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Temporal Responses of Spontaneous Plant Community Diversity to Sowing Density of Cultivated Herbs in Park Greenspaces

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ABSTRACT

Understanding how sowing density influences spontaneous plant communities over time is critical for optimizing vegetation management in urban park greenspaces. This study investigated the temporal responses of spontaneous plant community diversity to varying sowing densities of cultivated herbs in Hangzhou, China. A semi-controlled field experiment was conducted using three sowing densities (20, 100, and 200 plants m^{-2}), and spontaneous plant communities were monitored monthly from December to May. Diversity was assessed using the Shannon–Wiener index, Pielou's evenness index, and Margalef's richness index, and the data were analyzed with linear mixed-effects models. Spontaneous plant diversity exhibited clear seasonal dynamics, with diversity indices increasing from winter to spring and peaking in March–April. The effects of sowing density were strongly time-dependent. Differences among density treatments were relatively small during the initial stages but became more pronounced during the spring growth period. Specifically, medium and high densities were associated with lower diversity and species richness during the peak period. In contrast, evenness was primarily influenced by temporal variation rather than sowing density. Community composition varied among treatments, mainly through shifts in species abundance rather than species turnover. These findings indicate that sowing density can serve as a practical tool for regulating spontaneous plant diversity and highlight March–April as a key period for management interventions in park greenspaces.

KEYWORDS

Sowing density; Spontaneous plants; Urban park greenspaces; Seasonal dynamics; Plant diversity; Community composition.

1. INTRODUCTION

Urban park greenspaces are key components of urban green infrastructure, providing recreational, aesthetic, and ecological benefits under increasing urbanization pressure. In these designed and managed systems, spontaneous plants, defined here as naturally established vascular plants that are not deliberately sown or planted, are commonly present [1, 2]. Although traditionally regarded as weeds or indicators of poor maintenance, a growing body of research has recognized their potential contributions to urban biodiversity, habitat heterogeneity, and low-maintenance vegetation cover [3].

Nevertheless, spontaneous vegetation should not be viewed as either uniformly undesirable or universally beneficial. While its presence can enhance species richness and habitat heterogeneity, excessive or poorly regulated spontaneous growth may reduce landscape order, visual acceptability, and management controllability [4, 5]. Therefore, the key issue in park greenspace management is not a binary choice between complete removal and full retention of spontaneous plants. Rather, it is how their establishment and persistence can be coordinated with cultivated plant arrangements under different management objectives.

Sowing density is one of the most direct and practically manipulable factors influencing the early development of cultivated herbaceous communities. By determining the number of established individuals per unit area, sowing density modifies neighbor distance, canopy closure, aboveground space occupancy, and consequently the intensity of competition for key resources, especially light [6, 7]. High sowing density may enable cultivated plants to close the canopy more rapidly and reduce open microsites available for spontaneous plant germination. In contrast, low sowing density may leave more open gaps, potentially allowing spontaneous species to establish and persist [8, 9]. Hence, sowing density is not merely a technical parameter for establishing cultivated vegetation; it also represents a potential management tool for regulating the balance between cultivated plant dominance and spontaneous plant retention in park greenspaces.

Previous studies on sowing density in herbaceous vegetation have often focused on target plant establishment, weed resistance, or overall community performance, with less attention paid to continuous seasonal trajectories of spontaneous plant diversity [10]. These studies have shown that density can influence vegetation cover, species persistence, and community composition. However, spontaneous plant communities are inherently dynamic, particularly during the transition from winter to spring, when germination, early growth, canopy expansion, and competitive interactions change rapidly. Evaluating sowing density effects only at discrete time points may therefore miss important temporal variation in cultivated–spontaneous plant interactions. Specifically, it remains unclear whether the effects of sowing density on spontaneous plant diversity remain constant throughout the growing season, or whether they become more pronounced during specific windows of rapid community development.

To address this gap, we investigated the temporal responses of spontaneous plant community diversity to sowing density of cultivated herbs in park greenspaces. Using a semi-controlled field experiment with low, medium, and high sowing densities, we monitored spontaneous plant communities monthly from December to May and analyzed changes in three diversity indices (Shannon–Wiener, Pielou, and Margalef). Specifically, this study aimed to answer two questions: (1) Do the effects of sowing density on spontaneous plant diversity change over time? and (2) Can a key period be identified during which density-related differences become most evident? By focusing on density-driven temporal dynamics, this study provides evidence for optimizing sowing density and identifying temporal windows for managing spontaneous vegetation in park greenspaces, while acknowledging that specific density thresholds may require local calibration.

2. MATERIALS AND METHODS

2.1. Study site and experimental design

This study was conducted in an urban park greenspace in Hangzhou, Zhejiang Province, China. The experimental area was located within a managed herbaceous planting site where spontaneous plants were able to establish naturally during the growing season. To examine the temporal responses of spontaneous plant communities to cultivated herb sowing density, a semi-controlled field experiment was established using two cultivated herbaceous species, Cichorium intybus and Crepis rubra.

The density experiment included three sowing density treatments: low density, medium density, and high density, corresponding to 20, 100, and 200 established cultivated individuals m^{-2}, respectively. These density levels were defined according to the number of established mature individuals rather than seed input, in order to more directly represent the actual stand density experienced by spontaneous plants. Each density treatment was replicated three times for each cultivated species. In total, the density experiment included 18 sown plots, comprising 2 cultivated species × 3 density levels × 3 replicates.

Each experimental plot contained a central 1 m × 1 m quadrat for vegetation monitoring. Seeds of the cultivated species were sown evenly within each plot, and after seedling emergence, individuals were thinned to achieve the target density of each treatment. The plots were monitored for six consecutive months from December to May, covering the overwintering period, early spring emergence, rapid spring growth, and late spring community development stages of spontaneous plants. The six survey months were December, January, February, March, April, and May.

2.2. Initial soil seed bank and site homogeneity assessment

To ensure that differences in spontaneous plant communities among treatments were primarily driven by sowing density rather than pre-existing site heterogeneity, an initial assessment of soil seed bank and site conditions was conducted before the establishment of the experiment.

Soil samples were collected from each plot prior to sowing using a soil auger to a depth of 20 cm. Multiple subsamples were taken within each plot and thoroughly mixed to obtain a composite sample. A portion of each composite sample was used for a soil seed bank germination experiment under controlled greenhouse conditions. Emerging seedlings were recorded and identified over a six-month period to characterize the composition and potential abundance of spontaneous plant propagules.

The results indicated that the composition and abundance of the soil seed bank were broadly comparable among plots, with no pronounced differences in dominant species or total seedling emergence. Variation in total seedling density among plots was within a relatively narrow range, suggesting that initial propagule availability was generally homogeneous across the experimental area.

In addition, the experimental plots were located within a relatively uniform park greenspace with consistent soil conditions and management background. These measures collectively ensured that subsequent differences in spontaneous plant communities could be primarily attributed to the effects of sowing density rather than initial environmental heterogeneity.

2.3. Survey of spontaneous plant communities

Spontaneous plant communities were surveyed monthly in each 1 m × 1 m quadrat from December to May. During each survey, all naturally occurring spontaneous vascular plant species within the quadrat were identified and recorded, and the number of individuals of each species was counted to characterize species abundance and community structure.

Based on the monthly species abundance data, three diversity indices were calculated for each plot and survey month: the Shannon–Wiener diversity index, Pielou's evenness index, and Margalef's richness index. These indices were used to represent overall community diversity, species abundance distribution, and species richness, respectively. All indices were calculated following standard ecological methods.

2.4. Statistical analysis

All statistical analyses and visualizations were performed using R software. Linear mixed-effects models were used as the main analytical approach to evaluate the temporal responses of spontaneous plant community diversity to sowing density over the six-month monitoring period. For each cultivated species, separate models were fitted for the Shannon–Wiener diversity index, Pielou's evenness index, and Margalef's richness index.

In each model, survey month, sowing density, and their interaction were included as fixed effects, while plot identity was included as a random effect to account for repeated monthly measurements within the same plot. The general model structure was as follows:

Index ~ Month × Density + (1 | PlotID), where Month represented the six survey months from December to May, and Density represented the three sowing density treatments: low, medium, and high. The Month × Density interaction was used to test whether the effect of sowing density on spontaneous plant diversity changed over time. Model significance was evaluated based on fixed-effect tests, and $p < 0.05$ was considered statistically significant.

As a supplementary analysis, one-way analysis of variance (ANOVA) was used to compare diversity indices among density treatments during the peak response period. When significant differences were detected, post hoc multiple comparisons were conducted to identify differences among low-, medium-, and high-density treatments. This analysis was used only to support the interpretation of density-related differences during key months, while the linear mixed-effects models were treated as the main statistical evidence for temporal responses.

To visualize differences in spontaneous plant community composition among density treatments, a plot-by-species abundance matrix was constructed. Hierarchical clustering was performed based on species abundance data, and a clustering heatmap was generated to show variation in spontaneous plant composition among plots under different sowing densities. This analysis was used as an exploratory method to assess whether spontaneous plant community composition showed density-related grouping patterns.

3. RESULTS

3.1. Seasonal dynamics of spontaneous plant diversity under different sowing densities

Spontaneous plant community diversity exhibited clear seasonal dynamics under different sowing densities (Fig. 1). Across all treatments, both the Shannon–Wiener diversity index and Margalef's richness index generally increased from winter to spring, with relatively low values during December–February and pronounced increases from March onwards. Diversity indices reached peak levels in March–April, followed by a slight decline in May.

Differences among sowing density treatments were relatively small during the early observation period (December–February), but became more evident during the spring growth period. In particular, during April, plots under medium and high sowing densities showed noticeably lower Shannon–Wiener and Margalef values compared with low-density treatments, indicating that higher planting density may suppress spontaneous plant diversity during the peak growth stage.

In contrast, Pielou's evenness index showed weaker temporal variation and less consistent responses to sowing density. Although significant fluctuations occurred across months, no clear density-dependent pattern was observed, suggesting that sowing density had a stronger influence on species richness and diversity than on evenness.

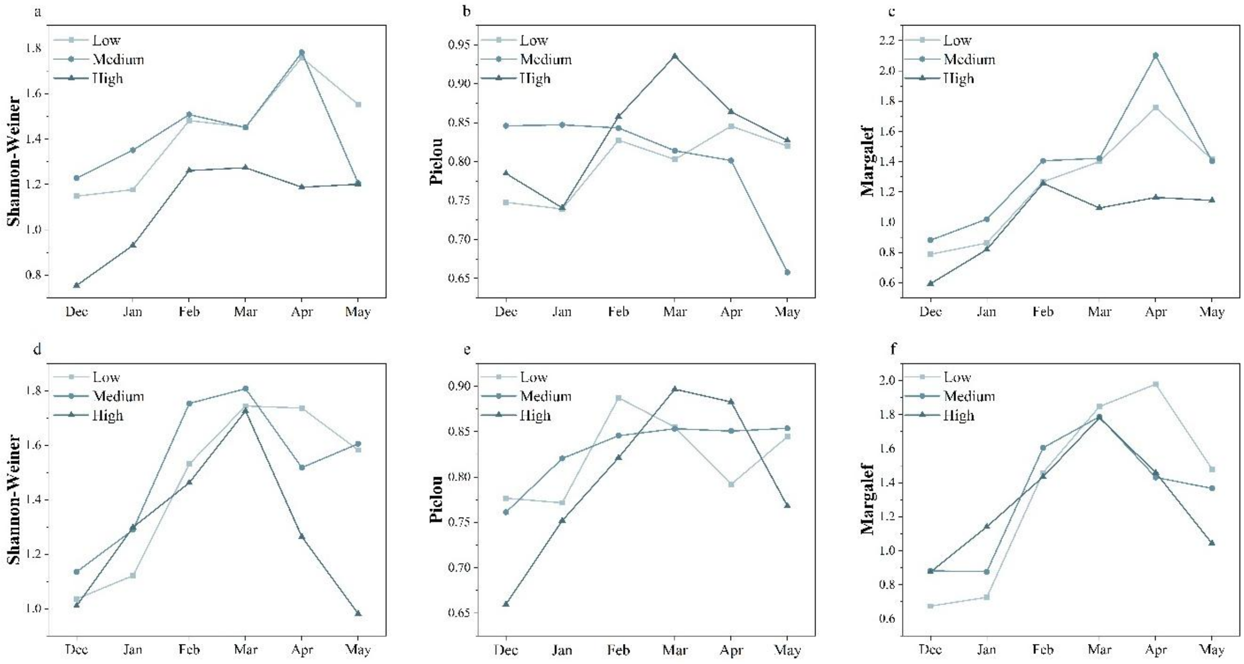

Fig 1. Temporal dynamics of spontaneous plant community diversity under different sowing densities.

3.2. Effects of month, density, and their interaction based on LMM

Linear mixed-effects models confirmed that spontaneous plant diversity was strongly influenced by temporal variation, with additional effects of sowing density and their interaction (Table 1).

For the Shannon–Wiener index, both sowing density and the interaction between month and density were significant (Density: $F = 8.90$, $p < 0.001$; Month × Density: $F = 3.49$, $p < 0.001$), indicating that the effect of density on diversity changed over time. Overall, Shannon–Wiener diversity tended to decrease with increasing sowing density, with the highest values observed under lower-density conditions.

For Pielou's evenness index, month had a significant effect ($F = 11.02$, $p < 0.001$), whereas neither the main effect of density nor the interaction term was significant ($p > 0.05$). This suggests that temporal variation was the primary driver of evenness, while sowing density had limited influence.

For Margalef's richness index, the interaction model provided the best fit, and the Month × Density interaction was significant ($F = 5.03$, $p < 0.001$), while the main effect of density was not significant. This indicates that density effects on species richness were not constant across time but were concentrated in specific periods. In particular, density-related differences became most pronounced during the peak growth period in April, when low-density plots exhibited significantly higher richness than medium- and high-density plots.

Overall, these results demonstrate that the influence of sowing density on spontaneous plant diversity is strongly time-dependent, with the most pronounced effects occurring during the spring growth period.

Table 1. Analysis of fixed effects for the linear mixed-effects model of sowing density and month on Pielou's evenness index

Effect	Sum of Squares	Mean Square	Num df	Den df	F	p
Month	0.35903	0.07181	5	195	11.02	<0.00
Density	0.00201	0.00100	2	39	0.15	0.858
Month × Density	0.06017	0.00602	10	195	0.92	0.513

3.3. Composition patterns of spontaneous plant communities among density treatments

The hierarchical clustering heatmap revealed that spontaneous plant community composition varied among plots under different sowing densities (Fig. 2). However, plots belonging to the same density treatment did not form completely distinct clusters, indicating that compositional differentiation among density treatments was present but not strictly separated.

Patterns observed during the key window period (April) further indicated that sowing density influenced community structure primarily through changes in species abundance rather than large-scale species turnover. High-density plots generally exhibited a more sparse abundance matrix, with fewer species reaching moderate or high abundance levels. In contrast, low-density plots tended to support a greater number of species with moderate abundance.

Several common spontaneous species, such as Mazus pumilus, Galium spurium, and Veronica polita, contributed substantially to the observed compositional patterns and were widely distributed across plots, although their relative abundances varied among density treatments.

Overall, these results suggest that sowing density influenced spontaneous plant community composition to some extent, but its effects were more moderate and heterogeneous compared with its influence on diversity indices, and were mainly reflected in shifts in species abundance structure.

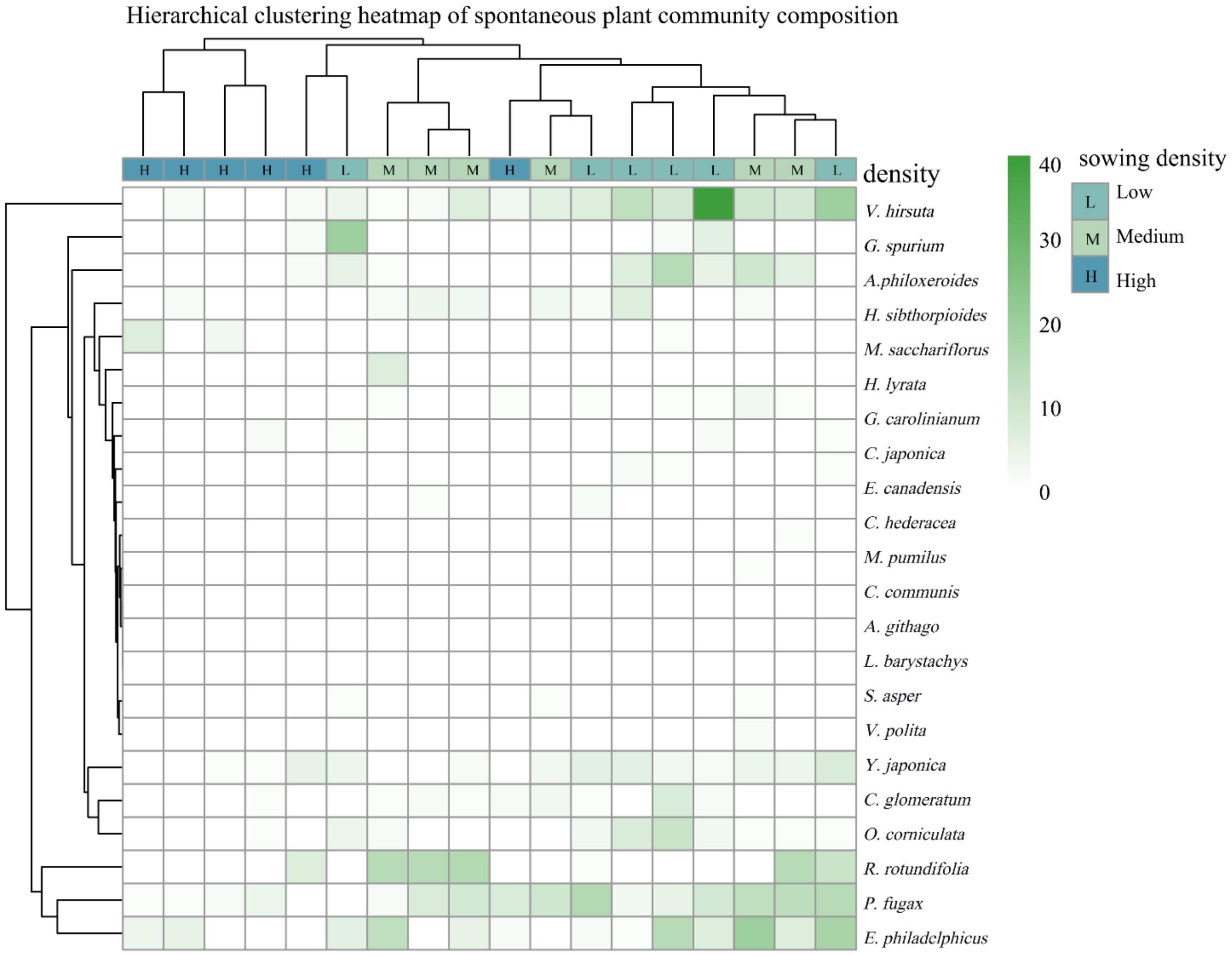

Fig 2. Hierarchical clustering heatmap of spontaneous plant community composition under different sowing densities.

4. DISCUSSION

4.1. Sowing density effects on spontaneous plant diversity were time-dependent

The effects of sowing density on spontaneous plant community diversity were strongly time-dependent. During winter (December–February), density effects were weak, consistent with studies showing limited influence during early establishment stages when competition is minimal [10]. In contrast, density effects intensified from March onwards, peaking in April as vegetation entered rapid growth and competition increased [11].

Significant Month × Density interactions for both Shannon–Wiener and Margalef's indices confirmed that density effects varied across seasons rather than remaining constant. These findings indicate that single-time-point assessments may underestimate the role of sowing density, and highlight the necessity of incorporating temporal dynamics when evaluating cultivated–spontaneous plant interactions in urban greenspaces.

4.2. High-density sowing may constrain spontaneous plant establishment during the rapid growth period

The observed decline in Shannon–Wiener diversity and species richness under medium and high sowing densities during the peak growth period suggests that increased planting density may constrain spontaneous plant establishment and persistence. This pattern is consistent with previous studies showing that higher sowing density can enhance competitive exclusion and reduce opportunities for non-target species establishment [7, 10].

One plausible mechanism is that higher sowing density increases canopy closure and aboveground biomass accumulation, thereby reducing light availability at the soil surface. Light limitation is widely recognized as a key factor influencing seed germination and seedling establishment in herbaceous communities [11]. In addition, increased density reduces the availability of open microsites, which are critical for the recruitment of spontaneous plants [3].

The results of the clustering heatmap further suggest that density effects were mainly reflected in shifts in species abundance rather than complete species turnover. This pattern is in line with previous findings in urban vegetation, where management intensity often alters the relative dominance of species without necessarily causing large-scale species replacement [12]. In this study, high-density plots generally supported fewer species with moderate to high abundance, indicating a more restricted community structure under stronger competitive conditions.

5. SUMMARY

This study showed that spontaneous plant community diversity in park greenspaces exhibited clear seasonal dynamics, with diversity increasing from winter to spring and peaking in March–April. The effects of sowing density were strongly time-dependent, with limited differences among treatments during early stages but more pronounced effects during the spring growth period.

Higher sowing densities were associated with lower diversity and species richness during the peak period, while evenness was mainly influenced by temporal variation. Sowing density also affected community composition primarily through changes in species abundance rather than species turnover.

Overall, sowing density can serve as a practical management tool for regulating spontaneous plant diversity, and March–April represents a key period for implementing management interventions.

CONFLICTS OF INTEREST

The authors declare that they have no conflict of interest.

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