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A photo-based assessment of wild bees in a filled-up gravel pit in Riem, Munich – with a species list of bees found in Central European gravel pits

(Hymenoptera, Apiformes)

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Gravel pits, both in active use and restored, provide important replacement habitats and nesting requisites for wild bees formerly specialized in nesting in dynamic fluvial landscapes. Species inventories in six Central European gravel pits report 245 species of wild bees, and this study found 48 species of wild bees and the domesticated *Apis mellifera* in the refilled section of the Obermayr gravel pit in Riem, Munich. The tested inventory method of in-situ photo-documentation, instead of voucher specimen collection, was feasible for most bee families, but is not applicable for Halictidae and some small nomad bees (genus *Nomada*) or mini-miners (*Andrena* subgenus *Micrandrena*), as well as species complexes in the genus *Bombus*.

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Introduction

Dynamic riverside landscapes are an important habitat for various wild bee species (Völkl et al. 2002), but became increasingly rare in Central Europe. An assessment of more than 76 000 km of watercourses in Germany, conducted by the water management authorities of the federal states, showed that only 1.6 % of the rivers are in their natural state, another 6.2 % are only slightly modified and 11.9 % moderately changed, the rest falls in the classes considerably, strongly, very strongly or completely changed (Arle et al. 2017). Thus, many of the bee species naturally specialized on riverside habitats are nowadays found in sand and gravel pits instead (Escher 1974, Westrich 2018), as these provide manifold different niches, like deep and shallow ponds, accumulations of clay, sand, gravel, rocks, shrubland and steep faces (Krebs & Wildermuth 1976) – especially for many soil-nesting bees species, the presence of open, poorly vegetated, freshly exposed soils is an essential habitat demand (Westrich 1989, Falk & Lewington 2015). The continuous de-novo succession of the habitat through ongoing gravel extraction simulates landscape dynamics typically induced in erosion banks and river landscapes by flooding events and fluvial erosion cycles (Meisterhans & Heusser 1970, Krebs & Wildermuth 1976). Inventories conducted in actively used and restored gravel pits in Central Europe identified 245 species of wild bees for this habitat (see Results section, Tables 1 and 2 for references).

The gravel pit of the Obermayr Company in the East of Munich offers both, renatured areas and areas which are still mined for sand and gravel.

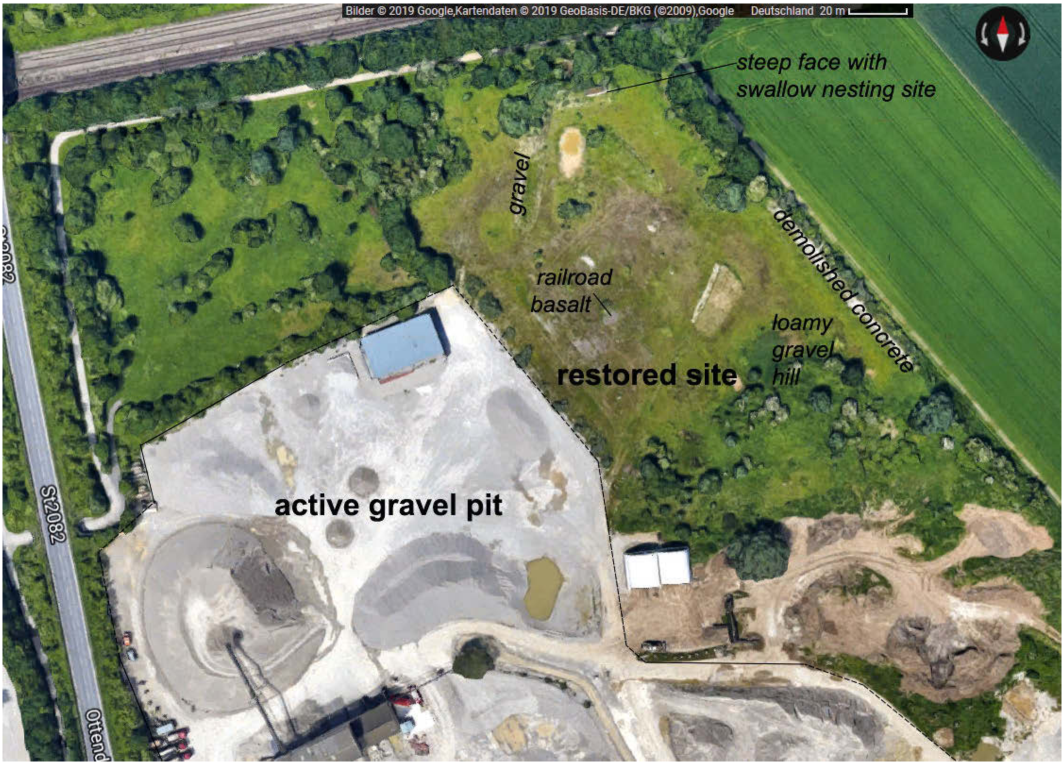

Fig. 1. The study site "Kiesgrube Obermayr" (modified from www.google.de/maps/@48.1462044,11.7084456,606 m/data=!3m1!1e3; last accessed 19.02.2019).

This study focused on a living bee inventory in the non-active parts of the gravel pit, applying a standardized in-situ photo-documentation, and vouchers were only collected for those taxonomically critical genera where determination in the field was not possible. Besides producing a species inventory for the Obermayr gravel pit in Riem, this study aimed to test the feasibility of using a non-invasive species determination based on bee specimen photography in the field instead of voucher collection. With current projects like the "Bundesprogramm Biologische Vielfalt – Schwerpunkt Sichern von Ökosystemdienstleistungen" of the Federal Office for Nature Conservation (BfN) and the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU), non-invasive monitoring methods become increasingly important and the possibility of reliable, reproducible documentation fulfilling scientific standards without specimen collection needs to be tested.

Material and methods

Species list for Central European gravel pits

We are aware of five published studies which have monitored wild bees in gravel pits (Table 1). Additionally, we requested an unpublished report (Dubitzky 2015) for another Munich gravel pit located in the East of Munich (Trudering). The species lists within these studies were compiled and a list of 239 species recorded in gravel pits was generated (Table 2). The honey bee *Apis mellifera* was excluded from the analyses, as this is a domesticated and ubiquist species. Each found study was scanned for the following information: (i) Where and when was the study conducted? (ii) Which sampling technique was used? (iii) Which taxa were found? If the information was not directly clear from the published material, the authors were contacted via e-mail.

Study site "Kiesgrube Obermayr"

"Kiesgrube Obermayr" is situated in the East of Munich, in Riem at N 48°8.833140' E 11°42.608280' 520 m a.s.l. While the southern part is still an active gravel pit, the northern part is refilled and maintained as an open-soil and nutrient-poor grassland site. The area is not open

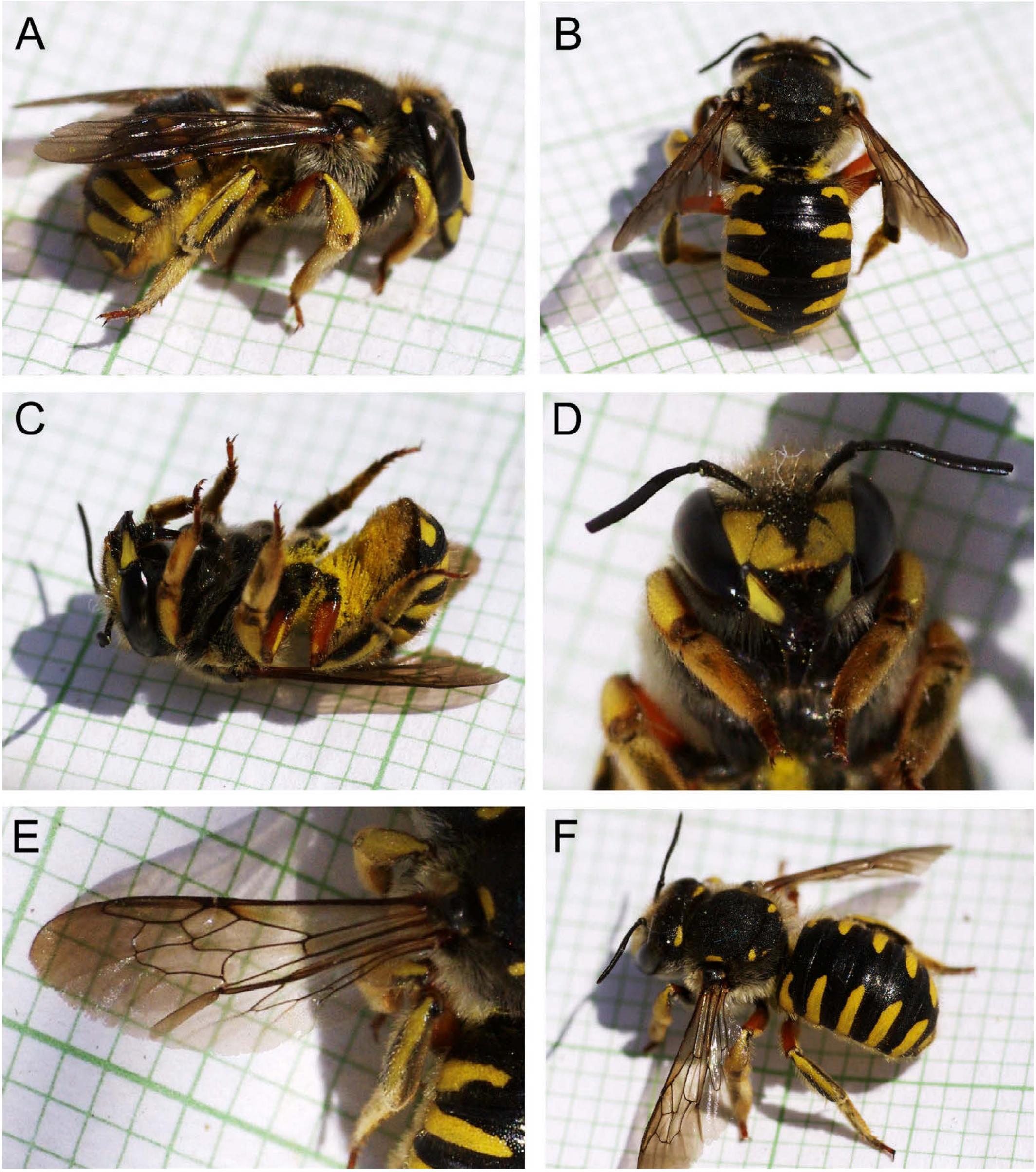

Fig. 2. Picture plate of an *Anthidium manicatum* female: **A.** lateral view; **B.** dorsal view; **C.** ventral view; **D.** detail face and front legs; **E.** detail wings; **F.** thorax and abdomen pattern. Images A–E: individual immobilized by chilling; F: recovering from paralyzation. Square grid = 1 mm. All photographs by M. Hofmann.

to the public and is maintained by the Landesbund für Vogelschutz (LBV) and the municipal department (Kommunalreferat). It borders to the Munich Trade Fair Center in the Southwest, a transshipment station in the West and arable fields to all other directions. Until 2004, the northern area had still been in active use as gravel pit, and then was refilled with several soil types. There are two experimental fields with washed dry mud (middle and eastern part), a fine sediment resulting from washing gravel, and washed sand, a sandy material also resulting from the washing process with fine cohesive components (H. Sedlmeier, pers. com.). The steep face in the northern part of the biotope consists of this washed sand. Unwashed gravel had been piled up to several walls and hills at the site. There is also a southeast-facing wall of demolished concrete that is not covered by vegetation. In the middle of the biotope there is railroad basalt disposed from the railroad tracks of former Neuaubing station. The bigger stones probably originated from the alpine upland. Loamy gravel derived from the topsoil removed for gravel extraction forms the hills in the south and the smaller walls in the northeastern and northern part of the biotope, these artificial hills are sparsely covered by woody vegetation, mainly consisting of willows (*Salix* spp., Salicaceae). The rest of the area is covered by a thin, compressed loam-gravel-layer on building rubble. Flat areas, hills, and ponds create a highly-structured area (Fig. 1). The area's flora (>545 documented species found during species monitoring from 2003–2016; a list excluding threatened taxa is available via the LBV administration) and its butterfly, grasshopper, and beetle fauna (see biotope reports available via the LBV administration) are extremely rich. Herbaceous plants and grasses were reintroduced by autochthonous transfer of mowed material from nearby dry grassland habitats of Munich, and *Hippophae rhamnoides*, *Sorbus aucuparia* and various *Rosa* sp., all of Munich provenance, had been actively planted by the LBV. Hundreds of trees and shrubs of eight *Salix* species have established by themselves (H. Sedlmeier, pers. com.).

Species inventory

Between the 14th of March and the 8th of August 2017, the Obermayr gravel pit was visited by the first author in regular intervals (every 2–3 weeks), the initial spring species survey was conducted by both authors. Monitoring walks were conducted between 10 am and 4 pm on sunny, warm days with little or no wind. The mapping did not follow a strict route, but bees were searched for on flowers and nesting requisites. If possible, species were identified directly in the field and were documented via macro-photography in a standardized setup: for detailed pictures, the bees were caught with an insect net and cooled down for 10 minutes in an Eppendorf cupped plastic vial stored on ice in a cooled box. When the bees fell into rigor of cold, they were transferred onto scale paper (using a small box lined with millimeter paper on its bottom) and photographed from all sides (SLR camera: Pentax K-x; Lens: Sigma DG 17–70 mm, 1:2.8, macro), carefully turning them by hand or using a pair of watchmaker's tweezers. Within one to two minutes, they warmed up again and were released at the location they were also caught. For species that are taxonomically difficult to distinguish by morphology alone, like most members of the genera *Sphecodes*, *Lasioglossum* or *Halictus*, voucher specimens, preferably males (for morphological re-identification by genitalia preparations), were collected and identified morphologically and via DNA barcoding (methods and primers as described in Hofmann et al. 2018). Photo vouchers are accessible via the Diversity Workbench (DWB) server, DNA barcodes were uploaded to NCBI GenBank (see Table 3 for GenBank Accession Numbers and DWB Accessions). The voucher specimens are deposited in the Zoologische Staatssammlung Munich (ZSM).

Additionally, we included species records from 2016 provided by M. Bräu in the species list. The domesticated honey bee *Apis mellifera* was abundantly observed at the Kiesgrube Obermayr, but not included in the species list.

Table 1. Inventories of active and renatured gravel pits in Central Europe, with study period and sampling method.

Site	Study period	Sampling method	Number of species	Publication
inactive gravel pit complex in Leverkusen	2000–2005	net sampling	98	[1] Cölln et al. 2012
former gravel pit Roth in Trudering, Munich	4 monitoring walks in 2015; one additional investigation day in 2008	net sampling	70	[2] Dubitzky, A. (2015) and Schuberth, J. (unpublished)
Ramsar area "Baggerweieren" at "Haff Réimech", Luxembourg	1997 to 2004; 209 monitoring walks	net sampling	110	[3] Feitz et al. 2006
gravel pits between Rhine and Lake Zurich	N/A	N/A	14	[4] Krebs & Wildermuth 1976
closed gravel pit Rutzendorf, Lower Austria	2003–2005 and 2007–2008; four-weekly rhythm	net sampling	82	[5] Pachinger & Prochazka 2009; with additional data from B. Pachinger for 2009 and later (personal communication)
gravel pit "am Hardtwald Durmersheim" south of Karlsruhe	1993 to 2005	net sampling	41	[6] Schiel & Rademacher 2008; with additional data from A. Schanowski for 2007 (personal communication)

Table 2. List of wild bees reported for Central European gravel pits. The numbers in squared brackets indicate the studies where the species was reported (numbers refer to Table 1). Species marked in bold were also found in this study.

Species	Family	Study
Andrena agilissima (Scopoli, 1770)	Andrenidae	[3]
Andrena apicata Smith, 1847	Andrenidae	[2]
Andrena barbilabris (Kirby, 1802)	Andrenidae	[1,6]
***Andrena bicolor* Fabricius, 1775**	Andrenidae	[1,2,6]
Andrena carantonica Pérez, 1902	Andrenidae	[1,6]
Andrena chrysopus Pérez, 1903	Andrenidae	[6]
***Andrena chrysosceles* (Kirby, 1802)**	Andrenidae	[3,5]
Andrena clarkella (Kirby, 1802)	Andrenidae	[2]
Andrena cineraria (Linnaeus, 1758)	Andrenidae	[2,3,6]
Andrena denticulata (Kirby, 1802)	Andrenidae	[6]
***Andrena dorsata* (Kirby, 1802)**	Andrenidae	[1,5,6]
***Andrena flavipes* Panzer, 1798**	Andrenidae	[1,2,5,6]
Andrena fulva (Müller, 1766)	Andrenidae	[1,3]
Andrena fulvata Stoeckhert, 1930	Andrenidae	[2]
Andrena gelriae van der Vecht, 1927	Andrenidae	[6]
***Andrena gravida* Imhoff, 1832**	Andrenidae	[2]
***Andrena haemorrhoa* (Fabricius, 1781)**	Andrenidae	[1,3,5,6]
Andrena hattorfiana (Fabricius, 1775)	Andrenidae	[3]
Andrena helvola (Linnaeus, 1758)	Andrenidae	[2]
Andrena impunctata Pérez, 1895	Andrenidae	[5]
Andrena intermedia Thomson, 1870	Andrenidae	[2]
Andrena labiata Fabricius, 1781	Andrenidae	[1,6]
Andrena lathyri Alfken, 1899	Andrenidae	[6]
Andrena minutula (Kirby, 1802)	Andrenidae	[1,2,3,6]
Andrena minutuloides Perkins, 1914	Andrenidae	[1,5]
Andrena mitis Schmiedeknecht, 1883	Andrenidae	[6]
Andrena nigroaenea (Kirby, 1802)	Andrenidae	[5]
Andrena nitida (Müller, 1776)	Andrenidae	[3]
Andrena nobilis Morawitz, 1873	Andrenidae	[5]
Andrena oralis Morawitz, 1876	Andrenidae	[5]
Andrena ovatula (Kirby, 1802)	Andrenidae	[1,5,6]
Andrena pilipes Fabricius, 1781	Andrenidae	[1,5,6]
Andrena praecox (Scopoli, 1763)	Andrenidae	[1,2,6]
Andrena propinqua Schenck, 1853	Andrenidae	[5]
Andrena proxima (Kirby, 1802)	Andrenidae	[1]
Andrena pusilla Pérez, 1903	Andrenidae	[6]
Andrena ruficrus Nylander, 1848	Andrenidae	[2]
Andrena schencki Morawitz, 1866	Andrenidae	[3]
Andrena scita Eversmann, 1852	Andrenidae	[5]
Andrena similis Smith, 1849	Andrenidae	[6]
Andrena simontornyella Noskiewicz, 1939	Andrenidae	[5]
Andrena strohmella Stoeckhert, 1928	Andrenidae	[2]
Andrena subopaca Nylander, 1848	Andrenidae	[2,3,6]
Andrena symphyti Schmiedeknecht, 1883	Andrenidae	[5]
***Andrena vaga* Panzer, 1799**	Andrenidae	[1,2,3,4,6]
Andrena ventralis Imhoff, 1832	Andrenidae	[2]
***Andrena viridescens* Viereck, 1916**	Andrenidae	[6]
Andrena wilkella (Kirby, 1802)	Andrenidae	[1,6]
Anthidiellum strigatum (Panzer, 1805)	Megachilidae	[3,4,6]

Table 2. (continued).

Species	Family	Study
Anthidium manicatum **(Linnaeus, 1758)**	Megachilidae	[2,3]
Anthidium nanum Mocsary, 1881	Megachilidae	[3,5]
Anthidium oblongatum **(Illiger, 1806)**	Megachilidae	[3]
Anthidium punctatum **Latreille, 1809**	Megachilidae	[2,3,5]
Anthophora bimaculata (Panzer, 1798)	Apidae	[6]
Anthophora plumipes (Pallas, 1772)	Apidae	[1,2,3,4]
Anthophora quadrimaculata (Panzer, 1798)	Apidae	[1]
Anthophora retusa (Linnaeus, 1758)	Apidae	[1,3,6]
Bombus hortorum **(Linnaeus, 1761)**	Apidae	[1,2,5]
Bombus humilis Illiger, 1806	Apidae	[5,6]
Bombus hypnorum **(Linnaeus, 1758)**	Apidae	[1,3]
Bombus lapidarius **(Linnaeus, 1758)**	Apidae	[1,2,5,6]
Bombus lucorum **(Linnaeus, 1761)**	Apidae	[1,2,5]
Bombus pascuorum **(Scopoli, 1763)**	Apidae	[1,2,3,5,6]
Bombus pratorum **(Linnaeus, 1761)**	Apidae	[1,2]
Bombus rupestris **(Fabricius, 1793)**	Apidae	[1,2,6]
Bombus soroeensis (Fabricius, 1776)	Apidae	[2]
Bombus sylvarum **(Linnaeus, 1761)**	Apidae	[3,5,6]
Bombus terrestris **(Linnaeus, 1758)**	Apidae	[1,3,5]
Bombus vestalis **(Geoffroy, 1785)**	Apidae	[1,2,5]
Camptopoeum frontale (Fabricius, 1804)	Andrenidae	[5]
Ceratina chalybea Chevrier, 1872	Apidae	[5]
Ceratina cucurbitina (Rossi, 1792)	Apidae	[1,3,5,6]
Ceratina cyanea (Kirby, 1802)	Apidae	[1,2,3,4,5,6]
Chelostoma campanularum (Kirby, 1802)	Megachilidae	[1,6]
Chelostoma distinctum (Stöckhert, 1929)	Megachilidae	[2,3,6]
Chelostoma florisomne (Linnaeus, 1758)	Megachilidae	[3]
Chelostoma rapunculi (Lepeletier, 1841)	Megachilidae	[1,2,3,6]
Coelioxys afra Lepeletier, 1841	Megachilidae	[3,6]
Coelioxys aurolimbata Förster, 1853	Megachilidae	[3]
Coelioxys elongata **Lepeletier, 1841**	Megachilidae	this study
Coelioxys inermis (Kirby, 1802)	Megachilidae	[2]
Coelioxys mandibularis Nylander, 1848	Megachilidae	[1]
Coelioxys quadridentata (Linnaeus, 1758)	Megachilidae	[1,3]
Colletes cunicularius **(Linnaeus, 1761)**	Colletidae	[1,2,3,6]
Colletes daviesanus **Smith, 1846**	Colletidae	[1,4,5]
Colletes fodiens (Geoffroy, 1785)	Colletidae	[1,6]
Colletes hederae Schmidt & Westrich, 1993	Colletidae	[3]
Colletes similis Schenck, 1853	Colletidae	[1,6]
Dasypoda hirtipes (Fabricius, 1793)	Melittidae	[3,4,5,6]
Dioxys tridentata (Nylander, 1848)	Megachilidae	[3]
Epeoloides coecutiens (Fabricius, 1775)	Apidae	[3]
Epeolus variegatus (Linnaeus, 1758)	Apidae	[1,3,6]
Eucera longicornis (Linnaeus, 1758)	Apidae	[3,5]
Eucera nigrescens Pérez, 1879	Apidae	[3,5,6]
Eucera pollinosa Smith, 1854	Apidae	[5]
Halictus confusus Smith, 1853	Halictidae	[6]
Halictus eurygnathus **Blüthgen, 1931**	Halictidae	[3]
Halictus gavarnicus Pérez, 1903	Halictidae	[5]

Table 2. (continued).

Species	Family	Study
Halictus kessleri Bramson, 1879	Halictidae	[5]
Halictus langobardicus Blüthgen, 1944	Halictidae	[3,6]
Halictus leucaheneus Ebmer, 1972	Halictidae	[6]
Halictus maculatus Smith, 1848	Halictidae	[3,5,6]
Halictus pollinosus Sichel, 1860	Halictidae	[5]
Halictus quadricinctus (Fabricius, 1777)	Halictidae	[5,6]
***Halictus rubicundus* (Christ, 1791)**	Halictidae	[1,3,6]
***Halictus scabiosae* (Rossi, 1790)**	Halictidae	[1,3,6]
Halictus seladonius (Fabricius, 1794)	Halictidae	[5]
Halictus sexcinctus Fabricius, 1775	Halictidae	[4,5,6]
Halictus simplex Bluethgen, 1923	Halictidae	[5,6]
Halictus smaragdulus Vachal, 1895	Halictidae	[6]
***Halictus subauratus* (Rossi, 1792)**	Halictidae	[3,5,6]
***Halictus tumulorum* (Linnaeus, 1758)**	Halictidae	[1,2,3,5,6]
Heriades crenulatus Nylander, 1856	Megachilidae	[6]
Heriades truncorum (Linnaeus, 1758)	Megachilidae	[1,2,3,5,6]
Hoplitis acuticornis (Dufour & Perris, 1840)	Megachilidae	[3]
Hoplitis adunca (Panzer, 1798)	Megachilidae	[5]
Hoplitis claviventris (Thomson, 1872)	Megachilidae	[2,3]
Hoplitis leucomelana (Kirby, 1802)	Megachilidae	[1,2,3,4,5]
Hoplitis tridentata (Dufour & Perris, 1840)	Megachilidae	[3,6]
Hylaeus angustatus (Schenck, 1859)	Colletidae	[3,6]
***Hylaeus annularis* (Kirby, 1802)**	Colletidae	[1,3,6]
Hylaeus brevicornis Nylander, 1852	Colletidae	[1,5,6]
Hylaeus cardioscapus Cockerell, 1924	Colletidae	[5]
Hylaeus clypearis (Schenck, 1853)	Colletidae	[3]
***Hylaeus communis* Nylander, 1852**	Colletidae	[1,2,6]
Hylaeus confusus Nylander, 1852	Colletidae	[1,2,6]
Hylaeus cornutus Curtis, 1831	Colletidae	[1,2,3,5]
Hylaeus difformis (Eversmann, 1852)	Colletidae	[3]
Hylaeus dilatatus (Kirby, 1802)	Colletidae	[5]
Hylaeus gibbus Saunders, 1850	Colletidae	[5,6]
Hylaeus gredleri Foerster, 1871	Colletidae	[1,3,5,6]
Hylaeus hyalinatus (Smith, 1842)	Colletidae	[1,3,5]
Hylaeus nigritus (Fabricius, 1798)	Colletidae	[3]
Hylaeus punctatus (Brullé, 1832)	Colletidae	[3]
Hylaeus punctulatissimus Smith, 1842	Colletidae	[1]
Hylaeus signatus (Panzer, 1798)	Colletidae	[1,3]
Hylaeus variegatus (Fabricius, 1798)	Colletidae	[3,6]
Lasioglossum aeratum (Kirby, 1802)	Halictidae	[5,6]
Lasioglossum albipes (Fabricius, 1781)	Halictidae	[2,6]
Lasioglossum brevicorne (Schenck, 1869)	Halictidae	[6]
Lasioglossum calceatum (Scopoli, 1763)	Halictidae	[1,2,3,5,6]
Lasioglossum clypeare (Schenck, 1853)	Halictidae	[5]
Lasioglossum costulatum (Kriechbaumer, 1873)	Halictidae	[3,6]
Lasioglossum aff. *cupromicans* (Pérez, 1903)	Halictidae	[2]
Lasioglossum discum (Smith, 1853)	Halictidae	[5]
Lasioglossum fulvicorne (Kirby, 1802)	Halictidae	[3,6]
Lasioglossum glabriusculum (Moraw., 1872)	Halictidae	[3]
Lasioglossum intermedium (Schenck, 1869)	Halictidae	[1.3]

Table 2. (continued).

Species	Family	Study
Lasioglossum interruptum (Panzer, 1798)	Halictidae	[5]
***Lasioglossum laticeps* (Schenck, 1869)**	Halictidae	[1,3,6]
Lasioglossum lativentre (Schenck, 1853)	Halictidae	[3,5,6]
Lasioglossum leucopus (Kirby, 1802)	Halictidae	[1,2,6]
***Lasioglossum leucozonium* (Schrank, 1781)**	Halictidae	[1,2,3,6]
Lasioglossum limbellum (Morawitz, 1876)	Halictidae	[3,6]
Lasioglossum lucidulum (Schenck, 1861)	Halictidae	[6]
Lasioglossum malachurum (Kirby, 1802)	Halictidae	[3,4,5,6]
Lasioglossum minutissimum (Kirby, 1802)	Halictidae	[1,6]
Lasioglossum monstrificum (Morawitz, 1891)	Halictidae	[1]
***Lasioglossum morio* (Fabricius, 1793)**	Halictidae	[1,2,3,5,6]
Lasioglossum nigripes (Lepeletier, 1841)	Halictidae	[5]
Lasioglossum nitidulum (Fabricius 1804)	Halictidae	[2]
Lasioglossum nitidiusculum (Kirby, 1802)	Halictidae	[3]
Lasioglossum pauperatum (Brullé, 1832)	Halictidae	[6]
***Lasioglossum pauxillum* (Schenck, 1853)**	Halictidae	[1,3,6]
Lasioglossum politum (Schenck, 1853)	Halictidae	[5,6]
Lasioglossum punctatissimum (Schenck, 1853)	Halictidae	[1,6]
Lasioglossum puncticolle (Morawitz, 1872)	Halictidae	[3]
Lasioglossum quadrinotatulum (Schenck, 1861)	Halictidae	[3,6]
Lasioglossum quadrinotatum (Kirby, 1802)	Halictidae	[5,6]
Lasioglossum rufitarse (Zetterstedt, 1838)	Halictidae	[2]
Lasioglossum semilucens (Alfken, 1914)	Halictidae	[2,3]
Lasioglossum sexnotatum (Kirby, 1802)	Halictidae	[5,6]
Lasioglossum sexstrigatum (Schenck, 1869)	Halictidae	[1,2,6]
Lasioglossum trichopygum (Bluethgen, 1923)	Halictidae	[5]
Lasioglossum villosulum (Kirby, 1802)	Halictidae	[1,2,3,6]
Lasioglossum xanthopus (Kirby, 1802)	Halictidae	[5,6]
Lasioglossum zonulum (Smith, 1848)	Halictidae	[5,6]
Macropis europaea Warncke, 1973	Melittidae	[3]
*Megachile alpicola*Alfken, 1924	Megachilidae	[6]
Megachile centuncularis (Linnaeus, 1758)	Megachilidae	[1,2,6]
Megachile circumcincta (Kirby, 1802)	Megachilidae	[1,2,3]
Megachile ericetorum Lepeletier, 1841	Megachilidae	[1,2,3]
Megachile lagopoda (Linnaeus, 1761)	Megachilidae	[5]
Megachile ligniseca (Kirby, 1802)	Megachilidae	[3]
Megachile nigriventris Schenk, 1869	Megachilidae	[2]
Megachile parietina (Geoffroy, 1785)	Megachilidae	[4]
Megachile pilidens Alfken, 1924	Megachilidae	[1,3,6]
Megachile rotundata (Fabricius, 1787)	Megachilidae	[6]
***Megachile versicolor* Smith, 1844**	Megachilidae	[1,2,5]
***Megachile willughbiella* (Kirby, 1802)**	Megachilidae	[1,2,3,4,5]
Melecta albifrons (Forster, 1771)	Apidae	[4]
Melitta leporina (Panzer, 1799)	Melittidae	[1,3,5,6]
Melitta nigricans Alfken, 1905	Melittidae	[3]
Nomada alboguttata Herrich-Schäffer, 1839	Apidae	[1,3,5,6]
Nomada bifasciata Olivier, 1811	Apidae	[3]
Nomada fabriciana (Linnaeus, 1767)	Apidae	[1,2,3,6]
Nomada ferruginata (Linnaeus, 1767)	Apidae	[2,3]
Nomada flava Panzer, 1798	Apidae	[1,3,6]

Table 2. (continued).

Species	Family	Study
***Nomada flavoguttata* (Kirby, 1802)**	Apidae	[1,2,3,6]
Nomada flavopicta (Kirby, 1802)	Apidae	[3]
Nomada fucata Panzer, 1798	Apidae	[1,3,6]
Nomada fulvicornis Fabricius, 1793	Apidae	[1,6]
Nomada fuscicornis Nylander, 1848	Apidae	[6]
***Nomada goodeniana* (Kirby, 1802)**	Apidae	[6]
***Nomada lathburiana* (Kirby, 1802)**	Apidae	[2,3,6]
Nomada leucophthalma (Kirby, 1802)	Apidae	[3]
Nomada marshamella (Kirby, 1802)	Apidae	[1,3]
Nomada obscura Zetterstedt, 1838	Apidae	[6]
Nomada panzeri Lepeletier, 1841	Apidae	[2,6]
Nomada rufipes Fabricius, 1793	Apidae	[6]
Nomada sexfasciata Panzer, 1799	Apidae	[3]
Nomada sheppardana (Kirby, 1802)	Apidae	[6]
Nomada signata Jurine, 1807	Apidae	[3]
Nomada succincta Panzer, 1798	Apidae	[1,3]
Nomada zonata Panzer, 1798	Apidae	[1]
***Osmia aurulenta* (Panzer, 1799)**	Megachilidae	[3,4]
***Osmia bicolor* (Schrank, 1781)**	Megachilidae	[1,3,4]
Osmia bicornis (Linnaeus, 1758)	Megachilidae	[1,3]
Osmia brevicornis (Fabricius, 1798)	Megachilidae	[3]
Osmia caerulescens (Linnaeus, 1758)	Megachilidae	[6]
Osmia gallarum Spinola, 1808	Megachilidae	[3,6]
Osmia rufohirta Latreille, 1811	Megachilidae	[3]
***Osmia spinulosa* (Kirby, 1802)**	Megachilidae	[3,5]
Panurgus calcaratus (Scopoli, 1763)	Andrenidae	[1,5,6]
Rhophitoides canus (Eversmann, 1852)	Halictidae	[5]
Sphecodes albilabris (Fabricius, 1793)	Halictidae	[1,3,6]
***Sphecodes crassus* Thomson, 1870**	Halictidae	[1,2,6]
Sphecodes cristatus Hagens, 1882	Halictidae	[6]
***Sphecodes ephippius* (Linnaeus, 1767)**	Halictidae	[1,5,6]
Sphecodes ferruginatus Hagens, 1882	Halictidae	[1]
Sphecodes geoffrellus (Kirby, 1802)	Halictidae	[1,6]
***Sphecodes gibbus* (Linnaeus, 1758)**	Halictidae	[1,2,5,6]
Sphecodes hyalinatus (von Hagens, 1882)	Halictidae	[2]
Sphecodes longulus Hagens, 1882	Halictidae	[1,6]
Sphecodes marginatus Hagens, 1882	Halictidae	[2]
Sphecodes miniatus Hagens, 1882	Halictidae	[1,2,5,6]
***Sphecodes monilicornis* (Kirby, 1802)**	Halictidae	[1,2,5,6]
Sphecodes niger Hagens, 1874	Halictidae	[1]
Sphecodes pellucidus Smith, 1845	Halictidae	[1,6]
***Sphecodes puncticeps* Thomson, 1870**	Halictidae	[1,6]
Sphecodes reticulatus Thomson, 1870	Halictidae	[1,6]
Sphecodes rufiventris (Panzer, 1798)	Halictidae	[6]
Stelis odontopyga Noskiewicz, 1925	Megachilidae	[3]
Stelis ornatula (Klug, 1807)	Megachilidae	[1]
Tetraloniella dentata (Germar, 1839)	Apidae	[5]
Trachusa byssina (Panzer, 1804)	Megachilidae	[3]

Results

We found six studies with wild bee species lists for Central European gravel pits (Table 1). In these studies, 245 species were documented (Table 2). Of these, 110 species were reported by only one study, while 135 were reported in at least two different studies (two studies: 56 spp., three studies: 48 spp., four studies: 22 spp., five studies: 8 spp., all six studies: 1 spp.). Of the 245 species with records published from gravel pits, 190 are also native in the Munich area (M. Bräu, pers. com.).

A total of 48 species were found in the survey area (see Table 3). 29 were documented via standardized in-situ photography, eight via DNA-barcoding, and 3 species were observed. Eight of theses have also been recorded by M. Bräu in 2016, and an additional six species had been documented in 2016, but were not seen in 2017. Amongst the observed species, four were oligolectic, 33 polylectic and eleven were cuckoo bees. Of the non-parasitic bees eleven nested above ground, five above and below ground and 21 below ground. A *Megachile* female could not be identified to species level, as the pollen brush was full and the colours relevant for determination were not visible. A *Megachile* male voucher (KGO-00081) was unclear, as coxa 1 and tergite 6 were not visible. Most likely it was a *Megachile rotundata* male, but it cannot be excluded that it was another species, thus we did not include it in our list. The photo voucher of *Megachile* cf. *versicolor* could also be *Megachile centuncularis*, as a definite separation of these two species is only possible via examination of the genitalia, but the redish tarsal segments hint towards *M. versicolor* (KGO-00021). The same applies for the *Halictus confusus/tumulorum* complex, the photo voucher was not unambiguous, but here we can confirm the presence of *H. tumulorum* via DNA barcoding (voucher MG792009). For one *Hylaeus* voucher, we strongly suspect it to be *H. nigritus*, but we lack a photo of sufficient quality of the face in frontal view to say for sure (KGO-00039). For *Andrena*, we had photo vouchers of one male and three females, where relevant features were not visible and they thus could not be identified. In total, 12 % of the photo vouchers (excluding *Halictus*, *Lasioglossum* and *Sphecodes* pictures) were not identifiable to species level.

Table 3. Species list for gravel pit Obermayr. The record type refers to the mode of documentation (o, observation; p, photodocumentation; b, barcoding of voucher specimen; ext, external data from M. Bräu), the record ID gives the GenBank or Biodiversiy Workbench accession numbers for barcoded or photographic vouchers, lecty describes the foraging preference and nest site preference whether a bee builds its nest below or above the surface or is parasitic. Species where determination was not sure on the photograph are printed in grey.

Species	record type	record ID	lecty	nest site preference
Andrena bicolor Fabricius, 1775	o	observation on 28.03.2017	polylectic	ground
Andrena chrysosceles (Kirby, 1802)	p	KGO-00099	polylectic	ground
Andrena dorsata (Kirby, 1802)	ext	M.Bräu, 21.04.2016	polylectic	ground
Andrena flavipes Panzer, 1798	ext, p	M.Bräu, 21.04.2016 KGO-00028	polylectic	ground
Andrena gravida Imhoff, 1832	p	KGO-00097	polylectic	ground
Andrena haemorrhoa (Fabricius, 1781)	p	KGO-00084	polylectic	ground
Andrena vaga Panzer, 1799	ext, p	M.Bräu, n. d. KGO-00096 KGO-00106	oligolectic	ground
Andrena viridescens Viereck, 1916	ext	M.Bräu, 21.04.2016	oligolectic	ground
Anthidium manicatum (Linnaeus, 1758)	p	KGO-00035	polylectic	above
Anthidium oblongatum (Illiger, 1806)	p	KGO-00014	polylectic	above
Anthidium punctatum Latreille, 1809	p	KGO-00073	polylectic	above
Bombus hortorum (Linnaeus, 1761)	p	KGO-00082	polylectic	above and ground
Bombus hypnorum (Linnaeus, 1758)	p	KGO-00074	polylectic	above
Bombus lapidarius (Linnaeus, 1758)	p	KGO-00069 KGO-00100	polylectic	above and ground
Bombus lucorum (Linnaeus, 1761)	p	KGO-00065	polylectic	ground
Bombus pascuorum (Scopoli, 1763)	p	KGO-00067	polylectic	above and ground
Bombus pratorum (Linnaeus, 1761)	o	observed 28.03.2017	polylectic	above

Table 3. (continued).

Species	record type	record ID	lecty	nest site preference
Bombus rupestris (Fabricius, 1793)	p	KGO-00070	parasitic	parasitic
Bombus sylvarum (Linnaeus, 1761)	p	KGO-00002 KGO-00068	polylectic	above and ground
Bombus terrestris (Linnaeus, 1758)	p	KGO-00079	polylectic	ground
Bombus vestalis (Geoffroy, 1785)	ext, p	M.Bräu, 21.04.2016 KGO-00101	parasitic	parasitic
Coelioxys elongata Lepeletier, 1841	p	KGO-00080		
	parasitic	parasitic		
Colletes cunicularius (Linnaeus, 1761)	ext, p	M.Bräu, n.d. KGO-00107	polylectic	ground
Colletes daviesanus Smith, 1846	o	observed 14.08.2017	oligolectic	ground
Halictus eurygnathus Blüthgen, 1931	p	KGO-00022 KGO-00034	polylectic	ground
Halictus rubicundus (Christ, 1791)	p	KGO-00103	polylectic	ground
Halictus scabiosae (Rossi, 1790)	p	KGO-00006	polylectic	ground
Halictus subauratus (Rossi, 1792)	b	MG792004	polylectic	ground
Halictus tumulorum (Linnaeus, 1758)	b	MG792009	polylectic	ground
Hylaeus cf. *nigritus* (Kirby, 1802)	p	KGO-00039	polylectic	above
Hylaeus communis Nylander, 1852	p	KGO-00027 KGO-00050 KGO-00052	polylectic	above
Lasioglossum laticeps (Schenck, 1869)	b	MG791965 MG791966 MG791967	polylectic	ground
Lasioglossum leucozonium (Schrank, 1781)	b	MG791993 MG791991	polylectic	ground
Lasioglossum morio (Fabricius, 1793)	b	MG791969 MG791970 MG791971 MG791972	polylectic	ground
Lasioglossum pauxillum (Schenck, 1853)	b, ext	M.Bräu, 21.04.2016 and 20.05.2016 MG791980 MG791981 MG791983	polylectic	ground
Megachile cf. *versicolor* Smith, 1844	p	KGO-00021	polylectic	above
Megachile willughbiella (Kirby, 1802)	p	KGO-00036 KGO-00037	polylectic	above and ground
Nomada flavoguttata (Kirby, 1802)	ext	M.Bräu, 21.04.2016	parasitic	parasitic
Nomada goodeniana (Kirby, 1802)	ext	M.Bräu, 21.04.2016	parasitic	parasitic
Nomada lathburiana (Kirby, 1802)	ext	M.Bräu, 21.04.2016	parasitic	parasitic
Osmia aurulenta (Panzer, 1799)	ext, p	M.Bräu, 20.05.2016 KGO-00071 KGO-00104	polylectic	above
Osmia bicolor (Schrank, 1781)	p	KGO-00105	polylectic	above
Osmia spinulosa (Kirby, 1802)	p	KGO-00072	oligolectic	above
Sphecodes crassus Thomson, 1870	b	MG845959	parasitic	parasitic
Sphecodes ephippius (Linnaeus, 1767)	ext	M.Bräu, 21.04.2016	parasitic	parasitic
Sphecodes gibbus (Linnaeus, 1758)	ext	M.Bräu, 21.04.2016	parasitic	parasitic
Sphecodes monilicornis (Kirby, 1802)	ext	M.Bräu, 21.04.2016	parasitic	parasitic
Sphecodes puncticeps Thomson, 1870	b	MG 845968	parasitic	parasitic

Discussion

With at least 48 species, the gravel pit Obermayr is an important wild bee habitat in the East of Munich, especially for ground-nesting species. In Germany, Austria and Switzerland, 50 % of the bees are nesting in self-burrowed tunnels in the ground and 19 % in hollow spaces (Zurbuchen & Müller 2012, p.57; Westrich 2018), but for the gravel pit the proportion ranges at 54 % ground-nesters (both self-burrowed or in existing cavities), and ten of the eleven parasitic species rely on the nests of ground-nesting species. This should be considered when it comes to the refill of idle gravel pits. By maintaining some open soil sites, they can enrich the landscape by providing nesting sites for wild bees. Moreover, if hollows and puddles hold the water, renatured gravel pits are important spawn habitats for amphibians (Escher 1974), and steep walls can serve swallows as nest sites (Wagner 1969), and such sites also have a high conservation value for butterflies (Lenda et al. 2012). With some planning effort, the conservation value of abandoned gravel pits can be strongly increased.

Photo-documentation in-situ instead of voucher collection proved feasible for most wild bee genera, but nevertheless taxonomic skills are necessary to be able to recognize bee sex and genera in the field, to be aware which different features need to be photographed or focused on in males and females and in different genera (see Table 4 for examples). The method is problematic for species from the Halictidae genera *Sphecodes*, *Lasioglossum* and *Halictus*, but also in certain groups of *Andrena*, *Nomada* or *Bombus*, as some species in these groups differ only in minute texture features difficult to document by photography. Generally, small individuals (<7 mm) can be problematic for another reason, as the rigor of cold only lasts for about a minute, thus time often is not sufficient to get all details documented. Moreover, another limitation to the photo-based identification of bee females is that individuals with pollen load usually cannot be identified, as the pollen generally obscures the colour of the scopae – hence we chilled down only foraging females without pollen load, and did not consider those carrying pollen.

Table 4. Species features for photo-documentation. This list is not attempting to be comprehensive and must be adapted depending on time and region of the monitoring and should be in accordance with the respective keys of determination.

General features	
Overview photograph from top, side and bottom	size, colours, body shape
Frontal view of the face	shape, colours, hairs, mandibles, clypeus, labrum
Details of thorax from above	sculpturation of scutum and potential rugosity of propodeum
Detail of abdomen from above	tergite bands and sculpturation
For females	
Pollen brush or scopae with flocci	colour(s), extension
For males	
Sternites	spines, shape of last sternite
Genus-specific features	
Andrena males	frontal and side view of the head, detail of antennae (front view)
Anthophora males	mid-tarsi and mid-basitarsi, hind tibiae and basitarsi
Bombus females	sternite 6, head in front and side view, hind tibiae and basitarsi
Bombus males	detail of antennae, hind tibiae and basitarsi
Chelostoma males	sternites 2 and 4
Coelioxys females	tergite 6 and sternites 5 and 6
Coelioxys males	tergite 5 (edges) and sternite 4
Colletes females	hind margin of tergite 1, dorsal fringe of hind tibiae, galeae, clypeus
Colletes males	sternite 6, galeae
Hylaeus	frontal face and antennal view, pronotal collar; additionally for males: mandibles and labrum
Megachile females	tergite 6 in side view
Megachile males	front tarsi, front coxae
Nomada	frontal and side view of head, labrum and tip of mandibles, detail of antennae, detail of hind femora and tibiae
Osmia	spurs of hind tibiae

Macro photographs need to be of sufficient quality, brightness and especially depth of field and resolution to be able to identify microstructures and sculpture on the thorax and tergites, thus a good macro lens is required, and if the weather is cloudy, an additional light source improves picture quality.

The big advantages of in-situ bee photo-documentation are the preservation of live individuals' colour information (which is often lost in specimens) and the possibility to share voucher information (e. g. with taxonomic specialists) via a cloud, thus it is not necessary to send fragile specimens per mail, if the determination needs to be confirmed by a second person. However, in comparison with collecting voucher specimens, this method certainly has certain limitations and also some disadvantages: firstly, the photographer needs to be quick in taking pictures of all relevant features, because the rigor of cold does not last long. Secondly, if pictures are not good enough to see the characters you need, there is no chance to go back to the original individual, after it was released. Moreover, the time effort in the field is increased compared to specimen collection, thus only smaller or fewer sites can be monitored at a time.

Although photo-documentation cannot replace voucher collection completely, it can be an approach towards non-invasive species documentation (especially in larger bees and easier to recognize groups), which becomes increasingly important in times of drastic decreases in many insect taxa worldwide (Sánchez-Bayo & Wyckhuys 2019). That bee identification from photographs is possible to a certain degree (considering above-mentioned limitations to the method), at least in the larger genera (especially Megachilidae), has been repeatedly shown in recent times in numerous web-based insect identification forums and discussion groups (including social media), where good macro-photographs have enabled specialists to securely identify bee taxa to genus and even species level, sometimes contributing new regional records with this method (e. g., BWARS.com 2018, Wildbienen-Forum 2019, Hummelforum 2019, BugGuide.net 2019).

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