, 1990; Stoll and Weiner, 2000). Our results cannot be extended to high-rise buildings, where microclimatic conditions can vary more drastically between higher and lower floors compared to our 8-storey building (Okafor et al., 2017). Similarly, since this study was only conducted in one specific building, one should exercise caution when extrapolating the results to buildings with different climates, locations, surrounding landscapes, etc. Lastly, we introduced mycorrhizal fungi by adding forest humus to the substrate, but we could not verify whether the mycorrhizal fungi successfully colonized the target plants or not. Non-destructive methods for mycorrhizal quantification on the balconies were not feasible in our study.

4. Conclusion

The integration of VGSs and VRs is an effective approach to enhance livability in densely populated urban areas. By utilizing unused urban spaces, these integrated systems create new greenery that is widely accepted and appreciated by residents. Our study assessed the effects of façade orientation, floor height, substrate pH, and mycorrhizal inoculation on plant performance in vegetated façades in Southern Finland. We aimed at selecting suitable plants for vegetated façades under these climatic conditions to achieve better ecosystem services and multiple design goals. Our findings provide practical implications for future vegetated façade design and installation. Firstly, our results underscore the critical role of façade orientation for plant selection in vegetated façades, advocating for the use of coniferous species in Nordic regions. Secondly, although our results showed that many of the selected plant taxa grew well on different façades, we suggest identifying more plant species suitable especially for south- and west-facing façades to support a broader range of ecosystem functions. Therefore, a holistic and tailored approach to investigate the microclimatic conditions of a specific building envelop is needed for successful vegetated façade construction. Lastly, given the variability in plant performance to different environmental conditions and substrate treatments, we strongly recommend conducting long-term research to further refine best practices and ensure the sustained success of urban greening initiatives.

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CRediT authorship contribution statement

Xi Shu: Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Software, Validation, Visualization, Writing - original draft. **Long Xie:** Data curation, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing – original draft. **D. Johan Kotze:** Formal analysis, Methodology, Supervision, Validation, Writing - review & editing. **Miia Jauni:** Investigation, Validation, Writing - review & editing. **Iiris Lettojärvi:** Investigation, Validation, Writing – review & editing. **Taina H. Suonio:** Resources, Validation, Writing – review & editing. **Ayako Nagase:** Investigation, Validation, Writing – review & editing. **Susanna Lehvävirta:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Resources, Project administration, Validation, Supervision, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.ufug.2024.128280.

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