A structurally rich natural garden supports an exceptionally high diversity of wild bees

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Natural gardens with a high diversity of native plants, heterogeneous habitats and the absence of pesticides can serve as refuges and important secondary habitats for numerous animal species. However, little is known about the diversity of wild bees, the most important pollinators worldwide, in such natural gardens, and even less is known about the wild bee fauna of natural gardens where measures to specifically support bees have been implemented. Here, the wild bee fauna of a highly structured private natural garden in Austria of about 3700 m², which is managed to specifically promote wild bees, was investigated. In seven investigation days in 2024 and sporadic investigations from 2021 to 2023, a total of 178 wild bee species have been recorded. Among them, there were many rare, endangered and highly specialised species. A comparison with the bee fauna of botanical gardens revealed that the studied natural garden contains a remarkably high diversity of bees on a relatively small area. Overall, our data show that highly structured private natural gardens with a diverse native flora have a strong potential in supporting and promoting a high diversity of bees.

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Durch die Förderung heimischer Pflanzenarten, die Schaffung einer hohen Habitat-Heterogenität und den Verzicht auf Pestizide können Naturgärten als Refugien und sekundäre Lebensräume für zahlreiche Arten dienen. Über die Diversität von Wildbienen, welche weltweit die wichtigsten Bestäuber darstellen, ist in solchen Naturgärten allerdings wenig bekannt. Noch geringer ist der Kenntnisstand über die Bienenfauna von Naturgärten, in denen gezielt Maßnahmen zur Förderung von Wildbienen durchgeführt wurden. In dieser Studie wurde die Wildbienenfauna eines reich und kleinräumig strukturierten, privaten, 3700 m² großen Naturgartens in Österreich untersucht, dessen Gestaltung und Management auf die Förderung von Wildbienen abzielt. An sieben Begehungstagen im Jahr 2024 und sporadischen Begehungen in den Jahren 2021 bis 2023 konnten insgesamt 178 Wildbienenarten nachgewiesen werden. Unter diesen befanden sich zahlreiche seltene, gefährdete sowie hoch spezialisierte Arten. Ein Vergleich mit den Bienenfaunen verschiedener botanischer Gärten ergab, dass der untersuchte Naturgarten auf einer verhältnismäßig kleinen Fläche eine bemerkenswert hohe Vielfalt an Wildbienen aufweist. Daraus schließen wir, dass reich und kleinräumig strukturierte Naturgärten, die eine hohe Vielfalt an heimischen Pflanzenarten aufweisen, ein großes Potenzial zur Förderung einer hohen Wildbienenvielfalt besitzen.

Keywords: Anthophila, wild bees, natural garden, native plants, Austria, pollinator conservation, habitat heterogeneity.

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Introduction

Domestic gardens, that often make up a large proportion of a country's total area (e.g. in Sheffield, UK, approximately 23 % of the urban land area; Gaston et al. 2005), can serve as refuges and important secondary habitats for many species as natural habitats continue to be lost, degraded and fragmented by, e.g., intensive agriculture, as well as increased impervious surfaces and urban structures (Goddard et al. 2009; Braschler et al. 2021). Gardens can further serve as important stepping-stones (Lynch 2019), especially when there are networks of gardens available that improve habitat connectivity (Goddard et al. 2009; Lynch 2019). However, the potential of gardens to support and work as refuges for wildlife, including rare and endangered species, strongly depends on how a garden is managed and structured (Lynch 2019). Natural gardens can serve as an ideal habitat for many native species when native plants are promoted, a high habitat heterogeneity is created, and no pesticides or other chemicals are used (Witt 2018). Among the organisms supported in such gardens are bees (e.g. Zurbuchen & Müller 2012; Rahimi et al. 2022; Bell et al. 2023), which are the most important pollinators (Michener 2007). Worldwide, approximately 20000 different bee species do exist (Michener 2007), while in Austria, where the study site was located, the number of documented species is about 700 (Wiesbauer 2023). Bees frequently visit flowers as they are dependent on their rewards, mostly pollen and nectar, both for their own nourishment and the nourishment of their larvae (Wiesbauer 2023). Concerning the collection of pollen as food for their larvae, some species, termed as oligoleges, are specialised on species of a plant genus or plant family, whereas others, the polyleges, have a more generalized host plant spectrum (Westrich 2019). Overall, bees show a high variety of different nesting behaviours (Zurbuchen & Müller 2012). For example, for constructing their nests, many bees are specialised on specific nesting sites (e.g., existing cavities in dead wood, sparsely vegetated ground patches, pithy stems, rotten wood or empty snail shells) (Zurbuchen & Müller 2012). In order to exist at a specific site, bees do need both their specific nesting sites and their host plants in close proximity, typically within a range of 200 to 300 m (Zurbuchen & Müller 2012). As in natural gardens a high diversity of different native plant species and potential nesting sites can be created within a short distance, they should serve as ideal habitats for wild bees. In contrast to bee species-rich botanical gardens (e.g. Schanz et al. 2023), however, very few investigations exist on the bee fauna of natural gardens. Bisschop and Sedivy (2024) surveyed the wild bee fauna of a natural garden (1150 m²) in Switzerland (Regensdorf) over the course of three vegetation periods and recorded 98 bee species. Westrich (1997) recorded within five years 115 bee species in a 320 m² private garden in Germany. Zettel et al. (2018) surveyed the wild bee fauna of a natural garden in Vienna and adjacent experimental agricultural plots (covering a total area of 17000 m²) in 2013, 2017, and 2018 and recorded 134 bee species.

The aim of this study was to record the wild bee fauna of a highly structured private natural garden in Upper Austria, which is managed specifically to promote wild bees. Based on literature data, the nesting and flower visiting behaviour of recorded bees, as well as their sociality and Red List status, were analysed. We compared the recorded bee fauna to other faunistic studies available for Upper Austria. Specifically, we asked, i) How many and which bee species do occur in the garden, ii) Are only generalist and non-endangered species or also specialist and endangered species among the bees recorded, and iii) How do species number and composition of the natural garden compare to other studies performed in Upper Austria?

Material and Methods

Study area

The study was conducted in a private natural garden in Haslach in Upper Austria, around 35 km north of Linz. The garden is next to a residential area, measures about 3700 m² in size and is approximately 530 m above sea level. It is adjacent to agricultural and industrial areas. The surrounding grasslands and forests (mainly monocultures of spruce) are predominantly managed intensively. For example, most of the surrounding meadows are drained, highly fertilized and mown at least three times a year. The garden is located about 3 km away from the European Green Belt, which in this region runs along the Austria-Czech border (Gaudry et al. 2014).

The majority of the structures available in the garden, except for some hedges, trees and ponds, for example, have been created in the course of the last 10 years. The garden mainly consists of hedges, single trees and shrubs, ponds or small brooks, dry areas, drystone walls, fallow areas, meadows, fringe vegetation areas and vegetable gardens (Figure 1). The dry areas contain, among others, stone piles, standing and lying dead wood, vertically placed empty and pithy stems, areas and small hills out of sand or a mixture of sand and soil, and harbour a ruderal and pioneer vegetation. In the fallow areas, the soil gets turned over in

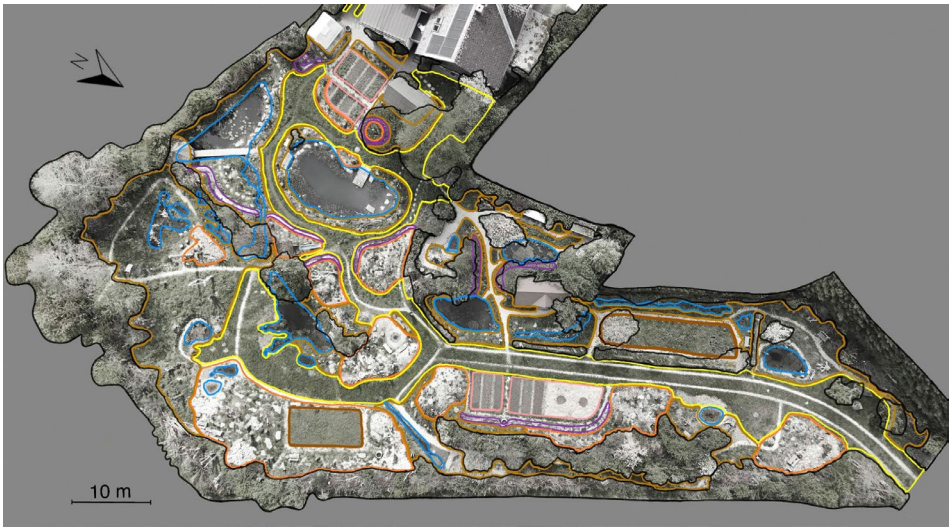


Fig. 1: Map of the studied garden. Hedges and other trees or shrubs are framed in **black,** ponds or small brooks in **blue**, dry areas (characterized e.g. by items such as stone piles, standing and lying dead wood, sandy hills and a ruderal or pioneer vegetation) in **orange**, drystone walls in **purple**, fallow areas in **brown**, and meadows in **yellow**. Fringe vegetation areas are indicated in **ochre** and vegetable gardens in **pink**. | **Abb. 1:** Karte des untersuchten Gartens. Hecken und andere Baum- oder Strauchstrukturen sind **schwarz** umrahmt; Teiche und kleine Bäche **blau**; Trockenbereiche (beinhalten z.B. Steinhaufen, stehendes oder liegendes Totholz, Sandhügel sowie eine Ruderal- oder Pioniervegetation) **orange**; Trockensteinmauern **violett**; Brachflächen **braun**; Wiesen **gelb**; Saumvegetationsbereiche **ocker** und Gemüsegärten **rosa**.

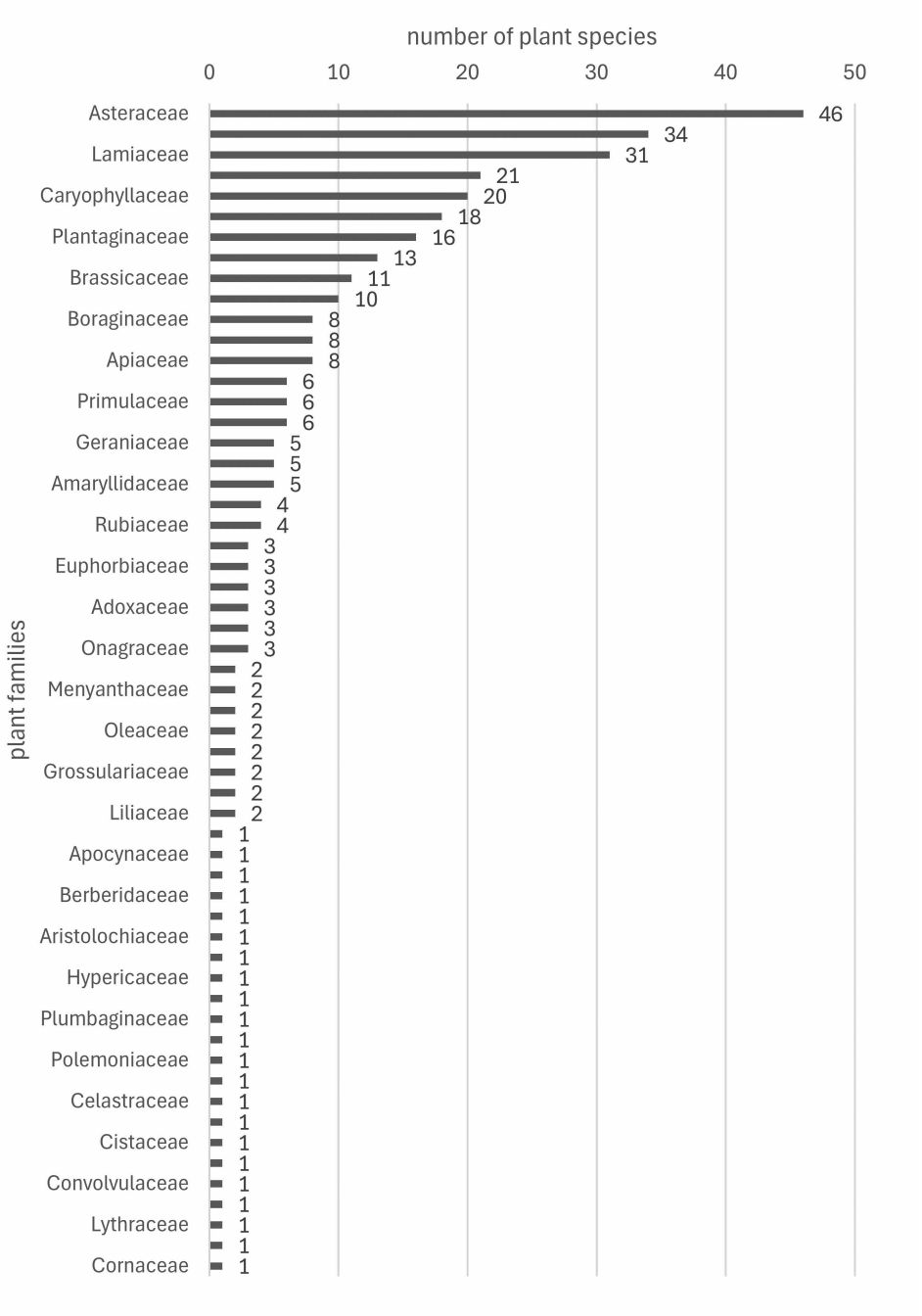


Fig. 2: Number of plant species per family of bee-relevant species flowering around the time of the bee survey days in 2024. | **Abb. 2:** Anzahl der während der Bienenbegehungstage in 2024 blühenden bienenrelevanten Pflanzenarten pro Pflanzenfamilie.

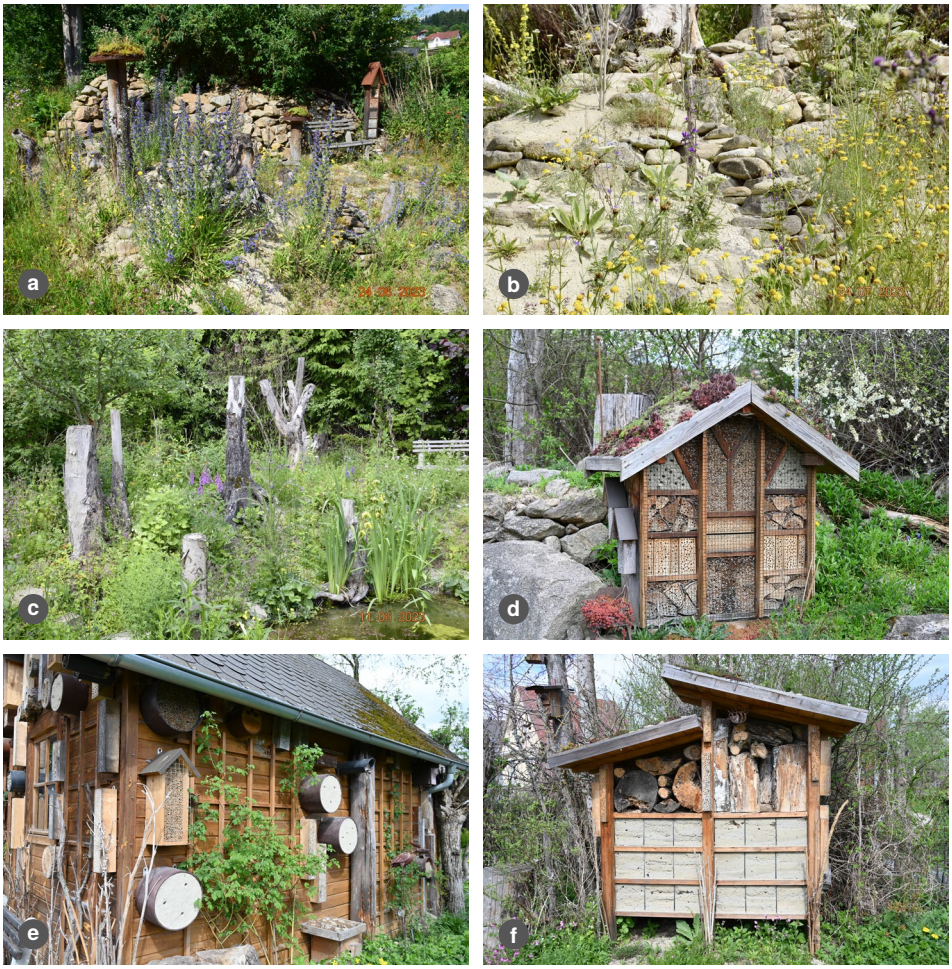


Fig. 3: Examples of nesting sites in the studied natural garden. **a, b**: sandy areas and small hills, **c**: vertically and horizontally placed dead or rotten wood, **d**: nesting aid mainly consisting of dead wood with drilled holes and hollow stems, **e**: various different nesting aids installed on the wall of a garden shed (e.g. dead wood with drilled holes and hollow stems, nesting aids that imitate vertical loess walls, vertically placed pithy stems and dead wood), **f**: nesting aid that imitates a vertical loess wall and contains dead wood structures. | **Abb. 3:** Beispiele für Nistmöglichkeiten im untersuchten Garten. **a, b**: sandige Flächen und Hügel, **c**: vertikal und horizontal ausgerichtetes Tot- und Morschholz, **d**: Nisthilfe hauptsächlich bestehend aus Totholz mit Bohrlöchern sowie hohlen Stängeln, **e**: verschiedenste Nisthilfen installiert an der Wand einer Gartenhütte (z.B. Nisthilfen bestehend aus Totholz mit Bohrlöchern sowie hohlen Stängeln; Nisthilfen, welche vertikale Lösswände imitieren; vertikal ausgerichtete markhaltige Stängel und stehendes Totholz), **f**: Nisthilfe, welche eine vertikale Lösswand imitiert, und zusätzlich Totholz-Strukturen enthält.

a biennial cycle. The meadows are mown 2 or 3 times a year, depending on the amount of nutrients they contain. In contrast to the meadows, the fringe vegetation areas are kept predominantly free of grass and get mown once a year at the end of vegetation period in autumn. In total, the garden approximately contains 72 square metres drystone walls and 92 stacked cubic metres stone piles including single rock structures. The total amount of deadwood in form of dead tree trunks, tree stumps and thicker branches starting from a diameter of about 5 cm is approximately 47 solid cubic metres. This high variety of different structures at a small-scale is enabled by the fact that the garden is modelled in the form of hills and depressions.

In the last few years, the management focused more and more on the promotion of wild bees by offering various different nesting sites and by introducing a high number of native plant species.

During the survey days in 2024, 341 bee-relevant plant species of 57 different families were flowering (Figure 2), among them >30 species each of Asteraceae, Rosaceae and Lamiaceae (Figure 2). Also highly represented with each between 21 to 10 flowering plant species were Fabaceae, Caryophyllaceae, Ranunculaceae, Plantaginaceae, Caprifoliaceae, Brassicaceae and Campanulaceae (Figure 2).

Nesting sites (Figure 3) were built by constructing sandy areas and small hills (Figure 3a,b), by placing pithy stems vertically (Figure 3e) and dead or rotten wood vertically and horizontally (Figure 3c), or by nesting aids consisting of dead wood with drilled holes or hollow stems (Figure 3d,e). In addition, nesting aids that imitate vertical loess walls were constructed and installed in the garden (Figure 3f).

Data collection and analysis

In order to investigate the wild bees, the garden (Figure 1) was surveyed in a total of seven days in 2024 (March 29; April 28; May 18; June 18; July 6; July 27, September 1), each from 10:00 to 16:00 by two persons, following a targeted netting approach. Bees that could be identified to species level in the field were either not collected or just one or a few individuals were collected, even if they were present in high abundances. In addition to this detailed survey, some bees were sporadically collected in 2021, 2022 and 2023. The collected bees were identified to species level using the following identification literature: Ebmer (1969,1970,1971,1973); Amiet (1996); Schmid-Egger and Scheuchl (1997); Scheuchl (2000); Amiet et al. (2001,2004); Scheuchl (2006); Amiet et al. (2007,2010); Bogusch and Straka (2012); Amiet et al. (2014); Dathe et al. (2016); Gokcezade et al. (2018); Praz et al. (2022). Several individuals were compared to bees available in reference collections at the Plant Ecology lab of the University of Salzburg and the Biodiversity Centre of Upper Austria in Linz. The managed honey bee *Apis mellifera*, which was also present in the garden, was not considered.

Nomenclature of the bees follows Scheuchl and Willner (2016), except for *Andrena afzeliella* and *Andrena stragulata*, which follows Praz et al. (2022) and Westrich (2019), respectively. Information on the biology and ecology of bees is primarily based on Westrich (2019), and for those species not mentioned in Westrich (2019), information is based on Wiesbauer

(2023) and/or Scheuchl and Willner (2016). For the evaluation of bees concerning their Red List status, the Red List of nearby Bavaria (Voith et al. 2021) was used as no Red list is available for (Upper) Austria. For four species not listed in the Bavarian Red List, the Red Lists of Switzerland (Müller & Praz 2024) and Germany (Westrich et al. 2011) were used.

The obtained bee data were compared with the data of three other studies performed in Upper Austria, i.e. in the Nature Park Mühlviertel (Schwarz et al. 2025), the Nature Park Obst-Hügel-Land (Ockermüller 2018), and the Botanical Garden Linz (Schwarz, personal communication, 2026), located at distances of about 35–55 km to the natural garden studied in the present work. The Nature Park Mühlviertel was surveyed on six days in 2011 and four days in 2025 (Schwarz et al. 2025), the Nature Park Obst-Hügel-Land on five days in 2017 (Ockermüller 2018), and the Botanical Garden Linz on five days each in 2023 and 2024 (Schwarz, personal communication, 2026).

Results

During the seven survey days in 2024, 663 wild bee individuals of 149 species were recorded (Table 1), whereas 29 further species were recorded during the sporadic surveys from 2021 to 2023, summing up to a total of 178 wild bee species for the garden (Table 1).

Of the 178 recorded species, 40 (22 %) were parasites and 138 (78 %) were nest-building. Among the nest-building bee species, 80 construct their nests in self-dug cavities in the soil (Figure 6a), followed by 23 and 21 species that build their nests in existing cavities (e.g. holes between or underneath rocks; crevices in stone) (Figure 6b) and existing cavities in dead wood (e.g. abandoned burrows of other insects), respectively (Figure 4). Seven species each nest in existing cavities in the soil (e.g. abandoned mice-burrows) and in self-made cavities in pithy stems (Figure 4; Figure 6c). Only a few species had other nesting behaviours (Figure 4; Figure 6d,e).

Forty-four (32 %) of the 138 nest-building bee species were oligoleges, specialized overall on 18 different plant families or genera, mostly on Asteraceae, Fabaceae, Campanulaceae or *Campanula* (Figure 5; Figure 6f).

In total, 39 (22 %) of the 178 bee species are threatened (categories 1, 2, 3, G, R), including five species each critically endangered and endangered (categories 1 and 2; Table 2). Eighteen (10 %) species are near threatened (category V; Table 2).

Most of the 178 recorded bee species have also been recorded in at least one of the studies performed in the Nature Park Mühlviertel (166 bee species recorded in total), the Nature Park Obst-Hügel-Land (96 bee species recorded in total), and the Botanical Garden Linz (128 bee species recorded in total). However, 29 species were exclusively found in the studied natural garden (Table 1, species marked in red).

Tab. 1: List of bee species recorded in 2024 and during the sporadic surveys between 2021 and 2023, including information on their nesting behaviour, sociality, lecty and Red List status of Bavaria (RL BY). For 2024, the number of collected individuals is given, for 2021-2023 the presence of a species is given. Bee species recorded in the studied natural garden but not in other studies recently performed in Upper Austria (Schwarz et al. 2025, Ockermüller 2018, Schwarz, personal communication) are highlighted in red. | **Tab. 1:** Artenliste der im Jahr 2024 oder während der sporadischen Begehungen von 2021 bis 2023 nachgewiesenen Bienenarten mit Informationen zur Nistweise, Sozialität, Pollenpräferenz und Rote Liste-Status Bayerns (RL BY). Für 2024 ist die Anzahl der gefangenen Individuen angegeben, für 2021-2023 dagegen die Präsenz einer Art. Bienenarten, die im untersuchten Naturgarten nachgewiesen wurden, aber in anderen kürzlich in Oberösterreich durchgeführten Studien (Schwarz et al. 2025, Ockermüller 2018, Schwarz, personal communication) nicht erfasst wurden, sind rot hervorgehoben.

			nesting behaviour				
species	**2024**	**2021–2023**	**underground[1]**	**overground[2]**	**sociality[3]**	**oligo[5]**	**RL BY**
Andrena afzeliella (Kirby, 1802)	3		scs		?		LC[6]
Andrena agilissima (Scopoli, 1770)		x	scs		co	Bra	3
Andrena apicata Smith, 1847		x	scs		sl	Sal	G
Andrena bicolor Fabricius, 1775	11	x	scs		sl		*
Andrena cineraria (Linnaeus, 1758)	2	x	scs		sl		*
Andrena clarkella (Kirby, 1802)	1		scs		sl	Sal	*
Andrena confinis Stoeckhert, 1930	2		scs		?		D
Andrena curvungula Thomson, 1870	1#	x	scs		sl	Camc	2
Andrena denticulata (Kirby, 1802)	5	x	scs		sl	Ast	V
Andrena dorsata (Kirby, 1802)	11	x	scs		sl		*
Andrena flavipes Panzer, 1798	7	x	scs		sl		*
Andrena fucata Smith, 1847		x	scs		sl		*
Andrena fulva (Müller, 1766)	2#	x	scs		sl		*
Andrena fulvago (Christ, 1791)	1		scs		sl	Ast	3
Andrena gravida Imhoff, 1832	6	x	scs		sl		*
Andrena haemorrhoa (Fabricius, 1781)	13	x	scs		sl		*
Andrena hattorfiana (Fabricius, 1775)	3#	x	scs		sl	Dip	3
Andrena helvola (Linnaeus, 1758)	5		scs		sl		*
Andrena humilis Imhoff, 1832	5		scs		sl	Ast	V
Andrena labiata Fabricius, 1781	4#	x	scs		sl		*
Andrena lathyri Alfken, 1899		x	scs		sl	Lat, Vic	V
Andrena minutula (Kirby, 1802)	8		scs		sl		*

species	2024	2021–2023	nesting behaviour: underground[1]	nesting behaviour: overground[2]	sociality[3]	oligo[5]	RL BY
Andrena minutuloides Perkins, 1914	2		scs		sl		*
Andrena nigroaenea (Kirby, 1802)	1		scs		sl		*
Andrena nitida (Mueller, 1776)		x	scs		sl		*
Andrena nitidiuscula Schenck, 1853	2		scs		sl	Api	3
Andrena pandellei Pèrez, 1895		x	scs		sl	Camp	3
Andrena paucisquama Noskiewicz, 1924	1		scs		sl	Camc	1[7]
Andrena praecox (Scopoli, 1763)	5	x	scs		sl	Sal	*
Andrena proxima (Kirby, 1802)	3		scs		sl	Api	*
Andrena rosae Panzer, 1801	1#	x	Scs		sl	Api	1
Andrena scotica Perkins, 1916	3		scs		co		*
Andrena stragulata Illiger, 1806	1		scs		sl		3[7]
Andrena strohmella Stöckhert, 1928		x	scs		sl		*
Andrena subopaca Nylander, 1848	8		scs		sl		*
Andrena susterai Alfken, 1914		x	scs		sl		R
Andrena synadelpha Perkins, 1914	1		scs		sl		G
Andrena viridescens Viereck, 1916	1		scs		sl	Ver	V
Andrena wilkella (Kirby, 1802)	13		scs		sl	Fab	*
Anthidiellum strigatum (Panzer, 1805)	1	x		f	sl		V
Anthidium manicatum (Linnaeus, 1758)	8#	x		oec	sl		*
Anthidium oblongatum (Illiger, 1806)	7#	x		oec	sl		*
Anthidium punctatum Latreille, 1809	4#	x		oec	sl		*
Anthophora aestivalis (Panzer, 1801)	1	x	scs		sl		3
Anthophora crinipes Smith, 1854	3	x	scs		sl		R
Anthophora furcata (Panzer, 1798)	4	x		rw	sl	Lam	V
Anthophora plumipes (Pallas, 1772)	1#	x	scs		sl		*
Anthophora quadrimaculata (Panzer, 1798)	3	x	scs		sl		3
Bombus bohemicus Seidl, 1838	1				pa		*
Bombus campestris (Panzer, 1801)	2				pa		*
Bombus hortorum (Linnaeus, 1761)	2#	x	ecs	oec	sc		*

species	2024	2021–2023	nesting behaviour: underground[1]	nesting behaviour: overground[2]	sociality[3]	oligo[5]	RL BY
Bombus humilis (Illiger, 1806)	2	x		hl	sc		3
Bombus hypnorum (Linnaeus, 1758)	1#	x		oec	sc		*
Bombus lapidarius (Linnaeus, 1758)	2#	x	ecs	oec	sc		*
Bombus lucorum (Linnaeus, 1761)	5#	x	ecs		sc		*
Bombus norvegicus (Sparre-Schneider, 1918)	2				pa		*
Bombus pascuorum (Scopoli, 1763)	4#	x	ecs	oec	sc		*
Bombus pratorum (Linnaeus, 1761)	3#	x		oec	sc		*
Bombus terrestris (Linnaeus, 1758)	4#	x	ecs		sc		*
Ceratina chalybea Chevrier, 1872	1			ps	sl		3
Ceratina cucurbitina (Rossi, 1792)		x		ps	sl		*
Ceratina cyanea (Kirby, 1802)	9	x		ps	sl		*
Chelostoma campanularum (Kirby, 1802)	7	x		ecw	sl	Camp	*
Chelostoma distinctum (Stoeckhert, 1929)	9	x		ecw	sl	Camp	*
Chelostoma emarginatum (Nylander, 1856)	1			ecw	sl	Ran	CR[6]
Chelostoma florisomne (Linnaeus, 1758)	5	x		ecw	sl	Ran	*
Chelostoma rapunculi (Lepeletier, 1841)	7	x		ecw	sl	Camp	*
Coelioxys alata Förster, 1853	2				pa		*
Coelioxys aurolimbata Förster, 1853	1				pa		3
Coelioxys conoidea (Illiger, 1806)	1	x			pa		3
Coelioxys elongata Lepeletier, 1841		x			pa		*
Coelioxys rufescens Lepeletier & Serville, 1825	5	x			pa		3
Colletes daviesanus Smith, 1846	7		scs		sl	Ast	*
Colletes hederae Schmidt & Westrich, 1993	2		scs		sl	Hed	*
Colletes similis Schenck, 1853	3		scs		sl	Ast	V
Dioxys cincta (Jurine, 1807)	3#				pa		R
Epeoloides coecutiens (Fabricius, 1775)		x			pa		*
Eucera longicornis (Linnaeus, 1758)		x	scs		sl	Fab	V

species	2024	2021–2023	nesting behaviour: underground[1]	nesting behaviour: overground[2]	sociality[3]	oligo[5]	RL BY
Halictus confusus perkinsi Blüthgen, 1926	2		scs		sc		*
Halictus maculatus Smith, 1848	9	x	scs		sl		*
Halictus rubicundus (Christ, 1791)	1		scs		sl, sc		*
Halictus scabiosae (Rossi, 1790)	2#	x	scs		sl		*
Halictus sexcinctus (Fabricius, 1775)	10#	x	scs		sl		V
Halictus simplex Blüthgen, 1923	9		scs		sl		*
Halictus subauratus (Rossi, 1792)	26	x	scs		sc		*
Halictus tumulorum (Linnaeus, 1758)	10	x	scs		sc		*
Heriades truncorum (Linnaeus, 1758)	15	x		ecw	sl	Ast	*
Hoplitis adunca (Panzer, 1798)	13	x		ecw	sl	Ech	*
Hoplitis anthocopoides (Schenck, 1853)	1			f	sl	Ech	3
Hoplitis claviventris (Thomson, 1872)	1			ps	sl		*
Hoplitis leucomelana (Kirby, 1802)	8	x		ps	sl		*
Hoplitis mitis (Nylander, 1852)	2#			hl	sl	Camp	2
Hoplitis tridentata (Dufour & Perris, 1840)	4#	x		ps	sl	Fab	*
Hylaeus brevicornis Nylander, 1852	1			oec	sl		*
Hylaeus communis Nylander, 1852	15	x		oec	sl		*
Hylaeus confusus Nylander, 1852	10			ecw, ps	sl		*
Hylaeus difformis (Eversmann, 1852)	6	x		oec	sl		*
Hylaeus dilatatus (Kirby, 1802)	6			oec	sl		*
Hylaeus gredleri Förster, 1871	1			ecw	sl		*
Hylaeus hyalinatus (Smith, 1842)	11			oec	sl		*
Hylaeus nigritus (Fabricius, 1798)	8			oec	sl	Ast	*
Hylaeus paulus Bridwell, 1919	6			oec	sl		D
Hylaeus punctatus (Brullé, 1832)	1			oec	sl		*
Hylaeus sinuatus (Schenck, 1853)	2	x		oec	sl		*
Hylaeus styriacus Förster, 1871	1			oec	sl		*
Hylaues signatus (Panzer, 1798)		x		oec	sl	Res	*
Lasioglossum albipes (Fabricius, 1781)	6	x	scs		?		*

species	2024	2021–2023	nesting behaviour: underground[1]	nesting behaviour: overground[2]	sociality[3]	oligo[5]	RL BY
Lasioglossum calceatum (Scopoli, 1763)	11	x	scs		sc		*
Lasioglossum costulatum (Kriechbaumer, 1873)	1		scs		sl	Camc	V
Lasioglossum fulvicorne (Kirby, 1802)	2		scs		sl		*
Lasioglossum intermedium (Schenck, 1869)		x	scs		?		3
Lasioglossum laticeps (Schenck, 1869)	6		scs		sc		*
Lasioglossum leucozonium (Schrank, 1781)	3	x	scs		sl		*
Lasioglossum marginatum (Brullè, 1832)		x	scs		sc		R
Lasioglossum morio (Fabricius, 1793)	27	x	scs		sc[4]		*
Lasioglossum nigripes (Lepeletier, 1841)	8		scs		sc		1
Lasioglossum nitidiusculum (Kirby, 1802)		x	scs		sl		V
Lasioglossum nitidulum (Fabricius, 1804)	4		scs		sl		*
Lasioglossum parvulum (Schenck, 1853)		x	scs		sl		V
Lasioglossum pauxillum (Schenck, 1853)	16		scs		sc		*
Lasioglossum politum (Schenck, 1853)	1		scs		sc		*
Lasioglossum rufitarse (Zetterstedt, 1838)	1	x	scs		sl		*
Lasioglossum villosulum (Kirby, 1802)	2		scs		sl		*
Lasioglossum zonulum (Smith, 1848)	1	x	scs		sl		*
Macropis europaea Warncke, 1973	4#	x	scs		sl	Lys	*
Macropis fulvipes (Fabricius, 1804)	6#		scs		sl	Lys	*
Megachile alpicola Alfken, 1924		x		ecw	sl		*
Megachile centuncularis (Linnaeus, 1758)	3			ecw	sl		V
Megachile circumcincta (Kirby, 1802)	1	x		ecw, oec	sl		V
Megachile ericetorum Lepeletier, 1841	8#	x		oec	sl	Fab	*
Megachile lagopoda (Linnaeus, 1761)	8#	x	ecs		sl		2
Megachile ligniseca (Kirby, 1802)	2	x		ecw	sl		3
Megachile nigriventris Schenck, 1869	2	x		rw	sl		*
Megachile rotundata (Fabricius, 1787)	3			ecw	sl		*

species	2024	2021–2023	nesting behaviour: underground[1]	nesting behaviour: overground[2]	sociality[3]	oligo[5]	RL BY
Megachile versicolor Smith, 1844	3	x	ecs	ecw	sl		*
Megachile willughbiella (Kirby, 1802)	4	x	scs	ecw	sl		*
Melecta albifrons (Forster, 1771)	2#	x			pa		V
Melitta haemorrhoidalis (Fabricius, 1775)	4#	x	scs		sl	Camc	*
Melitta nigricans Alfken, 1905	3#	x	scs		sl	Lyt	V
Nomada armata Herrich-Schäffer, 1839		x			pa		2
Nomada femoralis Morawitz, 1868		x			pa		1
Nomada ferruginata (Linnaeus, 1767)		x			pa		*
Nomada flava Panzer, 1798		x			pa		*
Nomada flavoguttata (Kirby, 1802)	1	x			pa		*
Nomada flavopicta (Kirby, 1802)		x			pa		*
Nomada fulvicornis Fabricius, 1793	1	x			pa		*
Nomada fuscicornis Nylander, 1848	1				pa		3
Nomada panzeri Lepeletier, 1841	1	x			pa		*
Nomada ruficornis (Linnaeus, 1758)	4				pa		*
Nomada signata Jurine, 1807		x			pa		*
Nomada stigma Fabricius, 1804		x			pa		3
Nomada striata Fabricius, 1793		x			pa		*
Osmia aurulenta (Panzer, 1799)	3#	x		ss	sl		*
Osmia bicolor (Schrank, 1781)	2	x		ss	sl		*
Osmia bicornis (Linnaeus, 1758)	9#	x		ecw, oec	sl		*
Osmia caerulescens (Linnaeus, 1758)	13	x		ecw	sl		*
Osmia cornuta (Latreille, 1805)	field	x		ecw, oec	sl		*
Osmia leaiana (Kirby, 1802)	20	x		ecw	sl	Ast	3
Osmia niveata (Fabricius, 1804)	1			ecw	sl	Ast	3
Panurgus calcaratus (Scopoli, 1763)	2#	x	scs		co	Ast	V
Sphecodes albilabris (Fabricius, 1793)		x			pa		*
Sphecodes crassus Thomson, 1870	1	x			pa		*
Sphecodes ephippius (Linnaeus, 1767)	7	x			pa		*

species	2024	2021–2023	nesting behaviour: underground[1]	nesting behaviour: overground[2]	sociality[3]	oligo[5]	RL BY
Sphecodes gibbus (Linnaeus, 1758)		x			pa		*
Sphecodes longulus Hagens, 1882	1				pa		*
Sphecodes monilicornis (Kirby, 1802)	2				pa		*
Sphecodes niger Hagens, 1874	1				pa		*
Sphecodes puncticeps Thomson, 1870		x			pa		*
Sphecodes reticulatus Thomson, 1870	1				pa		V
Stelis breviuscula (Nylander, 1848)	1				pa		*
Stelis minima Schenck, 1859	3	x			pa		D
Stelis minuta Lepeletier & Serville, 1825	1	x			pa		3
Stelis ornatula (Klug, 1807)	2				pa		*
Stelis phaeoptera (Kirby, 1802)	1	x			pa		2
Stelis punctulatissima (Kirby, 1802)	3#	x			pa		*
Stelis signata (Latreille, 1809)	1	x			pa		3
Trachusa byssina (Panzer, 1804)	2		scs		sl	Fab	3
Xylocopa violacea (Linnaeus, 1758)	field	x		rw	sl		*

\# Only a subset of individuals recorded in the garden have been collected.

1 underground nesting behaviours: ecs: existing cavities in the soil; scs: self-dug cavities in the soil.

2 overground nesting behaviours: ecw: existing cavities in dead wood or cavities in hollow stems; oec: other existing cavities; ps: self-made cavities in pithy stems; rw: self-made cavities in rotting wood; f: free-standing nests; hl: herb layer; ss: empty snail shells.

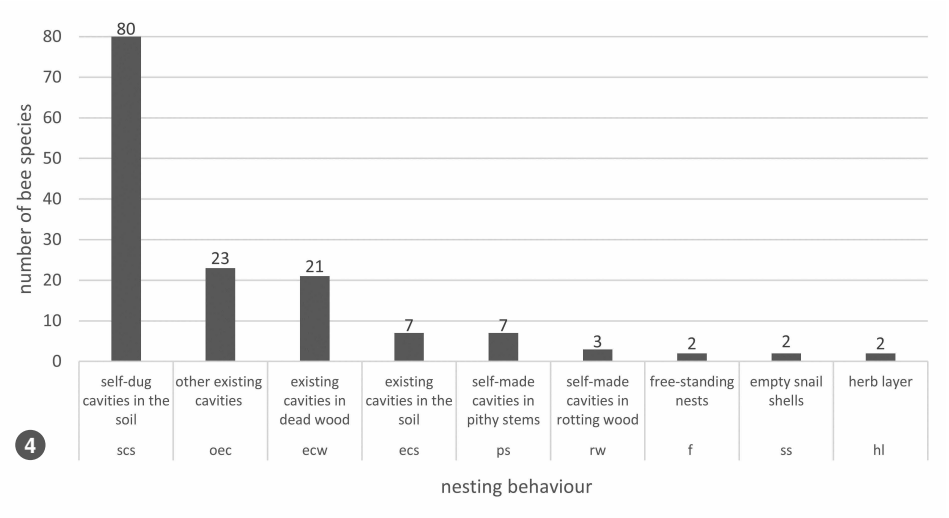
3 sociality: sl: solitary; co: communal; sc: social; pa: cleptoparasitic or social parasitic; ?: the sociality of these nest-building bee species is unknown

4 The sociality was suggested but not proven.

5 oligo: oligolectic; Bra: Brassicaceae; Sal: *Salix*; Camp: *Campanula*; Camc: *Campanulaceae*; Ast: Asteraceae; Dip: Dipsacaceae; Lat: *Lathyrus*; Vic: *Vicia*; Api: Apiaceae; Ver: *Veronica*; Fab: Fabaceae; Lam: Lamiaceae; Ran: *Ranunculus*; Hed: *Hedera*; Ech: *Echium*; Res: *Reseda*; Lys: *Lysimachia*; Lyt: *Lythrum;* if the cell is empty for a species and if this species is not marked as parasitic, it is polylectic.

6 Müller and Praz (2024)

7 Westrich et al. (2011)



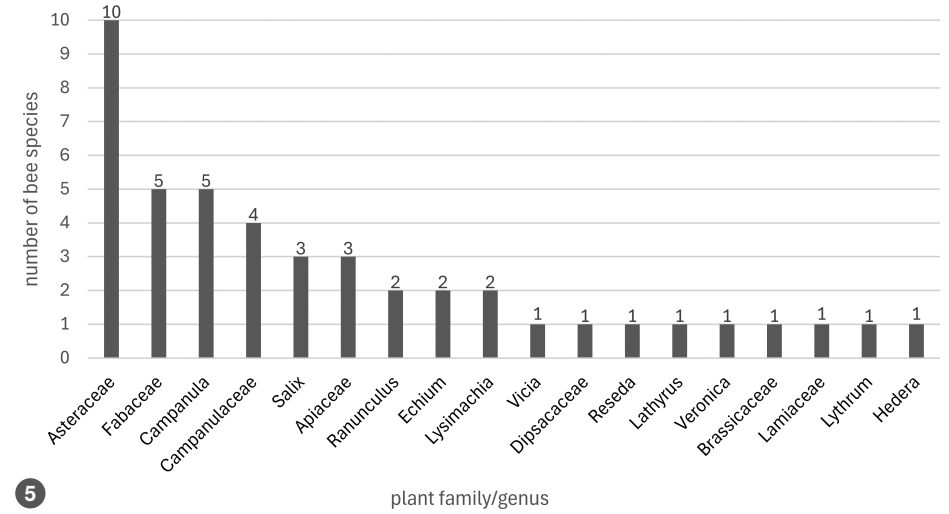


Fig. 4: Nesting behaviour of the 138 recorded nest-building bee species (several bee species are classified in different categories (Table 1)). The abbreviations are the same as given in Table 1. | **Abb. 4:** Nistweisen der 138 nachgewiesenen nestbauenden Bienenarten (einige Arten sind mehreren Kategorien zugeordnet, s.Tabelle 1). Die Abkürzungen entsprechen denen in Tabelle 1.

Fig. 5: Pollen sources of the 44 recorded oligolectic species (the bee species *Andrena lathyri* is listed twice, namely once for *Lathyrus* and once for *Vicia* (Table 1)). | **Abb. 5:** Pollenquellen der 44 nachgewiesenen oligolektischen Bienenarten (*Andrena lathyri* wurde zweimal zugeteilt, nämlich den Pflanzengattungen *Lathyrus* und *Vicia,* s. Tabelle 1).

Fig. 6: Examples of the recorded bee species. **a**: *Panurgus calcaratus,* which constructs its nests in self-dug cavities in the soil, next to a nest entrance, **b**: *Anthidium punctatum,* which builds its nests in existing cavities, sitting on a flower of *Cichorium intybus*, **c**: *Hoplitis tridentata* at the entrance of its nest in a self-made cavity in a pithy stem, **d**: *Osmia bicolor* while constructing its nest in an empty snail shell, **e**: *Xylocopa violacea,* which nests in self-made cavities in rotten wood, visiting flowers of *Carduus nutans*, **f**: *Melitta nigricans*, an oligolectic bee species, visiting flowers of *Lythrum salicaria.* | **Abb. 6:** Beispiele nachgewiesener Bienenarten. **a**: *Panurgus calcaratus,* die ihre Nester in selbstgegrabenen Hohlräumen im Boden anlegt, neben einem Nesteingang, **b**: *Anthidium punctatum*, welche ihre Nester in bereits bestehenden Hohlräumen anlegt, auf einer Blüte von *Cichorium intybus* sitzend, **c**: *Hoplitis tridentata* am Eingang ihres Nestes in einem selbstgenagten Hohlraum in einem markhaltigen Stängel, **d**: *Osmia bicolor* beim Bau ihres Nestes in einem leeren Schneckenhaus, **e**: *Xylocopa violacea*, die in selbstgenagten Hohlräumen in Morschholz nistet, beim Besuch einer Blüte von *Carduus nutans*, **f**: *Melitta nigricans*, eine oligolektische Bienenart, beim Besuch der Blüten von *Lythrum salicaria.*

Tab. 2: Number of recorded bee species for the different Red List categories. | **Tab. 2:** Anzahl der nachgewiesenen Bienenarten pro Rote-Liste-Kategorie.

Red List category	number of bee species
1 (critically endangered)	5[1]
2 (endangered)	5
3 (vulnerable)	23
G (threatened to an unknown extent)	2
R (extremely rare)	4
V (near threatened)	18
* (least concern)	118[2]
D (data deficient)	3

1 including the category CR of the Red List of Switzerland (Table 1)

2 including the category LC of the Red List of Switzerland (Table 1)

Discussion

With a total of 178 recorded wild bee species, the number of species in this garden accounts for a quarter (25 %) of the bee species recorded throughout Austria (Wiesbauer 2023) and for about two-fifths (41 %) of those recorded for Upper Austria (Gusenleitner et al. 2012; Ebmer et al. 2018; Ockermüller et al. 2021; Schwarz & Schwarz 2024). Of the 178 recorded wild bee species, 22 % were parasites and 78 % were nest-building. 32 % of the nest-building bee species were oligoleges. Most of the nest-building species construct their nests in self-dug cavities in the soil, in existing cavities or in existing cavities in dead wood. 22 % of the recorded bee species are threatened according to the Red List.

A total of 29 bee species were recorded in the studied natural garden but not in other studies recently performed in Upper Austria (Table 1, species marked in red). Among them are species such as *Hoplitis tridentata, Anthophora quadrimaculata, Lasioglossum costulatum, Lasioglossum intermedium* and *Coelioxys alata. Hoplitis tridentata* is an oligolectic bee species specialised on Fabaceae, and constructs its nests in self-made cavities in pithy stems (Westrich 2019). *Anthophora quadrimaculata* is polylectic and constructs its nests in self-dug cavities in the soil, preferably in vertical loess or clay walls (Westrich 2019). Such nesting sites are provided in the garden by nesting aids that imitate vertical loess and clay walls and by sandy areas/hills. *Lasioglossum costulatum* is specialised for its pollen on Campanulaceae and constructs its nests in self-dug cavities in the soil (Westrich 2019). This species benefits from the high number of different plant species of native Campanulaceae which were introduced into the garden. *Lasioglossum intermedium* is polylectic and nests in self-dug cavities in sandy soil (Westrich 2019). Such nesting sites are provided by the high variety of sandy areas and small hills in the garden. *Coelioxys alata* is a parasitic bee species and specialised on its host species *Megachile ligniseca*, which was also recorded in the Garden (Westrich 2019). Furthermore, our study provides confirmed records of *Megachile lagopoda* (Linnaeus, 1761) for Upper Austria, a species that had not previously been reliably documented in this

Tab. 3: Size, total number of bee species and number of bee species per 100 m² of three botanical gardens. | **Tab. 3:** Fläche, Gesamtanzahl nachgewiesener Bienenarten und Anzahl an Bienenarten pro 100 m² dreier Botanischer Gärten.

study area	area (m²)	number of bee species	number of bee species per 100 m²	Reference
Botanical Garden Bayreuth	135.000	228	0.2	Schanz et al. (2023)
Botanical Garden Graz	36.000	151	0.4	Teppner et al. (2016)
Botanical Garden Vienna	80.000	131	0.2	Hölzler (2004)

federal state (Gusenleitner et al. 2012; Ebmer et al. 2018; Ockermüller et al. 2021; Schwarz & Schwarz 2024). Verified records have also recently been reported from the Nature Park Mühlviertel (Schwarz et al. 2025). Overall, the natural garden is home for a high number of bees available in the region. The high number of flowers and nesting sites offered in the garden obviously also allowed bees otherwise rare in Upper Austria to colonize the garden.

When comparing the bee fauna recorded in this garden with that of the Botanical Garden Bayreuth (Germany), which is the botanical garden with the highest number of recorded bee species so far, and the two Austrian botanical gardens with available data (Graz and Vienna) (Table 3), the two Austrian botanical gardens show lower species numbers (≤ 151 species), whereas the Botanical Garden of Bayreuth has a higher species number, with 228 bee species recorded. Considering the different sizes of the three botanical gardens (36000–135000 m²; Table 3) and the studied natural garden (3700 m²), it is obvious that the relatively small natural garden contains a remarkably diverse bee fauna (approximately 5 species per 100 m²) when compared to the botanical gardens (0.2–0.4 species per 100 m²) (Table 3).

The percentage of parasitic bee species (22 %) observed in this garden is comparable to that reported for the bee fauna of Germany, Austria and Switzerland (Wiesbauer 2023), as well as to proportions found in botanical gardens (e.g. 24 % for the Botanical Garden of Vienna, (Hölzler 2004); 29 % for the Botanical Garden Bayreuth in 2022, (Schanz 2023)). This suggests that the surveyed garden contains stable populations of the necessary hosts and serves as a high quality habitat also for bee species with specialised life history requirements (Bell et al. 2023). This conclusion that the surveyed garden is not only suitable for generalists but also for specialists is supported by the finding that approximately one third of the nest-building species were oligoleges. Again, this number is similar to the proportion of oligoleges among all the nest-building wild bee species of Germany, Austria and Switzerland (Wiesbauer 2023), and to the proportion of oligoleges in botanical gardens (e.g. 30 % for the Botanical Garden Vienna, (Hölzler 2004); 33 % for the Botanical Garden Bayreuth in 2022, (Schanz 2023)). This high proportion of oligolectic species, and the high wild bee species richness in general, is very likely possible due to the high abundance, number and taxonomic diversity of flowering plant species available in the garden (Rahimi et al. 2022; Rotondi et al. 2024). Interestingly, most of the recorded oligoleges are specialised on Asteraceae, which is also the family which showed the highest abundance of blooming flowering plants in the garden. Similarly, the recorded fauna contained a high number of oligolectic species specialised on the genus *Campanula* or on Campanulaceae, of which 10 species have bloomed in the garden. This suggests that the species richness of plant families affects the number of oligoleges recorded on these plants. This conclusion is supported by

the fact that among those oligolectic bee species which are specialised on Asteraceae, for instance, some bee species are showing preferences for specific plant tribes, genera or species within the family and favour them over other such groups (Westrich 2019). Due to these further specialisations of oligoleges within a plant family, a garden that hosts a higher species richness of native plants per family therefore is very likely to promote a higher number of different oligoleges.

Our finding that most of the recorded species build their nests in self-dug cavities in the soil, in other existing cavities (e.g. holes between or underneath rocks; crevices in stone) and in existing cavities in dead wood (e.g. abandoned burrows of other insects) suggests that the bees accepted the various nesting aids offered in the garden. However, more research is needed to record the nesting sites of the different species and test which of them do indeed nest in the garden.

Our finding that 22 % of all recorded wild bee species can be classified as threatened (Red List categories 1, 2, 3, G, R) – a proportion slightly higher than that reported for the Botanical Garden in Bayreuth (approximately 19 % of the 228 recorded species; Schanz et al. 2023) – indicates that in this garden not only common but also rare and endangered species are present.

To conclude, this study shows that there is a high potential of highly structured private natural gardens in supporting and promoting a high diversity of bees in times, where this important group of pollinators is declining in Europe and around the globe (IPBES 2016, Michez et al. 2026). This not only is shown by the high number of 178 different bee species recorded in this garden but also by the fact that among them, there were not only common and generalist species, but also many rare, endangered and highly specialised ones. To the best of our knowledge, there is no other private garden in Central Europe known that has such a high species richness of bees. With a theoretical number of approximately 5 bee species per 100 m², this garden hosts a remarkably diverse bee fauna on a relatively small area. This high species richness of wild bees is particularly remarkable given the fact that the garden is rather young, with the majority of structures built within the last 10 years. Thus, it is likely that additional species will establish themselves in the future. This assumption that additional bee species will establish over time is indeed supported by the fact that in 2025, a further ten species were newly recorded for the garden during sporadic surveys: *Andrena alutacea* Stöckhert, 1942*; Andrena fulvata* Stöckhert, 1930*; Andrena varians* (Kirby, 1802); *Bombus mastrucatus* Gerstäcker, 1869; *Bombus barbutellus* (Kirby, 1802); *Coelioxys inermis* (Kirby, 1802)*; Epeolus variegatus* (Linnaeus, 1758); *Hylaeus cornutus* Curtis, 1831*; Lasioglossum semilucens* (Alfken, 1914); *and Nomada marshamella* (Kirby, 1802). With these additions, the total number of recorded wild bee species currently amounts to 188. The comparison with several botanical gardens revealed that, although they may support a similarly high or even higher total species richness, this occurs on significantly larger areas, and most botanical gardens have also been established for a far longer time (e.g. Dötterl 2001; Hölzler 2004; Teppner et al. 2016; Schanz 2023). To better understand which measures taken in this garden contribute most to the promotion of wild bees and which have lesser effects, further research is necessary. It would be very interesting to know which of the plant species are used by which bees as host plants, and which of the nesting sites and nesting aids available in the garden are used by the different bees. Such data could be a basis for suggesting conservation measures for bees in private gardens and elsewhere.

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