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Research Article

An evaluation of 'pollinator-friendly' wildflower seed mixes in Italy: are they potential vectors of alien plant species?

Ginevra Nota[1], Nicole Melanie Falla[1], Valentina Scariot[1*], Michele Lonati[1*]

1 University of Torino, Department of Agricultural, Forest and Food Sciences, Largo Paolo Braccini 2, 10095 Grugliasco (TO), Italy
Corresponding author: Ginevra Nota (ginevra.nota@unito.it)

Abstract

Wildflower areas are increasingly used in both urban and rural settings to enhance landscape aesthetics and help the conservation of pollinators, whose dramatic decline threatens both ecosystem functioning and agricultural production. Consequently, today many 'pollinator-friendly' wildflower seed mixes can be found on the market. Criteria for the design of these mixes are focused on the ability of the plants to attract pollinators, whereas the identity of the plants themselves in terms of their alien or native status is often not adequately considered. Moreover, seed mixes often lack sufficient floral resources in the early spring and late-season months, which are important to sustain pollinators throughout their whole life cycle. In this study, we analyzed 36 'pollinator-friendly' wildflower seed mixes commercially available in Italy in terms of (1) the abundance of native and alien species, (2) the occurrence of locally alien species with reference to three Italian geographic areas (northern, peninsular, and insular Italy), and (3) the flowering period of native and alien species. Most (83%) of the analyzed seed mixes contain species alien to Italy, with three of them also including invasive alien species. Among native species, many (41%) are locally alien to at least one of the geographic areas. Overall, native species provide earlier blooms than alien species and around 35% of the seed mixes lack blooms in early-spring (March) or prolonged throughout autumn (September-November). These findings highlight the widespread use of alien plant species in 'pollinator-friendly' wildflower mixes, which poses serious risks for biodiversity and habitat conservation, especially when sown in agricultural areas. We suggest a more careful design and use of such wildflower mixes, promoting a wider adoption of native seeds of local origin and a greater attention to the blooming period. If properly designed, wildflower mixes can represent an effective strategy for biodiversity conservation in both urban and rural areas.

Key words: Archaeophytes, biodiversity conservation, exotic plants, flowering period, invasive species, native plants, pollinators, wildflower strips

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Introduction

Wildflowers are annual or perennial herbaceous species having aesthetically pleasing flowers and being important for biodiversity conservation and pollination services (Bretzel and Romano 2013; Bretzel et al. 2016; Benvenuti et al. 2020). These species are suitable for planting in disturbed areas, such as in urban and agricultural settings, where floristic biodiversity is low due to anthropogenic pressure and agricultural intensification (Benvenuti et al. 2020; Nichols et al. 2022). In addition,

* Co-last authors.

as these areas are often dominated by autogamous and/or wind-pollinated plants, wildflowers provide important nectar and pollen resources to insect pollinators (Benvenuti et al. 2020). Currently, the decrease in abundance and diversity of pollinators such as bees, bumblebees, wasps and butterflies is a global emergency, which threatens agricultural production and the healthy functioning of natural and semi-natural ecosystems (Carvell et al. 2006; Ouvrard et al. 2018; Hevia et al. 2021). Flower scarcity due to land homogenization and habitat loss and changes in agricultural practices (e.g., pesticides use) are considered the main causes of this decline (Carvell et al. 2006; Goulson et al. 2015).

For these reasons, today many wildflower seed mixes are used to create wildflower areas, with the desire to restore floristically degraded areas and support pollination services. In the cities, such 'pollinator-friendly' wildflower mixes are sown in roundabouts, parks, meadows, and green roofs, where they provide an aesthetically pleasing landscape for citizens and contribute to pollinators' conservation (Blackmore and Goulson 2014; Hicks et al. 2016). In rural areas, farmers often plant wildflower strips along the margins of their fields, aiming to attract wild pollinators to benefit crops (Pontin et al. 2006; Lowe et al. 2021). This activity is also encouraged by policy, such as in the framework of European agri-environmental and eco-schemes, whose implementation resulted in an overall positive effect on pollinator populations (Ouvrard et al. 2018; Ganser et al. 2021; Lowe et al. 2021; Schmidt et al. 2022), although generalist species seem to have benefited the most (Scheper et al. 2013). In addition, wildflower areas could be used to create zones with natural features connecting the city with the farmland, promoting the creation of ecological corridors (Bretzel and Romano 2013; Blackmore and Goulson 2014).

Because of the growing interest for pollinator conservation by policy and people, today many 'pollinator-friendly' wildflower seed mixes can be found on the market. Selection criteria for plant species composing the mixes are mainly focused on showy flowers which attract pollinators and at the same time enhance the landscape with their aesthetics. However, other characteristics such as the native or alien status of the plants are often not kept in mind, resulting in many seed mixes containing species alien to the area where they are sold and utilized (Havens and Vitt 2016; Ganser et al. 2021; Barry and Hodge 2023). Alien plants can provide abundant resources to pollinators in both urban (Zaninotto et al. 2023) and agricultural areas (Seitz et al. 2020; Kovács-Hostyánszki et al. 2022), but they can interfere with pollination networks by outcompeting native vegetation and disadvantaging specialist wild bees (Ojija et al. 2019; Seitz et al. 2020; Kovács-Hostyánszki et al. 2022). Moreover, the seeding of alien species can pose risks to the conservation of the native plant communities with which they are in contact, especially in the case of invasive alien species. This is even more problematic in extra-urban areas where farmland can be interspersed with areas of high conservation value such as the Natura 2000 network.

Species are usually defined as alien at the country level. However, there are also species native to the country which can be alien at the sub-country level (hereafter, locally alien) because they were introduced by man in regions where they did not occur naturally. As for the species alien to the country, the introduction of locally alien species may result in problems to biodiversity and natural communities too, particularly on islands, where the distinct and endemic biodiversity may be highly vulnerable to plant invasion (Reaser et al. 2007; Moser et al.

2018). This issue has a great relevance in Italy, which is among the countries with the highest biodiversity in Europe, as it encompasses different biogeographical regions characterized by distinct flora, and hosts a large number of hotspots and endemisms, especially in the Alps and in Sicily and Sardinia islands (Médail and Quézel 1997; Peruzzi et al. 2014; Bartolucci et al. 2024). For instance, several species of the Italian native flora are not present in Sicily and Sardinia, thus their introduction here may adversely affect local biodiversity. At an even finer-scale, the introduction of foreign ecotypes of native species can also be detrimental to native plant communities, as it can modify the genetic structure of populations (Kaulfuß and Reisch 2021).

Another essential characteristic of an effective wildflower mix is to ensure prolonged and diversified bloomings. As a result, not only the aesthetic value of an area increases, but more importantly, pollen and/or nectar would be available throughout the entire biological cycle of pollinators. Particularly, early spring and late-summer and autumn months are critical periods for the survival of pollinators (e.g., early season bumblebees), since the availability of diverse and abundant resources is more limited. Moreover, evidence shows that this could even get worse with climate change due to temporal mismatches between plant flowering period and pollinators' activity season (Memmott et al. 2007, 2010; Hegland et al. 2009). Many authors have emphasized that wildflower mixes often lack plants that flower in such early- and late-season periods and have underlined the need to design seed mixes with more attention to plant phenology (Havens and Vitt 2016; Hicks et al. 2016; Ouvrard et al. 2018; Nichols et al. 2022). Moreover, a prolonged bloom that also covers the period of highest flower scarcity from late fall to winter, would benefit the aesthetics of both urban and rural areas.

Although the attention to the conservation of pollinators is high, with publications reporting lists of flowering plant species suitable for pollinators (e.g., Hicks et al. 2016; Warzecha et al. 2018), only a few studies focused on the possible threats to biodiversity and habitat conservation arising from alien plants available in 'pollinator-friendly' wildflower seed mixes (but see Barry and Hodge 2023). Moreover, the current availability of plants on the wildflower market providing flower resources for pollinators in the early- and late-season periods has been poorly investigated.

To fill these knowledge gaps, we analyzed the species composition of a large number of 'pollinator-friendly' wildflower seed mixes commercially available on the Italian market. Particularly, the specific purposes of this work were to:

1. analyze the abundance of native and alien plant species, with a particular focus on the status of invasiveness in Italy (casual, naturalized, invasive);
2. among those species considered native at the country level, evaluate the occurrence of locally alien species, with reference to three geographic areas in Italy: northern, peninsular and insular Italy;
3. evaluate the flowering period of the native and alien species included in the seed mixes.

With this information, we aimed to highlight possible risks to biodiversity and habitat conservation originating from the presence of alien species in the mixes and to provide indications for improving their botanical composition and for their careful use in urban and extra-urban areas.

Methods

Seed mixes database

Thirty-six seed mixes were selected according to the following criteria:

1) commercial availability, either online or in garden stores, for Italian customers;
2) clear reference as mixes for pollinating insects or as mixes of melliferous plants;
3) plant species listed on labels by their scientific name or for which the attribution to it was certain (mixes with doubtful common names were excluded).

The seed mix compositions were included in a database (Suppl. material 1), following the nomenclature of plant species of the Italian native (Bartolucci et al. 2024) and alien (Galasso et al. 2024) checklists. For the species not recorded in the Italian flora, nomenclature followed World Flora Online (WFO 2024). We considered the 36 mixes to be sufficiently representative of the pollinator-friendly wildflower market as fewer and fewer additional species were found as samples were added to the database, until we obtained a nearly constant species list.

Data analysis

Each plant species was assigned to one of the following five categories according to its status for Italy reported in the Portal to the Flora of Italy (PFI 2023):

1) Natives, i.e., autochthonous species in at least one Italian administrative region (e.g., *Achillea millefolium* L.);
2) Cryptogenics, i.e., doubtfully native plants, whose origin of occurrence in Italy is unknown (e.g., *Papaver rhoeas* L.);
3) Archaeophytes, i.e., alien plants introduced to Italy before 1492; among others, this group includes plants that were introduced by humans as cereal weeds (segetal vegetation) and that today are severely threatened by agricultural intensification (e.g., *Centaurea cyanus* L.);
4) Neophytes, i.e., alien plants introduced to Italy after 1492 (e.g., *Phacelia tanacetifolia* Benth.);
5) Not recorded, i.e., alien plants that are not recorded in the spontaneous Italian flora (= not present in the Portal to the Flora of Italy) (e.g., *Lupinus perennis* L.).

Neophytes were further assigned to one of the following three sub-categories, as reported by the Portal to the Flora of Italy (PFI 2023; definitions are based on Galasso et al. 2018):

1) Casual, i.e., neophytes that may thrive and even produce offsprings occasionally outside cultivation, but that usually disappear because they are unable to form self-maintaining populations; their persistence relies on repeated introductions. (e.g., *Bidens formosa* (Bonato) Sch.Bip.);
2) Naturalized, i.e., neophytes that occur with self-maintaining populations without direct human intervention (e.g., *Phacelia tanacetifolia*);
3) Invasive, i.e., neophyte plants that occur with self-maintaining populations without direct human intervention, produce fertile offspring at considerable

distances from the parent individuals, thus being able to spread over a large area (e.g., *Mirabilis jalapa* L.).

Native species were further classified according to their local native or alien status for three Italian geographic areas, which were defined based on regional administrative borders: (1) northern Italy; (2) peninsular Italy (central and southern Italy); and (3) insular Italy (Sicily and Sardinia islands). Subdivision of Italy into such geographic areas was based on the dissimilarity in the endemic vascular flora among Italian regions according to Peruzzi et al. (2014). Similarly, the endemism criterion was also used in the definition of the floristic realms at the global level by Takhtajan et al. (1986). Other classifications of Italy, such as the ecoregions proposed by Blasi et al. (2014) considering climatic, physiographic, biogeographic and vegetation criteria, might also be appropriate, but their boundaries do not align with the available data on species distribution, which are provided at the regional level by the Portal to the Flora of Italy (PFI 2023). Therefore, for each geographic area, native species were assigned to one of the following four categories, according to the species distribution maps available in the Portal to the Flora of Italy:

1) locally native, i.e., native species that are autochthonous in all the administrative regions of the corresponding geographic area;
2) locally casual alien, i.e., native species that established as casual alien in at least one administrative region of the geographic area, and did not establish as naturalized or invasive in any other of them (e.g., *Sinapis alba* L. in northern Italy; see Suppl. material 2; PFI 2023);
3) locally naturalized alien, i.e., native species that established as naturalized alien in at least one administrative region of the geographic area and did not establish as invasive in any other of them (e.g., *Lobularia maritima* (L.) Desv. in northern Italy; see Suppl. material 2; PFI 2023);
4) locally not recorded alien, i.e., native species that are absent in all the administrative regions of the corresponding geographic area (e.g., *Plantago media* L. is native to northern and peninsular Italy but absent in both the islands; see Suppl. material 2; PFI 2023).

Then, from the seed mixes database, we calculated i) the frequency of each species in the seed mixes, ii) the number of species per each family (APG IV), iii) the proportion of each status category (natives, cryptogenics, archaeophytes, neophytes, and not recorded) in the species list, and iv) the number of species per each status category and seed mix; moreover, we characterized v) the area of origin for neophytes and not recorded species according to the Kew Backbone Distributions (POWO 2024) and calculated vi) the proportion of each locally native and locally alien category in the species list for the three Italian geographic areas. We ran a G-test of independence to test if proportions of locally native and alien categories differed by Italian geographic area ('G.test' function from the 'RVAideMemoire' package in R Statistical Software (R Core Team 2018; Herve 2023).

Finally, we assessed the flowering period of i) natives, ii) cryptogenics and archaeophytes, and iii) neophytes and not recorded species by calculating the number of species that bloom each month of the year. We also performed the same calculation for each of the 36 seed mixes to assess the flowering period covered by each of them. Flowering months were retrieved from different sources, mainly Acta Plantarum (Acta

Plantarum 2024) for the Italian flora and the Missouri Botanical Garden (MBG 2024), Royal Horticultural Society (RHS 2024) and Floraveg.EU (Floraveg.EU 2024) for the species not recorded in Italy. All sources are provided in Suppl. material 1.

Results

Native and alien species abundance

In total, 204 species were identified in the 36 seed mixes analyzed (Suppl. material 1), of which the most frequent in the mixes are reported in Table 1. *Centaurea cyanus* is the most frequent species in the mixes (67%), followed by the alien species *Phacelia tanacetifolia* (50%). Among the 20 most frequent species, natives, neophytes and archaeophytes are similarly represented, with five, five, and four species, respectively. Annual species predominates. Species in the mixes belong to 34 families, of which Asteraceae is the most represented, followed by Lamiaceae and Fabaceae (Fig. 1).

Of the 204 species found, natives are the majority (119 species, 58% of the total), followed by neophytes (39, 19%), not recorded species (25, 12%), and archaeophytes (17, 8%) (Fig. 2). Cryptogenics account for a small fraction (4, 2%). Among neophytes, most are casual, but naturalized and even invasive alien are also present. Particularly, the invasive species to Italy are *Mirabilis jalapa*, *Oenothera glazioviana* Micheli, and *Tropaeolum majus* L. Moreover, some species included in the mixes are considered invasive to other parts of the globe (e.g., *Ageratum houstonianum* Mill., *Gaillardia aristata* Pursh, *Impatiens balsamina* L., *I. walleriana* Hook.f, *Lupinus polyphyllus* Lindl., and *Salvia coccinea* Buc'hoz ex Etl). Alien species (neophytes and not recorded) are mainly native to North America (Fig. 3).

The average number of species per mix is 15, with a minimum of 4 and a maximum of 36 species (Fig. 4). Of the 36 mixes, 6 (17% of the total) have exclusively natives, archaeophytes and cryptogenics, whereas most of them (30 mixes, 83%) have at least one neophyte or not recorded species (5 species on average, minimum 1, maximum 16). More specifically, 15 mixes (42%) include not recorded species and 3 mixes (8%) include invasive neophytes.

Table 1. Species frequency in the mixtures. List of the 15 most frequent plant species available in the seed mixes. Species are sorted by frequency, descendent.

Species	Status	Life cycle	Frequency (%)
Centaurea cyanus L.	Archaeophyte	Annual	67
Phacelia tanacetifolia Benth.	Neophyte	Annual	50
Papaver rhoeas L.	Cryptogenic	Annual	36
Calendula officinalis L.	Archaeophyte	Annual	33
Achillea millefolium L.	Native	Perennial	28
Anethum graveolens L.	Archaeophyte	Annual	28
Nigella damascena L.	Native	Annual	28
Borago officinalis L.	Native	Annual	25
Agrostemma githago L.	Archaeophyte	Annual	22
Glebionis segetum (L.) Fourr.	Native	Annual	22
Leucanthemum vulgare (Vaill.) Lam.	Native	Perennial	22
Bidens formosa (Bonato) Sch.Bip.	Neophyte	Annual	19
Bidens tinctoria (Nutt.) Baill. Ex Sennikov	Neophyte	Annual	19
Eschscholzia californica Cham.	Neophyte	Annual	19
Fagopyrum esculentum Moench	Neophyte	Annual	19

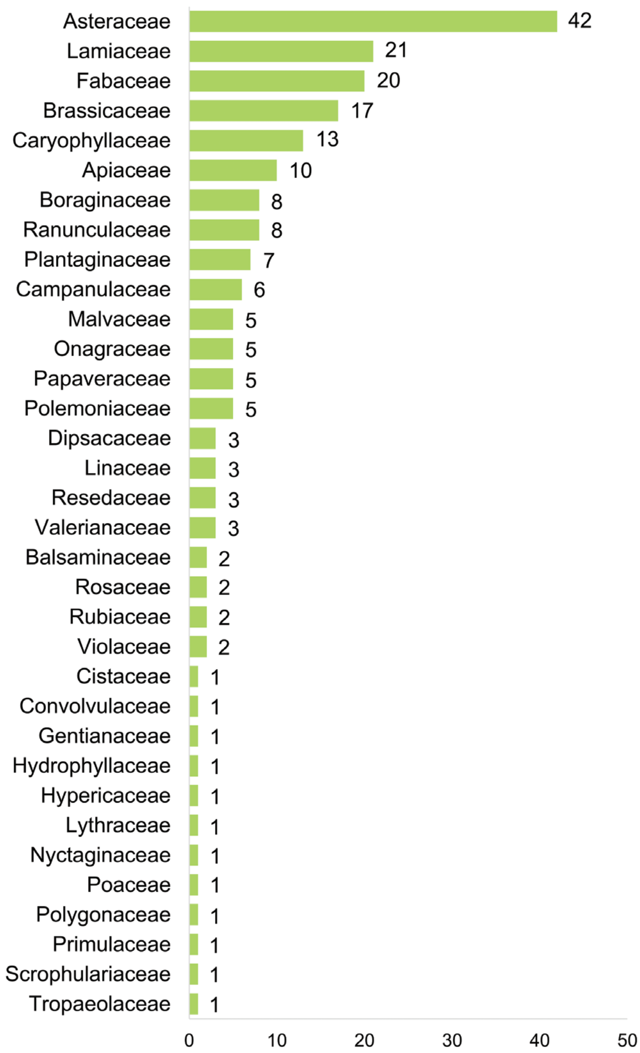

Figure 1. Species families. Number of species included in the mixtures belonging to each family (APG IV).

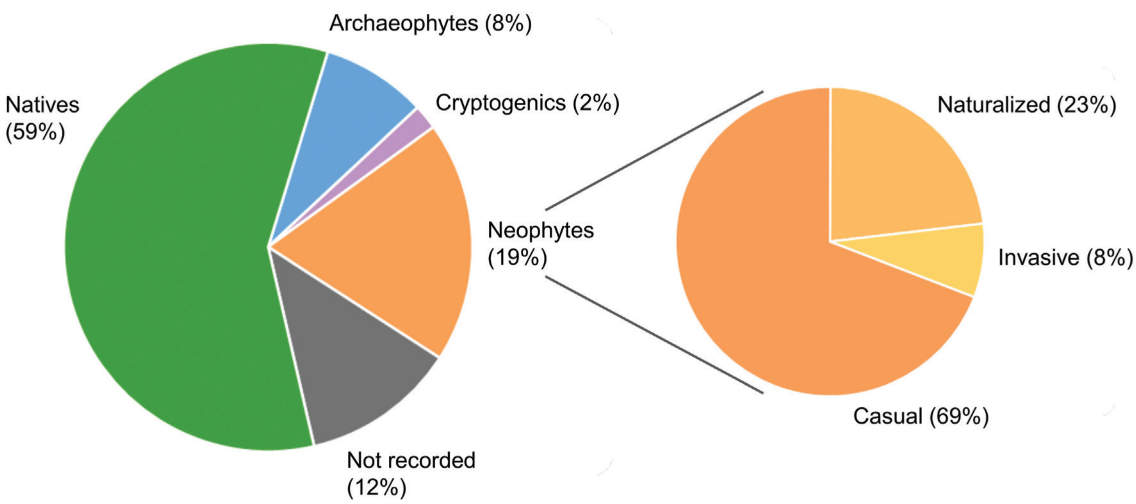

Figure 2. Native and alien species proportions. Proportion of the plant species available in the seed mixes by five categories according to their status for Italy. Neophytes are further divided into proportions of casual, naturalized and invasive species to Italy.

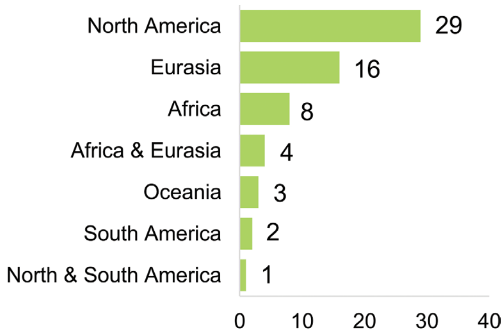

Figure 3. Alien species origin. Number of neophytes and not recorded species according to the region of the world where they are native to. The species *Oenothera glazioviana* Micheli is not included in the analysis of species origin as it is a cultigen originating from *O. elata* × *O. grandiflora* hybrids in Europe (POWO 2024).

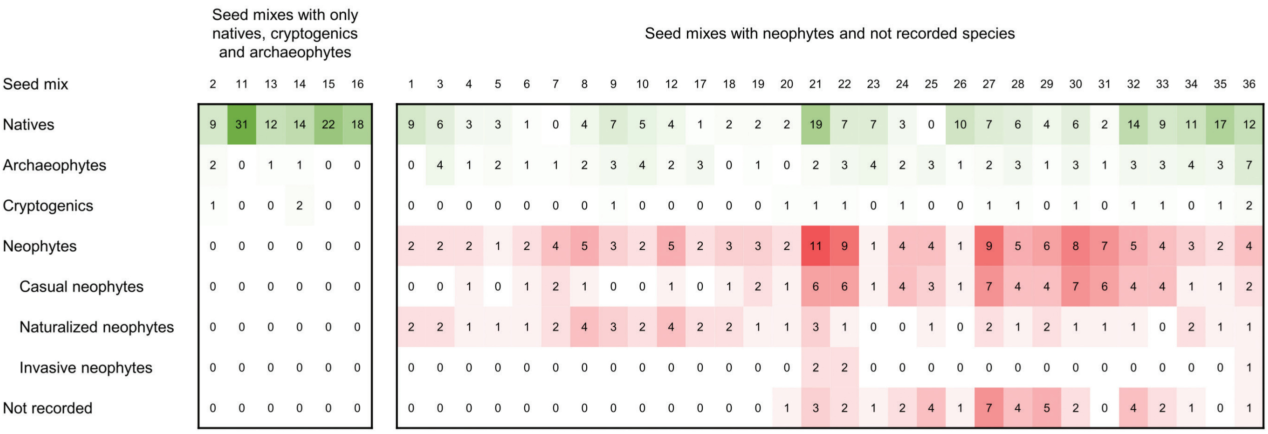

Figure 4. Species composition of the seed mixes. Numbers indicate the number of species per each category. Color scale increases white to green for natives, cryptogenics and archaeophytes and white to red for neophytes and not recorded species.

Evaluation of the native species status in the geographic areas of Italy

Of the 119 species that are native to Italy, 70 species (59%) are native to the entire Italian territory, while 49 species (41%) are absent or introduced by man (as a casual or naturalized alien species) in at least one of the three geographic areas (Suppl. material 1).

Italian geographic areas significantly differ in the proportion of locally native (G-test of independence, G = 32.354, $p < 0.001$), casual (G = 8.303, $p = 0.016$), naturalized (G = 6.531, $p = 0.038$), and not recorded species (G = 58.602, $p < 0.001$). Particularly, in northern Italy, 33% of the species are locally casual (16%) or naturalized (17%) alien taxa (Fig. 5). These species include many Mediterranean plants that are not autochthonous to northern Italy but established in specific ecological conditions after their introduction by man (e.g. *Lobularia maritima*, *Glebionis segetum* (L.) Fourr., *Trifolium resupinatum* L.; Suppl. material 2; PFI 2023). In the other geographic areas, instead, the locally casual and naturalized species are less abundant, with the sum of the two accounting for 11% and 17% in peninsular and insular Italy, respectively. Finally, insular Italy has a larger share of locally not recorded species (27%) compared to the other geographic areas.

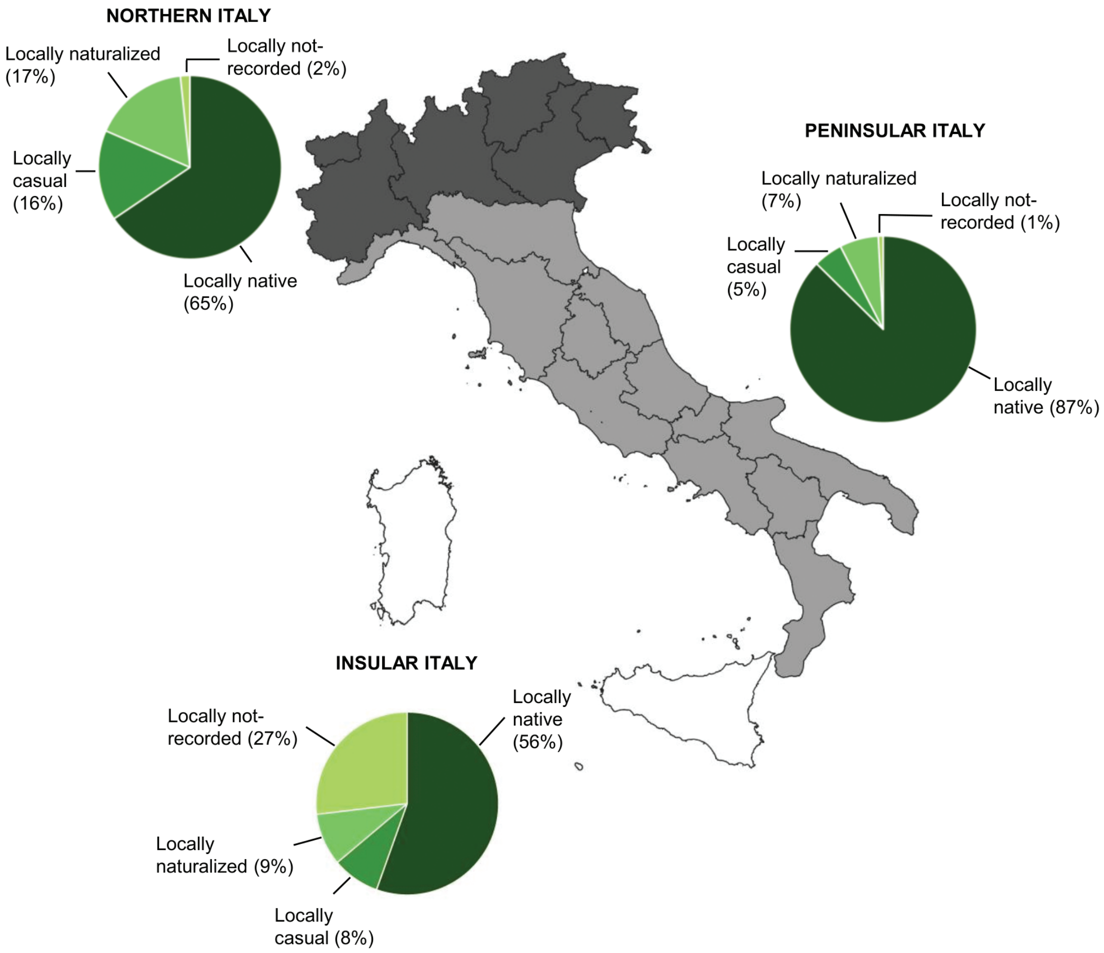

Figure 5. Native species proportion in the geographic areas. Proportion of the native species to Italy available in the seed mixes by four categories (i.e., locally native, casual, naturalized, and not recorded) according to their status for three Italian geographic areas (northern, peninsular, and insular Italy).

Plant species flowering period

The flowering period of plant species available in the seed mixes differs by plant status category (Fig. 6). Natives, cryptogenics and archaeophytes have blooms that potentially cover the whole year, with the peak of blooming in May and June. The distribution of species numbers is slightly skewed to the left, with proportionally more species blooming in early spring than in autumn (Fig. 6a, b). In addition, some native species potentially bloom in the period from November to January too, possibly providing aesthetic benefits during the period of highest flower scarcity (Fig. 7). Among these, three species (*Bellis perennis* L., *Reseda alba* L. and *Trifolium pratense* L.) have a potential continuous flowering along the whole year. Instead, for neophytes and not recorded species, the distribution of species numbers is skewed to the right, no species flower in December and January, and the peak of blooming is in June (Fig. 6c).

According to the flowering period potentially covered by each seed mix (Fig. 8), 39% of the mixes provide blooms throughout the whole year while 100% for the period from April to August. Part of the mixes (36%) lack flowers in early spring (March) or throughout the whole autumn (from September to November). Overall, neophytes and not recorded species provide flower resources later in the season compared to natives, cryptogenics and archaeophytes.

Discussion

Despite the current awareness of the negative impacts that the spread of alien species poses to the environment and humans (IPBES 2023), most (83%) of the commercially available wildflower seed mixes evaluated in this study contained plant species alien to Italy (neophytes and not recorded species). In total, 64 alien plants were found in 36 'pollinator-friendly' wildflower mixes, around 30% of the total number of species. These proportions highlight the widespread use of alien plants on the

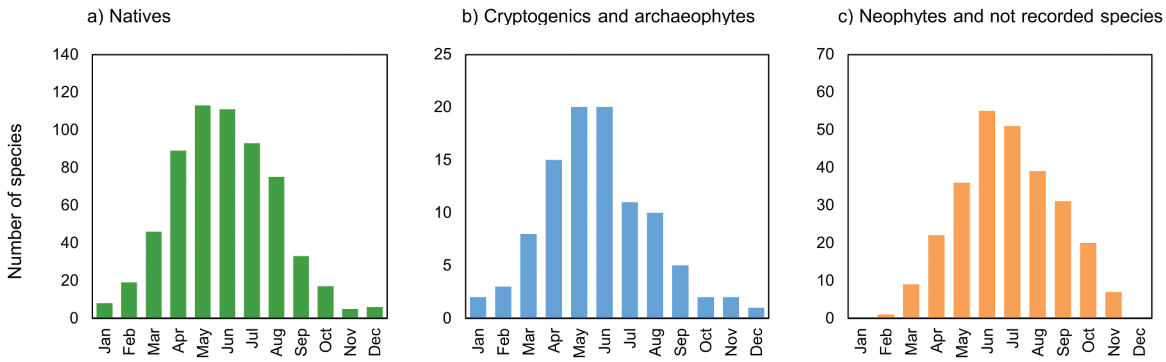

Figure 6. Flowering period of native and alien species. Number of a) natives, b) cryptogenics and archaeophytes, and c) neophytes and not recorded species available in the seed mixes that bloom each month.

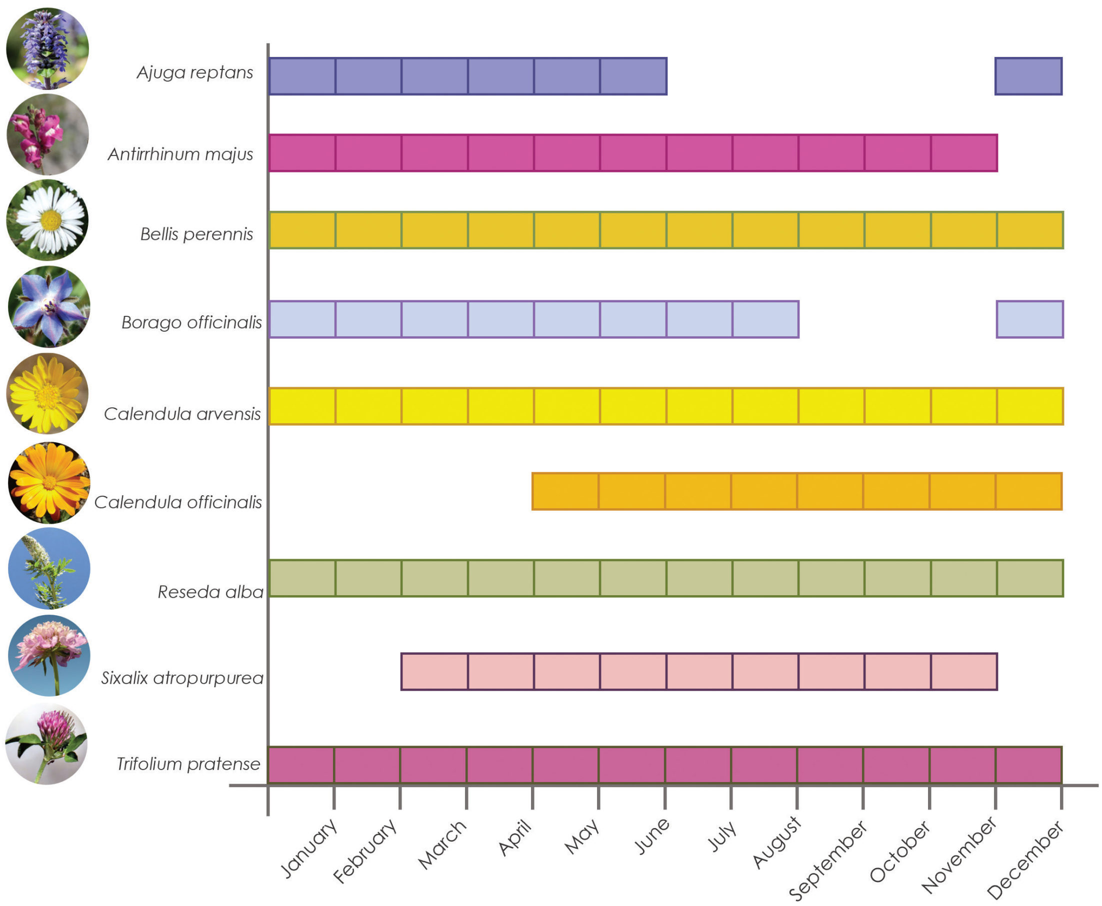

Figure 7. Flowering patterns of native plants with November to January blooms. Flowering patterns of native species available in the seed mixes that potentially flower also in the period from November to January.

Figure 8. Flowering period by seed mix. Number of species that bloom each month for each seed mix. The identification number of the mix is provided in the upper right of each chart.

wildflower market. Alien species are so often included in seed mixes because many of them grow quickly, have pleasant and abundant flowers, are attractive to pollinators, and provide a long flowering period (Seitz et al. 2020; Zaninotto et al. 2023).

Similarly to the findings of Barry and Hodge (2023) for Ireland, the most frequent alien species in our study (50% of the mixes) was *Phacelia tanacetifolia*, native to North America. This species is largely used by farmers and beekeepers in fields and field margins, in mixtures or as monoculture, due to its attractiveness for insect pollinators, especially honeybees (Warzecha et al. 2018; Giovanetti et al. 2022). However, concerns were raised about the potential of the species to become invasive out of its home range (Smither-Kopperl 2018) and possibly compete with native vegetation by affecting native pollination networks (Totland et al. 2006). In Italy, the species escaped from cultivation as a casual species in most of the country and is already naturalized in two regions, i.e., Friuli-Venezia Giulia and Lazio (Suppl. material 2; PFI 2023). Among the alien plants detected in this study, some were invasive to Italy or to other European or world countries. Particularly, three mixes contained invasive species to Italy, i.e., *Mirabilis jalapa*, *Oenothera glazioviana*, and *Tropaeolum majus*, which are mainly used as ornamental plants. The presence of these species in seed mixes is critical as it could favor their spread throughout the country, even in regions where they are not yet established (Suppl. material 2; PFI 2023). Another species of concern is *Lupinus polyphyllus*, which is invasive to northern and central Europe, Australia and New Zealand, where it negatively affects native species richness (Eckstein et al. 2023). This species is naturalized in northern Italy (Suppl. material 2; PFI 2023) and was found in three of the studied mixes. Moreover, *Ageratum houstonianum*, invasive to many countries of the globe except to Europe and two *Impatiens* species (*I. balsamina* and *I. wallerana*), invasive to South America, Oceania and to many tropical and subtropical islands (CABI 2024), are established as casual alien to Italy (PFI 2023). Finally, we also detected species that are not part of the spontaneous flora of Italy (not recorded) but are recorded as invasive in other countries. For instance, *Salvia coccinea* is considered invasive to China (Hao and Ma 2023), Australia (Murray and Phillips 2012), and South Africa (Moshobane et al. 2020) while *Gaillardia aristata* to Hungary, prompting Süle et al. (2023) to ask for its exclusion from seed mixes.

Apart from the obvious negative regard towards invasive species, even the presence of other alien categories (such as not recorded and casual species) in seed mixes could pose a serious threat to biodiversity and habitat conservation, as these plants could eventually establish as naturalized or, more seriously, invasive alien in the next future. Indeed, species invasiveness is extremely difficult to predict and there is a well-known time lag between introduction, establishment and spread of invasive species (Crooks 2005; Gigon and Weber 2005; Pyšek et al. 2020). Moreover, climate change could lead to more favorable environmental conditions for the naturalization of today's harmless alien species, which can gain advantage over native ones (Haeuser et al. 2019; Yang et al. 2022). Thus, caution should be paid when including alien plants in wildflower mixes, especially if they are intended to sow in extra-urban areas such as in fields and field margins and as part of agri-environmental and eco-schemes, where their use is not advisable (Havens and Vitt 2016; Seitz et al. 2020; Barry and Hodge 2023). In urban settings, wildflower areas not only benefit biodiversity, but also provide an aesthetically pleasant space which increases people's well-being (Bretzel et al. 2016). In this context, the use of alien species is of lower concern, but only for those plants whose biology, ecology and mode of interaction with native plants and pollinator populations are well known. In fact, herbaceous ornamentals in urban areas can be an underestimated reservoir of potentially invasive plants (Hu et al. 2023), thus a wider use of natives should be encouraged (Caser et al. 2022).

The legislation does not completely prevent the use of alien species in wildflower mixes, even if they are invasive. At the European level, Regulation EU 1143/2014 lists the invasive alien species of Union concern (Union List) for which keeping, cultivation, selling, and releasing into the environment are forbidden. However, this list misses many invasive species, e.g. plants that are alien to certain European countries but not to others. Other existing national or regional lists may restrict the use of alien species too, but they can miss many invasive plants as well. In Italy, regional black-lists of alien species are available in some but not all administrative regions, while a common national black list is missing (Brundu et al. 2020). For European agri-environmental and eco-schemes, each country establishes its own regulations, and often the use of alien plants is allowed. In Italy, legislation provides a list of plants that can be used for eco-schemes, which includes two neophyte crops (*Helianthus annuus* L. and *Fagopyrum esculentum* Moench) and one invasive alien (*Crepis sancta* (L.) Bornm.) (Suppl. material 2; PFI 2023) (Lettieri et al. 2023). While the use of crop neophytes raises no concerns from a biodiversity conservation perspective, as they have been cultivated by man for a long time and are not competitive in the wild, the inclusion of *C. sancta* in seed mixes could potentially damage native plant communities because of its acknowledged invasive status.

Although some alien species are effective in providing abundant resources to insect pollinators, native plant species can be very good pollen and nectar sources as well (Ouvrard et al. 2018; Warzecha et al. 2018). Among the key species for pollinators identified by Warzecha et al. (2018), the seed mixes of this study included the natives *Achillea millefolium*, *Malva sylvestris* L., *Daucus carota* L., *Echium vulgare* L. and *Linum usitatissimum* L. and the archaeophytes *Calendula officinalis* and *Centaurea cyanus*. Archaeophytes were well represented in the studied seed mixes, with 17 species in total and one species (i.e. *C. cyanus*) as the most frequent. Many of these archaeophytes are annual weeds of cereal crops that were introduced in Europe by man with agriculture (segetal vegetation) and now are considered rare due to agricultural intensification (Albrecht et al. 2016). In this regard, the use of ‘pollinator-friendly’ wildflower mixes could promote the conservation of such rare arable plants (e.g., *Agrostemma githago* L. and *C. cyanus*).

When evaluating the suitability of native species for sowing, attention should also be paid to their distribution range. This is especially significant in a country as diverse as Italy, where there are different biogeographical regions characterized by a diverse flora. In this study, the native range of many autochthonous species (41% of the species) available in the seed mixes do not cover the entire country, thus their use in certain areas can be problematic. This issue was more pronounced in the insular area, with 45% of the native species that were locally alien. Sicily and Sardinia are the biggest Mediterranean islands, are a macro-hotspot of plant diversity in the Mediterranean basin (Cañadas et al. 2014) and host a rich endemic flora (Médail and Quézel 1997; Peruzzi et al. 2014; Fois et al. 2022). Although there is so far little evidence of extinctions directly caused by introduced plant species on islands (Sax and Gaines 2008), insular biota is considered to be particularly vulnerable to the negative effects caused by the spread of alien taxa (Reaser et al. 2007). To account for the issue of not introducing locally alien species, it would be helpful to develop different mixtures depending on the area where they are intended to be sown. For instance, species native to northern and peninsular Italy only (e.g., *Betonica officinalis* L., *Plantago media* L. etc.) should not be used in seed mixes on the islands. In line with this, Italian legislation for eco-schemes states that only the plants already present in a certain administrative region can be used for seeding wildflower areas in that region (Lettieri et al. 2023).

In addition to the attention for species chorology, the origin of the seeds is another important factor to consider when planning the creation of wildflower areas (Barry and Hodge 2023). However, seed origin indications are usually not available in commercial seed mixes, which typically use foreign ecotypes and cultivated varieties, resulting in the risk of genetic pollution of native vegetation (Mainz and Wieden 2019; Barry and Hodge 2023). According to the EU Directive 2010/60 concerning the use of preservation mixtures, it would be advisable to promote the use of local species ecotypes through the geographical definition of regions of origin, where the seeds are to be collected, propagated and sown (Durka et al. 2017). Today, only seven countries in Europe defined regions of origin within their national borders (Austria, Czech Republic, France, Germany, Great Britain, Norway, and Switzerland). However, the definition of transnational regions of origin in Europe would have a more ecological and biological significance (De Vitis et al. 2017). Moreover, the establishment of a European certification system that guarantees the region of origin, similar to those already established in certain European countries, would be important to ensure the transparency and traceability of the native seed market (Mainz and Wieden 2019). Currently, the native seed market is underrepresented in Italy, with virtually only one company that produces native wildflower seeds and lots of plant species not available on the market. For instance, among the species allowed for use for eco-schemes in Italy, only a small number is actually available (Lettieri et al. 2023). If more of the species native to Italy (consisting of 8080 angiosperm taxa, Bartolucci et al. 2024) were commercially available on the seed market, the presence of alien species in wildflower mixes could be discouraged.

Finally, another key criterion when composing a 'pollinator-friendly' wildflower seed mix is ensuring blooms that cover the whole season of pollinators' activity, especially during critical periods such as early spring and from late-summer to autumn (Hicks et al. 2016; Ouvrard et al. 2018; Nichols et al. 2022). In this study, some of the seed mixes did not cover such critical periods with blooms, resulting in possible pollen and nectar shortages. Moreover, native and alien species differed in the flowering period, with native species characterized by more species blooming in spring and alien species in autumn. This highlights that alien species may play an important role in complementing the flowering period of native species by filling the late-season with feeding resources (Kovács-Hostyánszki et al. 2022; Zaninotto et al. 2023). In this context, the availability on the market of a greater number of native species with a late-season flowering period appears to be a crucial point for reducing the use of alien plants and developing effective native wildflower seed mixes.

Conclusions

This study showed that 'pollinator-friendly' wildflower seed mixes, increasingly used in both urban and rural settings, can be potential vectors of alien plant species, resulting in critical risks for biodiversity and habitat conservation. Thus, we underline the importance of taking into account the alien and native status of plant species in the design of such mixes, especially when sown in extra-urban areas. Moreover, another criterion worthy of attention when utilizing a seed mix is to consider the area where it is intended to be planted, avoiding introducing species which can be native to the country but locally alien to certain regions of it. Finally, to guarantee prolonged blooms throughout the pollinators' activity season, it appears crucial to introduce more native species with a late flowering period. Given the growing interest in wildflower areas, as part of green infrastructures in the cities or as wildflower strips targeted by European incentives, this study can help policy makers in suggesting a careful use of the seed mixes while promoting the use of local seeds by the development of the native seed market and the definition of regions of origin. The approach here used to analyze the current situation of 'pollinator-friendly' seed mixes in Italy can be transferred to other countries.

Additional information

Conflict of interest

The authors have declared that no competing interests exist.

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Author ORCIDs

Ginevra Nota https://orcid.org/0000-0002-1265-1201
Valentina Scariot https://orcid.org/0000-0003-0195-1361
Michele Lonati https://orcid.org/0000-0001-8886-0328

Data availability

All of the data that support the findings of this study are available in the main text or Supplementary Information.

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Supplementary material 1

Database of seed mixes species composition

Authors: Ginevra Nota, Nicole Melanie Falla, Valentina Scariot, Michele Lonati

Data type: xlsx

Link: https://doi.org/10.3897/neobiota.94.118480.suppl1

Supplementary material 2

Distribution maps of plant species

Authors: Ginevra Nota, Nicole Melanie Falla, Valentina Scariot, Michele Lonati

Data type: pdf

Link: https://doi.org/10.3897/neobiota.94.118480.suppl2