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RECEIVED 30 June 2026

REVISED 28 July 2026

ACCEPTED 29 July 2026

PUBLISHED 14 August 2026

### CITATION

Caser M, Pomatto E, Busato E, Gallizia S,  
Devecchi M, Ferracini C and Larcher F  
(2026) Functional composition of  
perennial herbaceous mixtures drives  
vegetation stability, weed control and  
biodiversity in low-maintenance urban  
green spaces.  
*Front. Hortic.* 5:1923775.  
doi: 10.3389/fhort.2026.1923775

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# Functional composition of perennial herbaceous mixtures drives vegetation stability, weed control and biodiversity in low- maintenance urban green spaces

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**Introduction:** Urban green spaces require planting strategies that simultaneously enhance biodiversity, reduce maintenance inputs, and improve resilience to climate change. Herbaceous perennial mixtures represent promising alternatives to conventional lawns and simplified ornamental plantings, although their long-term performance under low-input management remains insufficiently documented. This study evaluated the suitability of different perennial mixtures for sustainable urban landscaping, focusing on vegetation performance, management requirements, ornamental value, and insect biodiversity.

**Methods:** Twelve mixtures of ornamental perennial species were evaluated over three consecutive years under field conditions in northwestern Italy, without irrigation or fertilization. Plant performance was assessed through ground cover, weed suppression, ornamental quality, and flowering dynamics. In 2023–2024, carabid beetles and butterflies were monitored as bioindicator groups to assess the potential contribution of the experimental area to insect biodiversity.

**Results:** Perennial mixture significantly affected vegetation performance, with marked differences in establishment and persistence. Mixtures dominated by *Stachys byzantina*, *Sedum reflexum*, *Carex flacca*, *Festuca glauca* 'Elijah Blue', *Phlox subulata*, *Sedum spurium* 'John Creech', and *Geranium* × *cantabrigiense* 'Karmina' rapidly achieved stable canopy closure (>89%), maintained high ornamental quality (>81%), and effectively suppressed weeds. Conversely, mixtures lacking persistent canopy-forming species showed poor establishment, limited ground cover, and greater weed biomass. Flowering was strongly seasonal, peaking in late spring, while mixtures containing complementary flowering taxa provided more continuous floral resources. Biodiversity monitoring recorded 6,897 carabid beetles and 2,271 butterflies, with insect abundance showing pronounced seasonal variation. Species of conservation interest, including *Lycaena dispar* and *Lucanus cervus*, were also recorded.

**Discussion:** Functional composition, rather than species richness alone, emerged as a key determinant of perennial mixture performance by influencing canopy development, weed suppression, ornamental quality, and habitat structure. Combining flowering-rich mixtures that provide seasonally complementary

floral resources with structurally persistent, weed-suppressive vegetation may therefore represent an effective strategy for simultaneously supporting pollinators and ground-dwelling arthropods. Trait-based perennial mixtures can provide resilient, biodiversity-friendly, and low-maintenance solutions for climate-adapted urban green infrastructure.

#### KEYWORDS

low-input landscaping, pollinators, urban biodiversity, urban greening, weed suppression

## 1 Introduction

Urban green spaces are increasingly recognized as essential components of sustainable cities because they provide multiple ecosystem services, support biodiversity, and enhance human well-being (Larcher et al., 2021). However, conventional urban greenery is still largely dominated by intensively managed lawns and simplified ornamental plantings that require substantial inputs of water, fertilizers, and labour while providing limited ecological value (Smith and Fellowes, 2015). These management practices contribute to biotic homogenization and reduce the capacity of urban green spaces to function as effective habitats for native flora and fauna (Threlfall et al., 2017; Mata et al., 2021). Consequently, there is increasing interest in alternative planting systems capable of combining ecological functionality with reduced management inputs.

Among the available solutions, herbaceous perennial communities have emerged as one of the most promising approaches for developing resilient, low-maintenance urban landscapes. Compared with annual bedding plants and conventional lawns, perennial mixtures provide persistent vegetation cover, greater structural complexity, and long-term stability while reducing irrigation, fertilization, and weed control requirements (Benvenuti, 2014; Castelli et al., 2021). Dense and functionally complementary perennial communities rapidly occupy available space, limiting the establishment of spontaneous weeds through canopy closure and efficient resource capture (Bjørn et al., 2019; Pomatto et al., 2023). Increasing the continuity of the herbaceous layer has also been shown to improve habitat suitability for multiple taxonomic groups, including insects, birds, and bats, without compromising usability or ornamental value (Threlfall et al., 2017; Pomatto et al., 2023). Experimental studies have demonstrated that species composition is a major determinant of the ecological and management performance of perennial plantings. High plant density and sustained ground cover increase resistance to invasion by non-planted species and reduce the need for repeated manual or chemical weed control over multi-year periods (Bjørn et al., 2019; Pomatto et al., 2023). For example, Pomatto et al. (2023) evaluated seven combinations of six perennial species under non-irrigated, low-maintenance conditions and found that functionally complementary mixtures, particularly those including *Tulbaghia violacea* and *Phlox subulata*, ensured rapid canopy closure, stable ground cover, reduced weed biomass, and fewer manual weeding operations than more complex multi-species assemblages. Likewise, species-rich perennial meadows have been shown to persist over several years while simultaneously reducing maintenance costs and resisting invasion by non-target

species (Bjørn et al., 2019; Mody et al., 2020). These findings emphasize that functional complementarity, rather than species richness alone, is fundamental for designing effective perennial plantings.

Beyond their management benefits, perennial herbaceous communities provide important ecological functions by supporting urban biodiversity. Their structural complexity and extended life cycle create stable overwintering habitats and continuous floral resources that benefit pollinators such as bees, hoverflies, and butterflies. Erickson et al. (2021) demonstrated that pollinator abundance and plant–pollinator network complexity vary markedly among ornamental cultivars, indicating that cultivar selection strongly influences urban ecosystem services. Similarly, indigenous perennial vegetation supports greater insect species richness and functional diversity than conventional ornamental plantings because of its stronger ecological relationships with local fauna (Mata et al., 2021). At the same time, recent work has highlighted important ecological trade-offs. While flowering-rich perennial vegetation enhances pollinator abundance, changes in vegetation structure and litter dynamics may influence soil biodiversity, including *Collembola* and gastropods, through modifications of moisture conditions, decomposition processes, and management practices such as mowing (Rust et al., 2024). Consequently, perennial mixtures should be considered multifunctional systems in which vegetation structure simultaneously affects above- and belowground biodiversity. Assessing the ecological value of perennial plantings requires appropriate bioindicators. Carabid beetles are widely used as indicators of habitat quality because they respond rapidly to environmental changes, play important roles in pedogenesis, trophic interactions, and weed seed predation, and can be sampled efficiently using pitfall traps (Avgin and Luff, 2010; Busato et al., 2024). Butterflies also represent valuable bioindicators owing to their dependence on specific host plants, floral resources, and microclimatic conditions, making them highly sensitive to habitat modification (Sajjad, 2020; Chowdhury et al., 2023). Together, these taxa provide complementary information on the capacity of urban perennial vegetation to support insect biodiversity.

Climate change further reinforces the need for resilient urban planting systems. Increasing summer drought and water restrictions are challenging the sustainability of traditional urban greenery in Mediterranean and temperate regions. Many herbaceous perennials, particularly those adapted to dry and nutrient-poor environments, possess morphological and physiological traits that confer drought tolerance, reduced water demand, and long-term persistence under low-input management (Toscano et al., 2019; Pomatto

et al., 2023). Species such as *Sedum* spp., *Delosperma cooperi*, and *Phlox subulata* therefore represent promising candidates for climate-resilient urban landscapes. In addition to ecological performance, the successful implementation of biodiversity-oriented plantings depends on public acceptance and management feasibility. Recent studies indicate that both practitioners and urban green-space managers increasingly recognize the value of integrating ornamental and semi-natural vegetation when maintenance regimes are clearly defined (Barnes et al., 2018; Borysiak and Stepniewska, 2022). Although previous research has demonstrated the ecological and management benefits of perennial herbaceous plantings, most studies have focused on a limited number of species, short experimental periods, or single ecosystem functions such as weed suppression or pollinator attraction. Comparatively little information is available on how the functional composition of perennial mixtures simultaneously influences vegetation establishment, ornamental quality, weed suppression, and different components of urban insect biodiversity under long-term low-input management.

Therefore, the aim of this study was to evaluate the performance of twelve herbaceous perennial mixtures cultivated under low-input conditions over three consecutive years (2022–2024). Specifically, we assessed: (i) vegetation development and persistence; (ii) ground cover and weed suppression; (iii) ornamental quality; and (iv) the response of selected insect groups, namely Carabidae and Lepidoptera, as indicators of urban biodiversity. We hypothesized that mixtures composed of functionally complementary species would provide greater vegetation stability, more effective weed suppression, higher ornamental quality, and increased support for beneficial insect communities than mixtures lacking persistent canopy-forming species.

## 2 Materials and methods

### 2.1 Plant material and experimental design

The experiment lasted for three years (2022–2024) at the “Bosco Le Risere” nursery (Candiolo, Piedmont, Northwest Italy; 44° 57' 53.93" N Lat., 7° 34' 23.05" E Long.; 237 m. a.s.l.). Figure 1 shows the rainfall (mm) and medium temperature (°C) values detected during the entire experiment.

In Table 1 the traits of the 61 selected ornamental perennial herbaceous species within their mix combination are reported. All of them were selected for their rusticity, good adaptation to urban sun exposure, and low water and nutrient needs (Figure 2).

The selected mix of ornamental perennials were randomized and planted in the experimental field exposed to full sun.

As shown in Figures 3 and 4, the experimental field was divided into 36 plots, 4 m<sup>2</sup> each, with a space of 0.5 m between them. Three replicates for each mixture were evaluated. In each plot, 15 plants per m<sup>2</sup> (i.e., 60 plants per plot<sup>-1</sup>) were planted. These plants were previously grown at “Vivaio Purpurea di Alberto Peyron” (Piobesi torinese, TO, Italy) (pot diameter: 9 cm). Specifically, 6 or 15 plants for each taxa were used in plots with combinations of 10 or 4 different perennials, respectively. After land preparation of the experimental field a growing substrate consisted of agricultural soil amended with coconut fiber was added at a rate of 10 kg plot<sup>-1</sup> (Mattoni Natural Cocco, mod. BK5.OW.TOP.MIX5, AGEON S.R.L., Borgo San Dalmazzo, Italy). Plots were then fertilized once with 0.13 kg plot<sup>-1</sup> of Labin (mineral–organic fertilizer, NPK 12–12–15; Productos Agrícolas MACASA s.l., Igualada, Spain) and 0.12 kg plot<sup>-1</sup> of Nitrophoska Gold (slow-release fertilizer, NPK 15–9–16; COMPO EXPERT Italia Srl, Cesano Maderno, Italy). Plots were manually weeded to minimize competition during the establishment phase, applying 0.16 kg plot<sup>-1</sup> of PotClean 2G (DIACHEM S.P.A., Caravaggio, Italy). Perennial plants were transplanted into the plots on autumn 2021. Subsequently, plots were mulched with 148.5 kg plot<sup>-1</sup> of volcanic lapillus (particle size 8–15 mm; Centro Evergreen Turco di Amerio Eugenio & C. SAS, Moncalieri, Italy). An additional 16.5 kg plot<sup>-1</sup> of lapillus was applied during the first growing season. The experiment officially started on April 2022. Throughout the three-year experimental period, plots were managed according to a low-maintenance regime typical of public green spaces, without irrigation or fertilization and with periodic manual weed control. During late winter and mid-summer, senescent aboveground biomass was removed.

### 2.2 Data collection

Weed development and management were monitored throughout the experimental period. All visual evaluations were performed by the same trained observer throughout the three-year experiment

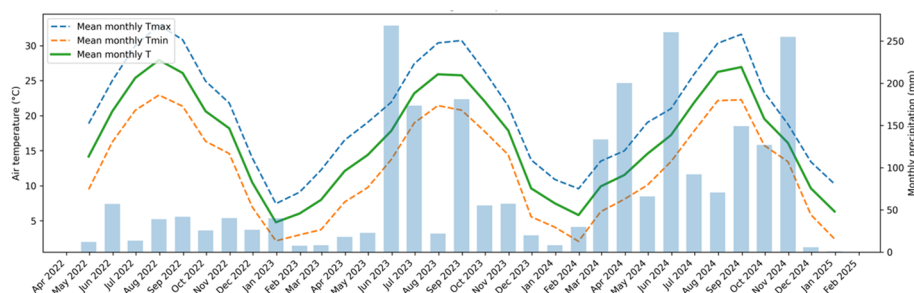


FIGURE 1

Monthly mean, maximum, and minimum air temperatures (°C, lines) and monthly cumulative precipitation (mm, bars) recorded from April 2022 to December 2024 at the ARPA Piemonte meteorological station used as climatic reference for the experimental site. Figure created by the authors from ARPA Piemonte meteorological data.

TABLE 1 Composition and functional traits of the perennial herbaceous combinations (Code) tested in the experiment.

| Code | Species/cultivar                              | Functional group      | Habit                                      | Blooming months |
|------|-----------------------------------------------|-----------------------|--------------------------------------------|-----------------|
| sA   | <i>Carex</i> spp.                             | Sedge                 | Clump-forming sedge                        | Apr–Jun         |
|      | <i>Ajuga reptans</i> L.                       | Forb – groundcover    | Creeping, stoloniferous, mat-forming       | Apr–Jun         |
|      | <i>Hieracium pilosella</i> L.                 | Forb – groundcover    | Rosette-forming, stoloniferous; low mat    | May–Aug         |
|      | <i>Lythrum salicaria</i> L.                   | Forb                  | Erect tall forb                            | Jun–Sep         |
|      | <i>Mentha suaveolens</i> Ehrh.                | Forb                  | Rhizomatous/spreading aromatic perennial   | Jul–Sep         |
|      | <i>Saponaria officinalis</i> L.               | Forb                  | Erect perennial; patch-forming             | Jun–Sep         |
|      | <i>Silene italica</i> L.                      | Forb                  | Tufted/erect perennial                     | May–Jul         |
|      | <i>Silene vulgaris</i> (Moench) Garcke        | Forb                  | Erect to semi-prostrate perennial          | May–Aug         |
|      | <i>Vinca minor</i> L.                         | Forb – groundcover    | Evergreen creeping groundcover             | Feb–Apr         |
|      | <i>Viola odorata</i> L.                       | Forb – groundcover    | Low rosette; short rhizomes                | Feb–Apr         |
| sB   | <i>Stipa tenuissima</i> Trin.                 | Grass                 | Fine-textured bunchgrass                   | Jun–Aug         |
|      | <i>Pennisetum alopecuroides</i> ‘Hameln’      | Grass                 | Clump-forming ornamental grass             | Aug–Oct         |
|      | <i>Iris germanica</i> ‘Harvest of Memories’   | Forb                  | Rhizomatous clumps; upright fans           | Apr–May         |
|      | <i>Rudbeckia fulgida</i> ‘Goldsturm’          | Forb                  | Upright clumps                             | Jul–Oct         |
| sC   | <i>Achillea millefolium</i> ‘Summer Pastels’  | Forb                  | Upright clumps; flat-topped inflorescences | Jun–Sep         |
|      | <i>Armeria pseudarmeria</i> ‘Ballerina Red’   | Forb                  | Tufted/cushion-forming                     | Apr–Jun         |
|      | <i>Dianthus barbatus</i> L.                   | Forb                  | Upright tufted                             | May–Jul         |
|      | <i>Gaura lindheimeri</i> ‘Siskiyou Pink’      | Forb                  | Airy upright habit                         | Jun–Oct         |
|      | <i>Hemerocallis</i> ‘Stella de Oro’           | Forb                  | Clump-forming; fleshy roots                | Jun–Oct         |
|      | <i>Phlox subulata</i> ‘Mac Daniels’           | Forb – groundcover    | Mat-forming evergreen groundcover          | Mar–May         |
|      | <i>Potentilla neumanniana</i>                 | Forb – groundcover    | Low mound; semi-evergreen                  | Apr–Jun         |
|      | <i>Sedum album</i> ‘Coral Carpet’             | Succulent groundcover | Mat-forming succulent                      | Jun–Aug         |
|      | <i>Tulbaghia violacea</i> Harv.               | Forb                  | Clump-forming; strap leaves (bulb-like)    | Jun–Oct         |
|      | <i>Delosperma cooperi</i> (Hook. f.) L. Bolus | Succulent groundcover | Mat-forming succulent                      | Jun–Sep         |
| sD   | <i>Oxalis acetosella</i> L.                   | Forb – groundcover    | Low woodland groundcover                   | Apr–Jun         |
|      | <i>Sedum</i> ‘John Creech’                    | Succulent groundcover | Mat-forming succulent                      | Jun–Aug         |
|      | <i>Phlox subulata</i> ‘Candy Stripes’         | Forb – groundcover    | Mat-forming groundcover                    | Mar–May         |
|      | <i>Saponaria officinalis</i> L.               | Forb                  | Erect perennial; patch-forming             | Jun–Sep         |
| sE   | <i>Ajuga reptans</i> L.                       | Forb – groundcover    | Creeping, stoloniferous                    | Apr–Jun         |
|      | <i>Nepeta nepitella</i> L.                    | Forb                  | Clump-forming aromatic perennial           | May–Sep         |
|      | <i>Saponaria officinalis</i> L.               | Forb                  | Erect perennial; patch-forming             | Jun–Sep         |
|      | <i>Silene italica</i> L.                      | Forb                  | Tufted/erect perennials                    | May–Aug         |
|      | <i>Pennisetum alopecuroides</i> ‘Hameln’      | Grass                 | Clump-forming ornamental grass             | Aug–Oct         |
|      | <i>Imperata cylindrica</i> ‘Red Baron’        | Grass                 | Upright clumps; colored foliage            | Aug–Oct         |

(Continued)

TABLE 1 Continued

| Code | Species/cultivar                                  | Functional group       | Habit                              | Blooming months |
|------|---------------------------------------------------|------------------------|------------------------------------|-----------------|
|      | <i>Festuca glauca</i> 'Elijah Blue'               | Grass                  | Low clump-forming grass            | May–Jun         |
|      | <i>Phlox subulata</i> 'Trot Pink'                 | Forb – groundcover     | Mat-forming groundcover            | Mar–May         |
|      | <i>Tulbaghia violacea</i> Harv.                   | Forb                   | Clump-forming                      | Jun–Oct         |
|      | <i>Sedum spurium</i> 'John Creech'                | Succulent groundcover  | Mat-forming succulent              | Jun–Aug         |
| sF   | <i>Phlox subulata</i> 'Mac Daniels'               | Forb – groundcover     | Mat-forming groundcover            | Mar–May         |
|      | <i>Tulbaghia violacea</i> Harv.                   | Forb                   | Clump-forming                      | Jun–Oct         |
|      | <i>Sedum spurium</i> 'John Creech'                | Succulent groundcover  | Mat-forming succulent              | Jun–Aug         |
|      | <i>Geranium</i> × <i>cantabrigiense</i> 'Karmina' | Forb – groundcover     | Spreading mound; aromatic foliage  | May–Jul         |
| sG   | <i>Carex flacca</i> Schreb.                       | Sedge                  | Clump-forming sedge                | Apr–Jun         |
|      | <i>Festuca glauca</i> 'Elijah Blue'               | Grass                  | Low clump-forming grass            | May–Jun         |
|      | <i>Achillea tomentosa</i> 'Aurea'                 | Forb                   | Low mound                          | May–Aug         |
|      | <i>Alyssum saxatile</i> L.                        | Forb                   | Cushion-forming                    | Mar–May         |
|      | <i>Artemisia ludoviciana</i> Nutt.                | Forb                   | Upright clumps; aromatic           | Jul–Sep         |
|      | <i>Cerastium tomentosum</i> L.                    | Forb – groundcover     | Mat-forming, silvery groundcover   | Apr–Jun         |
|      | <i>Cineraria maritima</i> Pels & Meijden          | Subshrub               | Woody-based mound; silvery foliage | Jun–Aug         |
|      | <i>Marrubium supinum</i> L.                       | Forb                   | Low clump; aromatic                | Jun–Aug         |
|      | <i>Sedum reflexum</i> L.                          | Succulent groundcover  | Mat-forming succulent              | Jun–Aug         |
|      | <i>Stachys byzantina</i> K.                       | Forb                   | Clump-forming; woolly foliage      | Jun–Aug         |
| sH   | <i>Festuca glauca</i> 'Elijah Blue'               | Grass                  | Low clump-forming grass            | May–Jun         |
|      | <i>Cerastium tomentosum</i> L.                    | Forb – groundcover     | Mat-forming groundcover            | Apr–Jun         |
|      | <i>Dianthus deltoides</i> 'Albus Plenus'          | Forb – groundcover     | Low mat/tuft                       | Jun–Aug         |
|      | <i>Geranium</i> 'Biokovo'                         | Forb – groundcover     | Spreading mound                    | May–Jul         |
| oW   | <i>Ajuga tenorii</i> 'Chocolate Chip'             | Forb – groundcover     | Very low creeping mat              | Apr–Jun         |
|      | <i>Campanula poscharskyana</i> Degen              | Forb – groundcover     | Prostrate/spreading groundcover    | Jun–Sep         |
|      | <i>Carex comans</i> 'Bronze Form'                 | Sedge                  | Fine-textured clumps               | May–Jul         |
|      | <i>Geranium</i> 'Johnson's Blue'                  | Forb                   | Spreading mound                    | May–Jul         |
|      | <i>Hosta</i> 'Francee'                            | Forb                   | Clump-forming                      | Jun–Aug         |
|      | <i>Hosta ventricosa</i> Stearn                    | Forb                   | Clump-forming                      | Jul–Aug         |
|      | <i>Lamium maculatum</i> 'Silver Beacon'           | Forb – groundcover     | Creeping groundcover               | Apr–Jun         |
|      | <i>Liriope muscari</i> 'Majestic'                 | Forb                   | Clump-forming; grass-like foliage  | Aug–Oct         |
|      | <i>Polemonium yezoense</i> 'Purple Rain Strain'   | Forb                   | Clump-forming                      | May–Jun         |
|      | <i>Tradescantia andersoniana</i> 'Little Doll'    | Forb                   | Clump-forming                      | Jun–Aug         |
| oY   | <i>Acorus gramineus</i> 'Ogon'                    | Graminoid              | Clump-forming; grass-like leaves   | May–Jun         |
|      | <i>Hyacinthoides hispanica</i> (Mill.) Rothm.     | Geophyte               | Bulbous; upright leaves            | Apr–May         |
|      | <i>Tradescantia andersoniana</i> 'Little Doll'    | Forb                   | Clump-forming                      | Jun–Aug         |
|      | <i>Carex</i> 'Ice Dance'                          | Sedge                  | Clump-forming; evergreen           | Apr–Jun         |
| oX   | <i>Iberis sempervirens</i> 'Snowflake'            | Subshrub – groundcover | Evergreen, dense mound             | Mar–May         |
|      | <i>Astilbe japonica</i> 'Washington'              | Forb                   | Clump-forming                      | Jun–Jul         |

(Continued)

TABLE 1 Continued

| Code | Species/cultivar                                  | Functional group   | Habit                                  | Blooming months |
|------|---------------------------------------------------|--------------------|----------------------------------------|-----------------|
|      | <i>Convallaria majalis</i> L.                     | Geophyte           | Rhizomatous colony-forming groundcover | May             |
|      | <i>Hosta ventricosa</i> Stearn                    | Forb               | Clump-forming                          | Jul–Aug         |
| oZ   | <i>Carex comans</i> ‘Bronze Form’                 | Sedge              | Fine-textured clumps                   | May–Jul         |
|      | <i>Ajuga reptans</i> L.                           | Forb – groundcover | Creeping mat-forming                   | Apr–Jun         |
|      | <i>Convallaria majalis</i> L.                     | Geophyte           | Rhizomatous colony-forming groundcover | May             |
|      | <i>Viola odorata</i> L.                           | Forb – groundcover | Low rosette                            | Feb–Apr         |
|      | <i>Geranium</i> × <i>cantabrigiense</i> ‘Karmina’ | Forb – groundcover | Spreading mound                        | May–Jul         |
|      | <i>Campanula poscharskyana</i> Degen              | Forb – groundcover | Spreading groundcover                  | Jun–Sep         |
|      | <i>Liriope muscari</i> ‘Majestic’                 | Forb               | Clump-forming                          | Aug–Oct         |
|      | <i>Scolopendrium officinale</i> L.                | Fern               | Rosette fern                           | —               |
|      | <i>Hosta ventricosa</i> Stearn                    | Forb               | Clump-forming                          | Jul–Aug         |
|      | <i>Heuchera</i> ‘Palace Purple’                   | Forb               | Mounded foliage; flowering panicles    | May–Jul         |

For each taxon, the functional group, growth habit, and blooming period (expressed as flowering months under temperate conditions of Northern Italy) are reported.

in order to minimize observer bias. Manual weed removal was carried out twice per year, according to the schedule reported in Table 2, and the fresh weight of the harvested weed biomass was recorded separately for each plot immediately after weeding. Fresh weed biomass was selected to quantify the actual maintenance effort required for weed removal in urban green spaces.

The percentage ground cover of each plot was visually estimated on a monthly basis by the same trained evaluator, using a standardized scale ranging from 0% (completely bare soil) to 100% (complete vegetation cover of the plot surface). Intermediate values were assigned proportionally according to the estimated percentage of soil covered by the perennial canopy (e.g., 25, 50, 75%), considering the entire plot surface. This visual assessment method is commonly adopted in ornamental and ecological field trials because it provides a rapid and reliable estimate of canopy development under field conditions. In parallel, the ornamental quality of each perennial combination was also evaluated monthly through visual scoring, adopting a scale from 0% (experimental plot severely compromised) to 100% (excellent ornamental quality without visible defects). Intermediate scores reflected the overall aesthetic performance of the mixture by considering plant vigor, canopy uniformity, flowering abundance, persistence of foliage, and the presence of visual defects such as dead or senescent plants, excessive pruning requirements, lodging, or conspicuous spent inflorescences. Scores between the two extremes represented proportional reductions in ornamental value. For example, values around 75% indicated minor visual imperfections with good overall appearance, 50% corresponded to moderate aesthetic deterioration while maintaining acceptable visual quality, whereas values below 25% represented poor ornamental performance with severe loss of aesthetic value. Additionally, the number of taxa per plot with fully open flowers was recorded monthly as an indicator of flowering performance.

## 2.3 Carabid beetle and butterfly monitoring

Carabid beetles and butterflies were used as bioindicators within the entire experimental trial, during the two-year period 2023–2024. The firsts were monitored using pitfall traps positioned along a transect, spaced 2–3 meters apart, to ensure a valid sampling methodology. A total of 20 traps were deployed in the study area. Each trap consisted of a plastic cup (top diameter: 7.0 cm, base diameter: 4.5 cm, height: 8.5 cm) buried in the ground up to its rim and protected with a plastic cover to prevent flooding, minimize vinegar evaporation, and reduce non-target catches. The cups were filled three-quarters full with red vinegar (Ponti®, Ghemme (NO), Italy; acidity 6%) to enhance attraction and with dish soap to break surface tension. Traps were checked every 15 days, and their contents transferred into 50 mL plastic tubes (Sarstedt Ag. & Co., Nümbrecht, Germany) filled with 60% ethanol to preserve the collected individuals (Busato et al., 2024; Ferracini et al., 2025). Subsequently, only carabid beetles among all species caught were identified at the Department of Agricultural, Forest, and Food Sciences (DISAFA) using dichotomous keys (Casale et al., 1982; Sciaky, 1987; Casale, 1988; Pesarini and Monzini, 2010, 2011; Neri et al., 2011; Allegro, 2021, 2024; Allegro et al., 2022).

Butterfly monitoring, on the other hand, was conducted in 2023–2024 using the Pollard transect walk method (Pollard, 1977; Pollard et al., 1994). The method consists in counting and capturing individuals with an entomological net within a standardized observation area of 5 meters in width, height, and depth ahead of the observer. The transect had a length of 200 meters, and was divided into fixed sections of 50 meters. Butterflies were counted separately in each section with a brief pause of one to two minutes between sections, to facilitate data collection and minimize errors (Pellet, 2008; D’Amico, 2012). Surveys were carried out during the peak activity period for butterflies (approximately from 10 am to 4 pm)



FIGURE 2  
List of the 61 tested ornamental perennials.

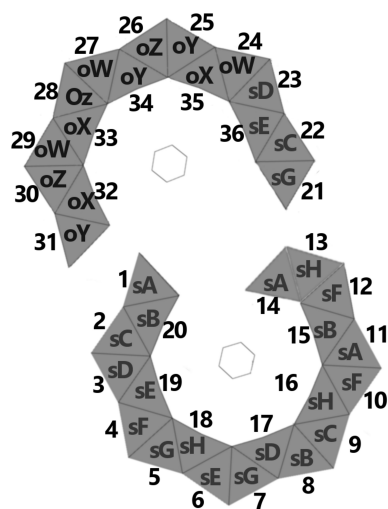


FIGURE 3  
Spatial layout of the experimental field and arrangement of perennial herbaceous combinations (see Table 1 for Code identification).

under optimal weather conditions: air temperature above 13 °C, cloud cover below 50%, and wind speed below level five on the Beaufort scale (Favilli, 2018; Pellet, 2008). Species identification was performed directly in the field whenever possible. When immediate identification was not feasible, specimens were further examined using a stereomicroscope and/or by comparison with voucher specimens deposited at the DISAFA-Entomology laboratory.

## 2.4 Data analysis

An arcsin transformation was performed on all data before statistical analysis to improve the homogeneity of the variance (Levene test;  $p < 0.05$ ). Statistical analyses were done using SPSS Version 29.0 (IBM SPSS Statistic, Segrate, Italy). All analysed data were checked for the normality of variance by using Shapiro–Wilks test ( $p > 0.05$ ). For all parameters, mean differences were computed using a one-way or two-way ANOVA with interaction by using Tukey's Bonferroni adjustment *post-hoc* test ( $p \leq 0.05$ ). Shannon–Wiener diversity indices were calculated for both butterflies and carabid beetles. This analysis aimed to investigate the biological diversity of their communities within the studied area (Parisi, 2021;



FIGURE 4  
Overview of the experimental field at “Bosco le Risere” site (Candiolo, TO), showing the layout of perennial herbaceous mixtures.

Gagnarli et al., 2023). All these statistical analyses were performed using R software (4.4.2).

### 3 Results

#### 3.1 Effect of mixture on plot coverage and weed biomass

Plot cover was significantly affected by perennial mixture, year, and their interaction ( $p < 0.001$  for all factors; Table 3). Among the tested mixtures, sG (94.2%), sB (93.6%), sH (92.1%), and sF (89.8%) achieved the highest mean cover values and rapidly provided almost complete soil coverage. Intermediate cover was observed in sA (84.9%) and sE (81.9%), whereas sC (75.9%) and sD (78.5%) showed slower canopy establishment. The lowest cover values were recorded in sY (30.8%) and sZ (29.5%), indicating poor establishment throughout the study. Ground cover increased significantly over time, from 63.4% in Year 1 to 75.9% in Year 2 and 80.2% in Year 3, although the rate of increase differed among mixtures (Figure 5). High-performing mixtures (sG, sB, sH and sF) reached stable cover already during the first year and maintained values above 90% thereafter. In contrast, sY and sZ showed only limited improvement over time, while intermediate mixtures progressively increased their cover during establishment. Seasonal trends (Supplementary Figures 1–5) showed that cover generally

increased from spring to summer and declined during winter, with the highest-performing mixtures exhibiting limited seasonal fluctuations. Mean weed fresh biomass was significantly affected by perennial mixture, year, and their interaction (Table 4). The strongest weed suppression was achieved by sG, which produced only 160.6 g of fresh weed biomass per weeding event (963.5 g accumulated over the three-year experiment). Low weed biomass was also recorded for sA (312.8 g; total 1,876.7 g) and sH (415.2 g;

TABLE 3 Effect of different studied perennial mixtures (code), years and their interaction on the plot coverage (%).

| Code        | Plot coverage (%) |
|-------------|-------------------|
| sA          | 84.9 a-d          |
| sB          | 93.6 ab           |
| sC          | 75.9 de           |
| sD          | 78.5 cde          |
| sE          | 81.9 bcd          |
| sF          | 89.8 abc          |
| sG          | 94.2 a            |
| sH          | 92.1 ab           |
| sW          | 59.7 f            |
| sX          | 67.6 ef           |
| sY          | 30.8 g            |
| sZ          | 29.5 g            |
| <i>p</i>    | ***               |
| Year        |                   |
| 1           | 63.4 c            |
| 2           | 75.9 b            |
| 3           | 80.2 a            |
| <i>p</i>    | ***               |
| Interaction |                   |
| Mix*Year    | ***               |

The statistical relevance is provided (\*\*\* $p < 0.001$ ). Different letters indicate significant differences according to Tukey’s Bonferroni adjusted *post-hoc* test ( $p < 0.05$ ).

TABLE 2 The dates of the two manual weeding scheduled per year.

| Year | Date              |
|------|-------------------|
| 1    | 19 July 2022      |
|      | 21 September 2022 |
| 2    | 04 May 2023       |
|      | 24 July 2023      |
| 3    | 14 May 2024       |
|      | 16 July 2024      |

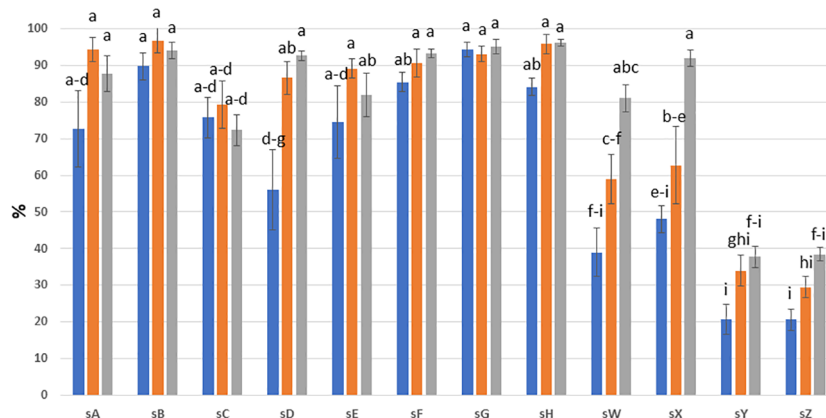


FIGURE 5

Interaction between perennial mixtures and year (blue bars, 1 year; orange bars, 2 year; grey bars, 3 year) on mean percentage plot ground cover (%). Different letters indicate significant differences according to Tukey's Bonferroni adjusted *post-hoc* test ( $p < 0.05$ ).

total 2,491.3 g). In contrast, sY accumulated the greatest amount of weeds (1,363.5 g per weeding event; total 8,181.2 g), followed by sW and sZ, whereas the remaining mixtures showed intermediate weed suppression. Weed biomass increased significantly after the establishment year, rising from 269.7 g in Year 1 to 920.5 g in Year 2 and 876.0 g in Year 3, although temporal patterns varied among mixtures (Figure 6). The best-performing mixtures (sG, sA and

sH) maintained consistently low weed biomass throughout the experiment, demonstrating stable weed suppression under low-input management. Conversely, sY, sW and sZ exhibited a marked increase in weed biomass over time, while the remaining mixtures showed intermediate behaviour, suggesting partial weed suppression that improved with canopy development but remained less effective than the best-performing treatments.

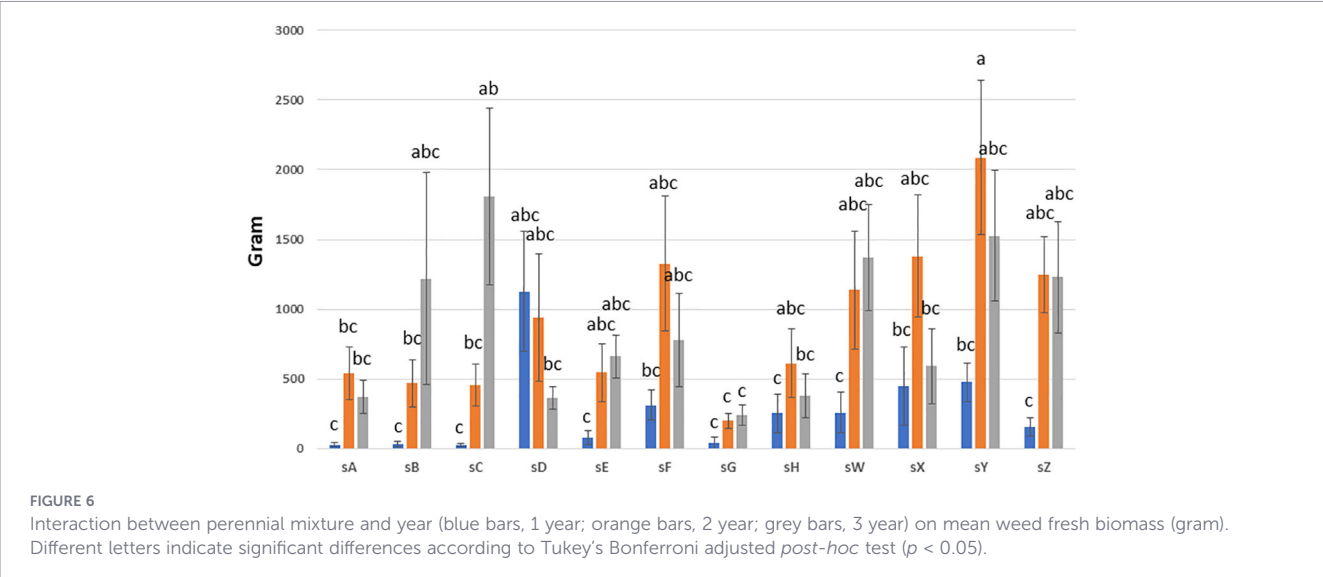
TABLE 4 Effect of different studied perennial mixtures, years and their interaction on the mean weed fresh weight (gram) harvested during the entire experiment.

| Mixture     | Fresh weight (gram) | Total fresh weight |
|-------------|---------------------|--------------------|
| sA          | 312.8 bc            | 1,876.7            |
| sB          | 573.6 abc           | 3,441.8            |
| sC          | 762.2 abc           | 4,573.4            |
| sD          | 810.3 ab            | 4,861.8            |
| sE          | 455.9 bc            | 2,559.3            |
| sF          | 805.9 abc           | 4,835.6            |
| sG          | 160.6 c             | 963.5              |
| sH          | 415.2 bc            | 2,491.3            |
| sW          | 921.9 ab            | 5,531.2            |
| sX          | 805.7 abc           | 4,834.4            |
| sY          | 1363.5 a            | 8,181.2            |
| sZ          | 877.2 ab            | 5,263.1            |
| <i>p</i>    | ***                 |                    |
| Year        |                     |                    |
| 1           | 269.7 b             |                    |
| 2           | 920.5 a             |                    |
| 3           | 876.0 a             |                    |
| <i>p</i>    | ***                 |                    |
| Interaction |                     |                    |
| Mix*Year    | **                  |                    |

The statistical relevance is provided (\*\*\* $p < 0.001$ ; \*\* $p < 0.01$ ). Different letters indicate significant differences according to Tukey's Bonferroni adjusted *post-hoc* test ( $p < 0.05$ ). The total weed fresh weight harvested in the three years.

### 3.2 Effect of mixture on ornamental quality and biodiversity

Mean ornamental quality was significantly affected by perennial mixture and year ( $p < 0.001$  for both factors), whereas the Mix  $\times$  Year interaction was not significant (Table 5). The highest ornamental quality was recorded for sH (89.7%), followed by sB (86.4%), sG (84.7%), and sF (81.4%), which consistently maintained high visual performance throughout the experiment. Intermediate values were observed for sA, sC, sD (75–77%) and sE (73.4%), whereas sW (59.0%) and sX (65.7%) showed reduced aesthetic value. The poorest ornamental performance was recorded for sY (27.5%) and sZ (27.8%), reflecting their limited establishment and persistence. Ornamental quality improved significantly over time, increasing from 60.5% in Year 1 to 71.1% in Year 2 and 74.4% in Year 3. Seasonal trends (Supplementary Figures 6–8) showed that visual quality generally increased from spring to summer, corresponding to maximum vegetative growth and flowering, before declining during autumn and winter. The best-performing mixtures (sH, sB, sG and sF) maintained consistently high ornamental quality across seasons, whereas intermediate mixtures progressively improved after the establishment year. In contrast, sY and sZ remained visually poor throughout the experiment, while sW and sX showed acceptable summer appearance but pronounced declines during early spring and winter. The mean number of blooming taxa was significantly affected by perennial mixture ( $p < 0.001$ ) and year ( $p < 0.05$ ), whereas the Mix  $\times$  Year interaction was not significant (Table 6). Mixture sC supported the highest flowering diversity, with an average of 1.9 blooming taxa per assessment, followed by sA (1.2) and sG (1.0). All remaining mixtures averaged fewer than one



blooming taxon, with sZ showing the lowest flowering performance (0.3 taxa). Flowering diversity declined over time, decreasing from 1.0 taxa in Year 1 to 0.9 in Year 2 and 0.6 in Year 3, indicating a progressive reduction in the number of simultaneously flowering species. Flowering was also strongly influenced by season ( $p < 0.001$ ; Table 7). The highest flowering activity occurred in late spring (1.9 taxa), followed by early summer (1.4) and early spring (1.2), whereas flowering progressively declined from late summer

onwards and was almost absent during winter. Figure 7 highlights the different seasonal flowering patterns among perennial mixtures. Mixture sC consistently provided the greatest floral diversity during spring and early summer (2.0–4.7 blooming taxa), mainly due to the complementary flowering of *Dianthus barbatus*, *Gaura lindheimeri* ‘Siskiyou Pink’, *Hemerocallis* ‘Stella de Oro’, *Phlox subulata* ‘Mac Daniels’, and *Potentilla neumanniana*. Mixture sA ranked second

TABLE 5 Effect of different studied perennial mixtures, years and their interaction on the mean ornamental quality (%).

| Mixture     | Ornamental quality (%) |
|-------------|------------------------|
| sA          | 76.6 abc               |
| sB          | 86.4 ab                |
| sC          | 76.8 abc               |
| sD          | 74.9 abc               |
| sE          | 73.4 bc                |
| sF          | 81.4 ab                |
| sG          | 84.7 ab                |
| sH          | 89.7 a                 |
| sW          | 59.0 d                 |
| sX          | 65.7 cd                |
| sY          | 27.5 e                 |
| sZ          | 27.8 e                 |
| <i>p</i>    | ***                    |
| Year        |                        |
| 1           | 60.5 b                 |
| 2           | 71.1 a                 |
| 3           | 74.4 a                 |
| <i>p</i>    | ***                    |
| Interaction |                        |
| Mix*Year    | ns                     |

The statistical relevance is provided (\*\*\* $p < 0.001$ ; ns =  $p > 0.05$ ). Different letters indicate significant differences according to Tukey's Bonferroni adjusted *post-hoc* test ( $p < 0.05$ ).

TABLE 6 Effect of different studied perennial mixtures, years and their interaction on the mean number of blooming variety or species.

| Mixture     | Blooming taxa (nr.) |
|-------------|---------------------|
| sA          | 1.2 ab              |
| sB          | 0.6 b               |
| sC          | 1.9 a               |
| sD          | 0.8 b               |
| sE          | 0.8 b               |
| sF          | 0.9 b               |
| sG          | 1.0 ab              |
| sH          | 0.5 b               |
| sW          | 0.8 b               |
| sX          | 0.5 b               |
| sY          | 0.6 b               |
| sZ          | 0.3 b               |
| <i>p</i>    | ***                 |
| Year        |                     |
| 1           | 1.0 a               |
| 2           | 0.9 a               |
| 3           | 0.6 b               |
| <i>p</i>    | *                   |
| Interaction |                     |
| Mix*Year    | ns                  |

The statistical relevance is provided (\*\*\* $p < 0.001$ ; \* $p < 0.05$ ; ns =  $p > 0.05$ ). Different letters indicate significant differences according to Tukey's Bonferroni adjusted *post-hoc* test ( $p < 0.05$ ).

TABLE 7 Effect of seasons on the mean number of blooming taxa during the entire experiment.

| Season       | Blooming taxa (Nr.) |
|--------------|---------------------|
| Early Spring | 1.2 b               |
| Late Spring  | 1.9 a               |
| Early Summer | 1.4 ab              |
| Late Summer  | 1.2 b               |
| Early Autumn | 0.4 c               |
| Late Autumn  | 0.1 c               |
| Early Winter | 0.0 c               |
| Late Winter  | 0.3 c               |
| p            | ***                 |

The statistical relevance is provided (\*\*\* $p < 0.001$ ). Different letters indicate significant differences according to Tukey's Bonferroni adjusted *post-hoc* test ( $p < 0.05$ ).

(1.3–2.5 blooming taxa), with flowering supported by *Lythrum salicaria*, *Mentha suaveolens*, *Saponaria officinalis*, *Silene italica*, *Silene vulgaris*, and *Vinca minor*. Most of the remaining mixtures generally supported one or fewer blooming taxa even during peak flowering. Although flowering declined in late summer, sC, and to a lesser extent sA and sG, maintained floral resources through species such as *Cerastium tomentosum*, *Marrubium supinum*, and *Stachys byzantina*. Flowering became negligible from early autumn onwards, confirming the strong seasonal limitation in floral availability. In the experimental area, during the 2023–2024 survey period, a total of 6897 carabid beetles individuals were collected. The most dominant species was *Abax contractus* (Heer, 1841), accounting for 2387 individuals (34.6% of the total catch), followed by *Harpalus rufipes* (De Geer, 1774) with 1506 individuals (21.8%), *Pterostichus melas italicus* (Dejean, 1828) with 808 individuals (11.7%), *Calathus fuscipes graecus* (Dejean, 1831) with 742 individuals (10.8%), and *Nebria brevicollis* (Fabricius, 1792) with 424 individuals (6.1%). For carabid beetles, both diversity indices showed higher values recorded in 2024. The Shannon index increased from 1.87 in 2023 to 2.01 in 2024 (Figure 8).

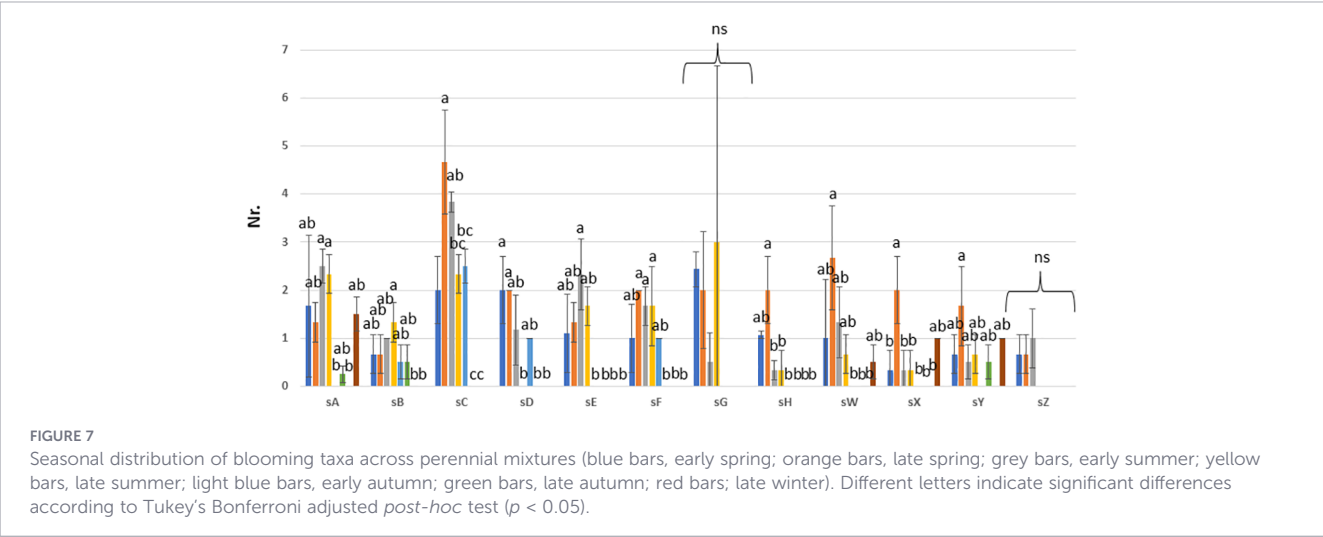
Moreover, a total of 2271 butterfly individuals was recorded. The most abundant species was *Pieris napi* (Linnaeus, 1758), with

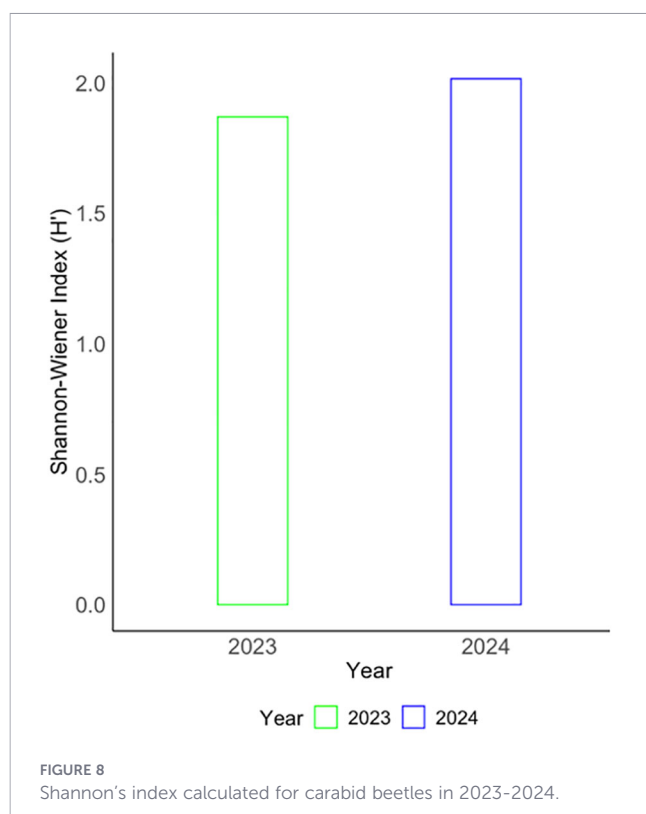
744 individuals (32.8% of the total catch), followed by *Polyommatus icarus* (Rottemburg, 1775) with 235 individuals (10.3%), *Maniola jurtina* (Linnaeus, 1758) with 216 individuals (9.5%), and *Melitaea didyma* (Esper, 1778) with 136 individuals (6.0%). The Shannon index for butterflies was higher in 2023 (1.68) than in 2024 (1.50) (Figure 9).

The abundance of both Coleoptera Carabidae and Lepidoptera Rhopalocera showed a pronounced seasonal pattern during the 2023–2024 monitoring period (Table 8). Adult specimens were recorded from early spring to early autumn, with abundance increasing progressively, reaching a maximum in late summer. For carabid beetles, mean abundance increased from 291 individuals in early spring to 568 in late spring and remained stable in early summer (563 individuals). Activity-density peaked in late summer (1,396 individuals) and subsequently declined to 614 individuals in early autumn, although values remained substantially higher than those recorded in spring. This trend suggests that the progressive establishment of dense perennial vegetation created increasingly favourable conditions for carabid communities by improving habitat structure, shelter, and trophic resources, rather than reflecting a reduction in biodiversity. A similar trend was observed for diurnal butterflies. Mean abundance increased from 71 individuals in early spring to 437 in late spring and 516 in early summer, reaching a maximum of 999 individuals in late summer. Numbers then decreased to 248 individuals in early autumn.

4 Discussion

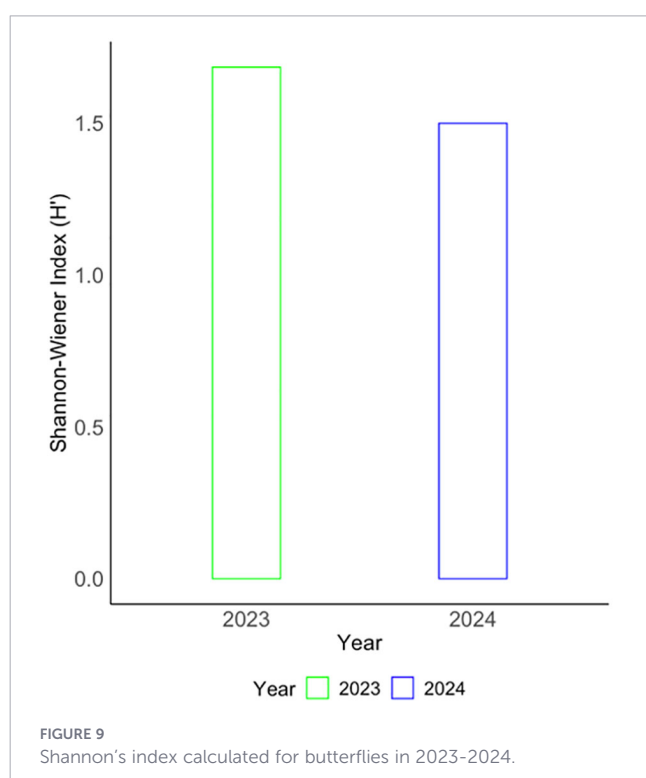
Overall, our three-year field trial confirms that perennial herbaceous mixtures can provide a robust low-input alternative to simplified urban plantings by simultaneously reducing maintenance requirements and improving ecological functionality. The significant Mix  $\times$  Year interaction for plot coverage indicates that mixtures differed not only in final cover but also in their rate of canopy closure under low-input management. Such temporal divergence is consistent with previous studies showing that rapid space occupation and canopy persistence are key determinants of





long-term performance because they reduce light availability at the soil surface and limit recruitment niches for spontaneous vegetation (Bjørn et al., 2019; Pomatto et al., 2023; Foo et al., 2018; Weston and Eom, 2008).

The highest-performing mixtures (sG, sB, sH and sF) achieved near-complete cover during the first year and maintained it



throughout the experiment. The excellent performance of sG can be attributed to the complementary combination of drought-tolerant graminoids (*Carex flacca*, *Festuca glauca* 'Elijah Blue'), mat-forming or high-cover species (*Cerastium tomentosum*, *Sedum reflexum*, *Stachys byzantina*), and aromatic stress-tolerant perennials (*Artemisia ludoviciana*, *Marrubium supinum*, *Cineraria maritima*). This functional composition likely enhanced near-ground shading and "living mulch" effects, mechanisms widely recognized as central to weed suppression in perennial groundcover systems (Bjørn et al., 2019; Pomatto et al., 2023; Foo et al., 2018; Weston and Eom, 2008). However, the progressive dominance of *Stachys byzantina* highlights the importance of interspecific competition in determining long-term mixture stability and species persistence under low-input conditions (Uppala, 2025; Forrester et al., 2022). Similarly, the high performance of sF reflects the complementary architecture of *Phlox subulata*, *Sedum spurium* 'John Creech', *Geranium × cantabrigiense* 'Karmina' and *Tulbaghia violacea*, confirming previous evidence that mixtures dominated by persistent mat-forming species rapidly stabilize cover and suppress weeds (Pomatto et al., 2023). The drought tolerance of *Phlox subulata* (Xiong et al., 2021) and the well-documented adaptation of *Sedum* species to dry, nutrient-poor substrates further support their suitability for climate-resilient urban plantings (Pérez et al., 2020; Moreno-García et al., 2025). In contrast, the poor performance of sY and sZ suggests that their species composition was poorly adapted to the combined stresses of full sun, summer drought and the absence of irrigation and fertilization, resulting in slow establishment, persistent bare soil and greater susceptibility to weed invasion (Weston and Eom, 2008; Foo et al., 2018).

Weed biomass followed a pattern closely associated with canopy development. Mixtures characterized by rapid and persistent cover, particularly sG, sA and sH, consistently maintained the lowest weed biomass throughout the experiment. In sA, species such as *Vinca minor*, *Ajuga reptans*, *Viola odorata* and *Hieracium pilosella* likely promoted rapid soil occupation and reduced opportunities for weed establishment, supporting previous findings that dense and persistent canopies are the primary mechanism driving weed suppression in ornamental perennial systems (Weston and Eom, 2008; Foo et al., 2018). Conversely, sY, and to a lesser extent sW and sZ, accumulated the greatest weed biomass, reflecting prolonged periods of incomplete canopy closure. The increase in weed biomass during Years 2 and 3 further emphasizes the importance of long-term evaluations, as weed

TABLE 8 Effect of season on the mean number of detected carabid beetles and diurnal butterflies during 2023–2024 in the experimental area.

| Season       | Carabid beetle (No.) | Diurnal butterflies (No.) |
|--------------|----------------------|---------------------------|
| Early spring | 291                  | 71                        |
| Late spring  | 568                  | 437                       |
| Early summer | 563                  | 516                       |
| Late summer  | 1396                 | 999                       |
| Early autumn | 614                  | 248                       |

pressure may intensify over time where canopy development remains incomplete (Bjørn et al., 2019; Pomatto et al., 2023). These findings confirm that mixtures capable of rapid canopy closure substantially reduce the maintenance effort required under low-input management (Weston and Eom, 2008; Pomatto et al., 2023).

The absence of irrigation and fertilization throughout the experiment reflects the increasing constraints affecting Mediterranean and temperate cities under climate change (Toscano et al., 2019; Pomatto et al., 2023). Mixtures including drought-adapted functional groups, such as *Sedum album*, *Sedum reflexum*, *Sedum spurium* 'John Creech', *Delosperma cooperi*, *Phlox subulata*, *Festuca glauca* 'Elijah Blue' and *Carex flacca*, proved particularly effective in maintaining high cover, limiting weed development and preserving ornamental quality under minimal management. These results are consistent with studies on urban nature-based solutions demonstrating the value of trait-diverse, drought-tolerant plant palettes for resilient green infrastructure (Pérez et al., 2020; Xu et al., 2026).

Ornamental quality also differed markedly among mixtures but improved after the establishment year. The consistently high performance of sH, followed by sB, sG and sF, demonstrates that perennial mixtures combining persistent foliage with seasonal flowering can maintain an attractive appearance throughout the year. The stable ranking of mixtures indicates that species composition, rather than plant age, primarily determined visual performance. In particular, the combination of *Festuca glauca* 'Elijah Blue', *Cerastium tomentosum*, *Dianthus deltoideus* 'Albus Plenus' and *Geranium* 'Biokovo' produced a cohesive vegetation structure that remained visually attractive beyond the flowering period, an important characteristic for increasing public acceptance of low-maintenance urban plantings (Barnes et al., 2018; Borysiak and Stępniewska, 2022).

Flowering dynamics revealed a progressive reduction in the number of simultaneously blooming taxa as the communities matured, suggesting increasing dominance of the most competitive species under low-input conditions. Flowering peaked during late spring and early summer before declining sharply from autumn onwards. Among the tested mixtures, sC, followed by sA, maintained the highest flowering diversity owing to complementary flowering periods provided by *Gaura lindheimeri* 'Siskiyou Pink', *Hemerocallis* 'Stella de Oro', *Achillea millefolium* 'Summer Pastels', *Tulbaghia violacea*, *Delosperma cooperi*, *Sedum album* 'Coral Carpet', *Lythrum salicaria* and other species. These findings support previous evidence that pollinator abundance depends not only on floral richness but also on the continuity of floral resources through time (Erickson et al., 2021; Mata et al., 2021).

Consistent with these flowering patterns, both butterflies and carabid beetles reached their highest abundance during late summer, likely reflecting favourable temperatures together with the availability of nectar, host plants, prey and suitable microhabitats (Avgin and Luff, 2010; Sajjad, 2020; Chowdhury et al., 2023). While sC and sA provided the richest floral resources for pollinators, the dense and structurally diverse vegetation of sG likely created favourable habitats for ground-dwelling arthropods. Together, these findings reinforce the importance of designing perennial mixtures that combine structural complexity with complementary flowering phenologies to enhance insect biodiversity. They further support previous evidence that heterogeneous

herbaceous vegetation and a well-developed midstorey layer are key drivers of faunal richness in urban ecosystems (Threlfall et al., 2017; Mata et al., 2021). Moreover, evidence from urban meadow conversions shows that replacing simplified plantings with flower-rich herbaceous systems can increase arthropod abundance while reducing maintenance costs and supporting the broader rationale for low-input herbaceous design strategies (Mody et al., 2020; Bretzel et al., 2016). However, the strong seasonal compression of both flowering and insect detections highlights a key design challenge: improving early- and late-season resource continuity without increasing inputs. Beyond community-level metrics, the monitoring produced records of high applied relevance. The detection of *Lycaena dispar* (Haworth, 1802) and *Lucanus cervus* (Linnaeus, 1758), both listed as priority species under the Habitat Directive, strengthens the conservation value of the study area. This evidence supports the argument that low-input, structurally diverse green spaces can significantly contribute to broader biodiversity targets. In addition, we report the presence of the carabid beetle *Stenolophus marginatus* (Dejean, 1829), hygrophilous and paludicolous specialist species typically associated with humid, organic-matter-rich substrates (e.g., fertilised hay meadows and vegetable gardens), often detected through light-attraction sampling; its regional expansion has been documented for Piedmont (since 2013), Switzerland (first record 2019), and Aosta Valley (first record 2019) (Bisio and Allegro, 2019; Chittaro and Marggi, 2015). This record is noteworthy as it suggests that the experimental perennial mixtures effectively foster moist micro-refugia and high organic matter accumulation, even within an urban matrix. The importance of soil conditions for carabid ecology has also been highlighted by Sukhodolskay et al. (2026), who demonstrated that soil organic carbon can modulate body-size patterns in *C. granulatus* populations.

## 5 Conclusion

Perennial herbaceous mixtures represent an effective alternative to simplified urban plantings under low-input management by combining stable ground cover, effective weed suppression, and high ornamental quality. Mixtures dominated by dense graminoids and persistent ground-covering species, particularly sG, sH, sB, and sF, achieved rapid canopy closure, maintained low weed biomass, and ensured stable visual performance, whereas mixtures lacking persistent canopy-forming species (sY and sZ) consistently showed poor establishment and limited weed suppression.

Flowering and insect activity followed marked seasonal patterns, with the highest floral diversity and pollinator abundance occurring from late spring to late summer. Among the tested mixtures, sC provided the greatest support for pollinators through its complementary assemblage of long-flowering species, including *Hemerocallis* 'Stella de Oro', *Gaura lindheimeri* 'Siskiyou Pink', *Achillea millefolium* 'Summer Pastels', *Tulbaghia violacea*, and *Rudbeckia fulgida* 'Goldsturm', while sA further extended nectar availability through *Lythrum salicaria*, *Saponaria officinalis*, and *Mentha suaveolens*. These results indicate that pollinator support depends primarily on the temporal continuity of floral resources combined with vegetation structure rather than on plant diversity

alone. The structurally complex vegetation of sG, characterized by *Carex flacca*, *Festuca glauca* ‘Elijah Blue’, *Stachys byzantina*, *Sedum reflexum*, and *Cerastium tomentosum*, also created favourable microhabitats for ground-dwelling arthropods, particularly Carabidae. In addition to their role as generalist predators, carabids may contribute to weed seed regulation (Charalabidis et al., 2025), while the dense perennial canopy promotes soil moisture and supports diverse communities of *Collembola*, other soil microarthropods, gastropods, and associated soil fauna.

The integration of flowering-rich mixtures (e.g., sC and sA) with structurally stable, weed-suppressive mixtures (e.g., sG) represents the most effective strategy for designing multifunctional urban plantings. Such combinations simultaneously enhance pollinator resources, support beneficial ground beetles, reduce maintenance requirements, and improve the ecological resilience of urban green spaces. These findings highlight the importance of trait-based species selection, long-term field evaluation, and integrated ecological assessments for developing biodiversity-oriented urban green infrastructure under increasing climatic and management constraints.

## Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

## Author contributions

MC: Data curation, Investigation, Methodology, Writing – original draft, Writing – review & editing. EP: Conceptualization, Methodology, Writing – review & editing. EB: Data curation, Investigation, Methodology, Writing – review & editing. SG: Data curation, Writing – original draft, Writing – review & editing. MD: Conceptualization, Supervision, Writing – review & editing. CF: Conceptualization, Supervision, Validation, Writing – original draft, Writing – review & editing. FL: Conceptualization, Data curation, Funding acquisition, Investigation, Methodology, Project administration, Supervision, Validation, Writing – review & editing.

## Funding

The author(s) declared that financial support was not received for this work and/or its publication.

## Acknowledgments

The authors gratefully acknowledge Alberto Peyron, Giorgio Quaglio, and Isotta Camarota for their valuable collaboration and

support during the experimental activities carried out at the “Le Risere” nursery.

## Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

The author FL declared that they were an editorial board member of Frontiers at the time of submission. This had no impact on the peer review process and the final decision.

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## Supplementary material

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/fhort.2026.1923775/full#supplementary-material>

### SUPPLEMENTARY FIGURE 1

Seasonal appearance of the sG perennial mixture during the experimental period. Photographs illustrate the visual development and persistence of the vegetation in (A) late spring, (B) summer, (C) autumn, and (D) winter, highlighting the rapid canopy closure, high ground cover, and structural stability of the mixture throughout the year under low-input management.

### SUPPLEMENTARY FIGURE 2

Seasonal appearance of the sY perennial mixture during the experimental period. Representative photographs taken in (A) late spring, (B) summer, (C) autumn, and (D) winter illustrate the limited canopy development and persistent areas of exposed mulch throughout the year, reflecting the low ground cover and poor establishment of this mixture under low-input management.

## SUPPLEMENTARY FIGURE 3

Seasonal variation in plot ground cover (%) of the perennial mixtures (sA–sZ) during Year 1 of the experiment. Bars represent the mean percentage ground cover recorded in each season, illustrating differences in canopy development and seasonal persistence among the perennial mixtures under low-input management. Error bars indicate standard deviation.

## SUPPLEMENTARY FIGURE 4

Seasonal variation in plot ground cover (%) of the perennial mixtures (sA–sZ) during Year 2 of the experiment. Bars represent the mean ornamental quality recorded at each seasonal assessment, illustrating differences in visual performance during the establishment phase of the perennial mixtures under low-input management. Error bars indicate standard deviation.

## SUPPLEMENTARY FIGURE 5

Seasonal variation in plot ground cover (%) of the perennial mixtures (sA–sZ) during Year 3 of the experiment. Bars represent the mean ornamental quality recorded at each seasonal assessment, illustrating differences in visual performance after the establishment phase under low-input management. Error bars indicate standard deviation.

## SUPPLEMENTARY FIGURE 6

Seasonal variation in ornamental quality (%) of the perennial mixtures (sA–sZ) during Year 1 of the experiment. Bars represent the mean ornamental quality recorded at each seasonal assessment, illustrating differences in visual performance after the establishment phase under low-input management. Error bars indicate standard deviation.

## SUPPLEMENTARY FIGURE 7

Seasonal variation in ornamental quality (%) of the perennial mixtures (sA–sZ) during Year 2 of the experiment. Bars represent the mean ornamental quality recorded at each seasonal assessment, illustrating differences in visual performance after the establishment phase under low-input management. Error bars indicate standard deviation.

## SUPPLEMENTARY FIGURE 8

Seasonal variation in ornamental quality (%) of the perennial mixtures (sA–sZ) during Year 3 of the experiment. Bars represent the mean ornamental quality recorded at each seasonal assessment, illustrating differences in visual performance after the establishment phase under low-input management. Error bars indicate standard deviation.

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