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Plant-pollinator interactions on green roofs are mediated by substrate characteristics and plant community composition

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Keywords

Urban ecology, soil-plant interactions, pollination, substrate depth and type, plant community, biodiversity

Abstract

Green roofs can support pollinator communities in cities. However, little is known about the influence of green roof characteristics such as substrate and vegetation type on the abundance and diversity of

attracted pollinators. Here we aimed to assess how green roof design impacts their attractiveness to pollinators. Using mesocosms on a rooftop in Paris (France), we studied the impact of two substrate types, two substrate depths (10 and 30 cm) and either monocultures or mixtures of 5 plant species on plant pollinator interactions. In the case of mixtures, we also tested the effect of substrate type (natural soil vs. artificial substrate). We counted the number of floral units and recorded the visits by pollinators once a week from mid-June to mid-August. The pollinator assemblage visiting plant communities included 4 functional groups of pollinators: domesticated honey bees, bumble bees, solitary bees and syrphid flies. Effects of treatments on pollinator community composition were variable and plant species dependent. Deep monoculture treatments resulted in the highest number of floral units and visits. Although plants grown on natural soil had less floral units than on artificial substrate, both treatments resulted in a similar number of visits. This paper provides evidence that plant-pollinator interactions on green roofs are modulated by substrate type, substrate depth and plant community. We suggest that combining plant species with diverse flowering morphologies and phenologies can enhance pollinator diversity. When possible, increasing substrate depth can result in higher levels of attractiveness.

1. Introduction

Urbanisation is a major cause of the global pollinator decline because it is associated with habitat destruction and fragmentation (Steffan-Dewenter *et al.* 2002; McKinney 2008; Potts *et al.* 2010). There is evidence that urbanization reduces the functional diversity of pollinator species assemblages, with a shift from small specialist to large generalist species such as honey or bumble bees that can cover long horizontal and vertical distances to forage from patches to patches (Banaszak-Cibicka & Zmihorski 2012; Braaker *et al.* 2013; Geslin *et al.* 2013; MacIvor, Ruttan & Salehi 2015; Deguines *et al.* 2016). In densely constructed environments characterized by resource scarcity for pollinators, the promotion of green areas and infrastructures with abundant and diverse floral resources can enhance pollinator diversity and abundance (McKinney 2006; Banaszak-Cibicka & Zmihorski 2012; Matteson, Grace & Minor 2012; Geslin *et al.* 2016). Green roofs, as urban green infrastructures, can participate to support pollinator communities in addition to providing ecosystem services such as regulation of water runoff quantity and quality, urban heat island mitigation, air quality improvement, sound proofing or thermal protection of buildings (Oberndorfer *et al.* 2007; Lata *et al.* 2017). Designing green roofs to improve their attractiveness to pollinators has two purposes: supporting the pollination of the green roof plants and supporting diverse and abundant pollinator communities at the urban area scale, which should subsequently help the maintenance of diverse plant communities in cities. Indeed, more than 80% of flowering species are insect-pollinated (Ollerton *et al.* 2012) and pollinator diversity plays a key role in the persistence of diverse plant communities (Fontaine *et al.* 2006). Overall, this should help promoting biodiversity at the whole city scale. Few studies have directly addressed green

roof attractiveness to pollinators. Inventories have stressed the presence of diverse arthropod groups, including groups with pollinator species such as the Apidae, Lepidopterae, Syrphidae and Coleopterae (Brenneisen 2006; Kadas 2006; Macivor & Lundholm 2011; Madre *et al.* 2013). Colla, Willis & Packer (2009) showed that the diversity of bees on a green roof in Toronto (Ontario, Canada) was not different from the diversity at ground level. On the contrary, Tonietto *et al.* (2011) and Ksiazek, Fant & Skogen (2012) found that native bees in Chicago (Illinois, United States) were present on green roofs but at lower abundance and diversity than in other urban habitats. Braaker *et al.* (2013) investigated the role of landscape configuration and spatial patterns (habitat connectivity) on arthropod communities among 40 green roofs and 40 ground sites in Zurich (Switzerland). They suggested that improving green roof design (vegetation and soil type) should increase the effectiveness of short-range pollinating species in cities.

Green roof substrates are designed to be light. They are usually based on materials such as pozzolan (a porous volcanic stone) or expanded clay (Ondoño, Bastida & Moreno 2014). “Extensive” green roofs are based on substrates usually shallower than 15 cm and on low plant species diversity. Extensive green roofs theoretically require little maintenance. On the contrary, intensive green roofs have substrates deeper than 15 cm, can support more plant species but need more maintenance. Overall, extensive green roofs planted with the drought resistant *Sedum* species are the most widespread systems around the world (Vijayaraghavan 2016). However, there is increasing evidence that most green roof ecosystem services depend on substrate type, substrate depth and plant community (Dusza *et al.*, 2017). Testing different plant communities as well as substrates with different characteristics and depths should be important on the long run for green roofs. Many studies have provided guidelines to improve multiple ecosystem services through the choice of plant community and substrate composition (Lundholm 2015; Vijayaraghavan 2016; Dusza *et al.* 2017). But few authors have investigated the influence of plant community and substrate on pollinator communities (Hoffmann & Renner, 2017). Given the short bloom time of some *Sedum* species commonly used on green roofs, MacIvor, Ruttan & Salehi (2015) suggested that designers should be encouraged to plant green roofs with multiple species to provide food to pollinators over a longer period. Tonietto *et al.* (2011) showed that bee diversity on green roofs increased with the diversity of blooming plants. Overall, increasing plant diversity leads to the creation of more niches for organisms feeding on these plants, thereby promoting arthropod and pollinator diversity (Braaker *et al.* 2013; Madre *et al.* 2013, 2014). The role of substrate composition and depth on green roof attractiveness to pollinators has been less investigated, although there is evidence that substrate characteristics are strongly involved in plant development (Chenot *et al.*, 2017). Higher plant biomass was found for higher nutrient contents in substrates (Rowe, Getter & Durhman 2012; Clark & Zheng 2014; Kanechi *et al.* 2014) and deeper substrates (Durhman, Rowe & Rugh 2007; Dunnett, Nagase & Hallam 2008; Lu *et al.* 2015). Substrates with high porosities lead to higher plant development, as they present good aeration conditions for roots (Ondoño, Martínez-Sánchez & Moreno 2015). Substrate composition and

depth also affect various plant characteristics and functions such as leaf C/N ratio, stomatal density or transpiration (Dusza *et al.* 2017). Likewise, substrate composition and depth may affect, through changes in nutrient availability, plant traits related to pollination. Indeed, studies not focusing on green roofs suggested that soil characteristics and the availability of soil resources impact flower characteristics, which subsequently impact pollinators (Baude *et al.* 2011). Burkle & Irwin (2010) showed that adding nitrogen could lead to additional flowers production. Gorden & Adler (2013) observed that using fertilisers increased the volume of nectar and enhanced floral attractiveness. However, to our knowledge, the effect of substrate depth and type on green roof attractiveness to pollinators has been assessed only once (Kratschmer *et al.*, 2018). This study examines the influence of plant community composition, substrate type and substrate depth on the abundance and diversity of visiting insect pollinators. We addressed this issue with a mesocosm experiment on a roof top in Paris (Ile-de-France, France). In Paris and its region, guidelines created by the city of Paris and the Ile de France Agency for Biodiversity specify that new green roofs should have a minimum substrate depth of 10 cm (Ville de Paris 2012, Natureparif 2013). The guidelines also highlight the need to test deeper substrates, as well as local and more natural substrates. Focusing on this context, we tested two substrate depths (10 vs. 30 cm), two substrate types (commercial substrate and natural, local soil), and five plant species grown either in monoculture or in mixture. We focused on the following questions: 1. Are abundance and functional diversity of pollinators affected by substrate depth and substrate type? 2. Are abundance and functional diversity of pollinators modified when plants are grown in mixture?

2. Material and methods

2.1 Experimental site and mesocosms

The experimental site (48°54'06N, 2°22'23E) was located in the city of Paris (Ile-de-France, France) under subatlantic climate. The study took place on a roof 30 m above ground level and was part of a bigger experiment aimed at studying the provision of ecological service by green roofs. The roof was surrounded by two buildings 6 m taller on its West and East sides. We installed 56 mesocosms (0.8x0.8 m²) made of wooden trays lined on the inside with a waterproof membrane. Half of the mesocosms was 12 cm high, while the other half was 32 cm high. The bottom of each mesocosm was covered with a drainage layer consisting of a geotextile membrane with a 1 cm diameter perforated pipe (Teradrain FD200T1, Terrageos, Veurey Voroize, France) crossing the tray in the middle. A hole was drilled in the lowest part of the tray to connect the drainage pipe with a waterproof silicone tube to allow for drainage. A slight slope was set up (1.2%) to favour water flows out of the mesocosms.

2.2 Substrate material

Two different substrate types were used. The first was a substrate commercialised for green roofs, based on pozzolan (porous volcanic rock) and peat (i.D. Flore SP, Le Prieuré – Vegetal i.D., Moisy, France), hereafter named “artificial substrate”. The second was a natural sandy loam soil taken from a temperate grassland site (CEREED-Ecotron Ile-de-France, Saint Pierre-lès-Nemours, France), hereafter named “natural soil”. The City of Paris and the Ile-de-France Agency for Biodiversity promote the use of local and natural soils for new green roofs. The natural soil was chosen to fulfil these requirements (Ville de Paris 2012, Natureparif 2013). Roots, plant debris and stones were removed from the natural soil by sieving (<5 mm) before homogenization. Substrate characteristics are summarized in Table 1.

2.3 Plant material

Mesocosms were planted with monocultures or 5 species mixtures of *Centaurea jacea*, *Dianthus carthusianorum*, *Hylotelephium maximum*, *Lotus corniculatus* and *Koeleria pyramidata*.

Centaurea jacea (Asteraceae) is a perennial species, with large, purple, tubular flowers grouped in capitulae. It is mainly pollinated by large bees and hoverflies, and to a lesser extent by butterflies (Albrecht et al, 2009). Flowering period ranges from June to September.

Dianthus carthusianorum (Caryophyllaceae) is a perennial species, with large, purple, open flowers grouped by 2 to 8. It is mainly pollinated by butterflies (Bloch et al, 2006) and flowers from June to September.

Hylotelephium maximum (Crassulaceae) is a perennial species with small, white, open flowers grouped in large corymbs. It is pollinated by bees and butterflies and flowers in August and September.

Lotus corniculatus (Fabaceae) is a perennial, nitrogen fixating species, with small, yellow tubular flowers. It is mainly pollinated by *Bombus* species (Pellissier et al, 2012) and flowers from May to September.

Koeleria pyramidata (Poaceae) is a perennial wind pollinated grass species that produce leaves during the whole growing season.

Plant species were chosen on the basis that they are= native to the Ile-de-France region (France), were known to have already been used on green roofs and were tested, among other plant species, for their ability to survive under dry conditions while providing high levels of water retention and runoff quality as well as air cooling (Dusza et al. 2017). This resulted in the inclusion of the grass *K. pyramidata*, although this species is not insect-pollinated. Previous studies have shown that the main pollinators of *L. corniculatus* are bumble bees. For all other plant species, pollinating insects also include other bees and pollinators of *D. carthusianorum* also include butterflies (Arnold et al. 2010; Lundgren, Lazaro & Totland 2015). Seed germination was carried out in greenhouse (University

Pierre et Marie Curie, Paris, France) and at least 5 cm tall seedlings were planted in mesocosms on July 4th, 2014. 25 plants were planted in each mesocosm on a regular grid spaced by 13.5 cm. During the first two months, mesocosms were watered once a week (10 L per mesocosm) to ensure optimal growth conditions and no plant mortality was observed during the start of the experiment. Contrary to artificial substrates, plant colonization was observed in natural treatments. Plants different from the selected species were regularly weeded out.

2.4 Experimental design

The experimental design is shown in Fig. 1 and was aimed at testing the effects of substrate type, substrate depth and plant diversity on pollinator communities visiting green roofs. Artificial substrate mesocosms were planted with either a monoculture of one of the five species (25 plants), or a mixture of the five species (25 plants, 5 individuals per plant species). Natural soil mesocosms were only planted with the 5 species mixture. For each substrate type, mesocosms were filled with either 10 cm or 30 cm of substrate, hereafter named “shallow” or “deep” treatments, respectively. 10 cm corresponds to the minimum depth required by the City of Paris and the Ile-de-France Agency for Biodiversity for the implementation of new green roofs (Ville de Paris 2012, Natureparif 2013). The deep treatment corresponds to the will of these institutions to develop green roofs based on deeper and more natural soils. Each combination of treatments was replicated 4 times, making a total of 8 natural soil mesocosms (2 depths, mixture only) and 48 artificial mesocosms (2 depths, 6 vegetation types: 5 monocultures + 1 mixture). In mixtures, individuals of each species were assigned a randomly chosen position within the mesocosm.

Because higher buildings around the roof could lead to heterogeneity in climatic parameters, the roof was divided into four blocks, each containing one replicate of all experimental treatments. Each block was equipped with a weather station (Vantage pro II, Cima technologie, Montanay, France). No difference between blocks was detected in the daily amount of light, rain and temperatures during the experiment (July 2014 to September 2015). Monthly air temperature during the study period were 19.3°C (June), 21.6°C (July) and 21.9°C (August). During the pollination experiment, mesocosms received 57 mm water from natural rain. Each mesocosm was watered with 5 L of water to limit water stress when rain did not occur for 7 consecutive days.

2.5 Plant-pollinator observations

Plant-pollinator interactions were recorded as long as at least two species were flowering simultaneously. This resulted in a two months measurement period, from June 10th to August 12th 2015. This period encompassed the flowering peaks of all species: the earliest species (*D.carthusianorum*) had its flowering peak during the second half of June, while the latest species (*H.maximum*) had its flowering peak at the beginning of August. An observation round was carried out

about once a week. Observations were only carried out on sunny days, between 10 am and 5 pm, avoiding windy days. During an observation round, all visits by flower-visiting insects foraging on the experimental plant communities were recorded for 5 minutes on each mesocosm. Because we expected interactive effects between substrate treatments (depth and type) and plant species identity, pollinator visits were recorded at the plant level in all mesocosms. The order of observed mesocosms was modified at each round to limit the risk of a “time of day” effect. Before each observation round, the abundances of flowers in each mesocosm were evaluated: we counted open flowers of all species, with the exception of *C. jacea* for which we counted the number of capitulae. Hereafter, we refer to flowers and capitulae as “floral units”. To assess pollinator abundance and diversity, we used a non destructive method based on pollinator morphotypes (Geslin *et al.* 2013; Aguirre-gutiérrez, Kissling & Carnevalheiro 2016; Desaegeher *et al.* 2017). Three groups were distinguished within the Apidae superfamily. 1. Bumble bees (species from the *Bombus* genus) 2. Solitary bees (group enclosing all Apidae species, except the *Bombus* genus and domesticated honey bees. 3. Domesticated honey bees (*Apis mellifera*). The 3 other groups were 4. Syrphidae 5. Lepidopterae 6. Coleopterae.

2.6 Statistical analyses

Data analyses were performed using the R statistical software (version 3.2.2; R Core Team, 2015). Because the number of visits in a given mesocosm could also depend on the characteristics of neighbouring mesocosms, we checked for potential spatial autocorrelation among mesocosms. We computed a distance matrix for the total number of visits within each mesocosm and a distance matrix for the spatial distance between mesocosms. We tested the correlation between the two matrices, i.e. the spatial autocorrelation, with a Mantel test (9999 permutations, *ncf* package; Bjornstad 2016). Since there was no spatial autocorrelation ($p = 0.56$), the number of visits in neighbouring mesocosms was considered independent and we used standard linear models without autocorrelation term.

The “number of visits per mesocosm” was defined for each mesocosm as the total number of visits over the course of the experiment. In order to compare vegetation types (mixtures vs. monocultures), the 5 plant species grown in monocultures were considered together to calculate the mean number of visits per mesocosm for monocultures within each replicate block. For each species inside a mesocosm, the “number of visits per plant” was defined as the number of visits received by an individual plant. It was obtained by dividing the total number of visits on a species by the number of plant individuals for this species inside the mesocosm (25 for monoculture, 5 for mixtures). Although *K. pyramidata* is a wind-pollinated species, it was kept for analyses because its presence in mixtures might affect other plant-pollinator interactions through mechanisms such as competition for below-ground resources (Flacher *et al.* 2015). The same approach was applied to calculate the “number of floral units per mesocosm” and the “number of floral units per plant”. As the data for the “number of floral units per mesocosm” and the “number of visits per flower” are averages, and not real count

data, we fitted standard linear models. In any case, we checked for the normality and homoscedasticity of the residuals which justifies the use of standard linear models and data were log transformed when the residuals were non-normal.

Due to the unbalanced design, analyses were performed first within the artificial substrate treatment to test for the effects of vegetation type (types of monocultures and mixtures) and substrate depth and, second, within the mixture treatment to test for the effects of substrate type and depth. To evaluate whether the number of visits per mesocosm and the number of floral units differed between the mixture and the monoculture treatments, simple linear models were fitted with substrate depth and vegetation type as factors. Pairwise comparisons were calculated from these different models using the Tukey-Kramer method (*lsmeans* package; Lenth 2015). We used an analysis of covariance (ANCOVA) to test whether the number of visits per plant for each plant species was influenced by the number of floral units per plant and whether these relationships differed among growing conditions (vegetation type and substrate depth). For each plant species, a complete simple linear model including all factors and their interactions was simplified based on the Akaike Information Criterion. During the experiment, very few Lepidopterae, Coleopterae or Diptera other than Syrphidae visited the mesocosms and were merged into a single category “Other”. This category represents less than 5% of the total visits. To test whether the proportion of visits by a given pollinator group on a given plant species differed between combinations of vegetation type (mixture vs. monoculture) and substrate depth, we proceeded in two steps. First, for each plant species, we fitted a multinomial model to the proportion of visits of all flower visitor groups. Then, if the treatment had a significant effect on these proportions of visits, for each combination of plant species and flower visitor groups, a second binomial model was fitted for each pollinator group (Galyean and Wester, 2010) to test for the effect of treatments on the proportion of visits by group on each plant species. The same type of analysis was performed to test for differences between combinations of substrate type and substrate depth in mesocosms with plant mixtures.

3. Results

3.1 Effect of vegetation type and substrate depth in artificial substrate treatments

3.1.1 Phenology, number of floral units and visits per mesocosm

Overall, treatments did not alter the timing of flowering. *D carthusianorum* had its flowering peak mid-june in all treatments, *L corniculatus* at the start of July, *C jacea* at the start of August and *H telephium* mid-August. However, treatments altered the number of floral units as well as the number of visits. The number of floral units per mesocosm was 2 times higher in shallow monoculture treatments than in shallow mixtures and 5 times higher in deep monoculture treatments than in deep mixtures (Table 2a, Fig. 2a). A depth effect was found only for monocultures, with about 2 times more floral units per mesocosm when plants were grown on deep substrate. The number of visits per

mesocosm followed the same trend and was, on average, 3 times higher for plants grown in monocultures than for plants grown in mixture in the deep substrate treatments and 5 times higher in the shallow treatment (Table 2a, Fig. 2b). For monocultures, there were twice more visits per mesocosm when plants were grown on deep substrate.

3.1.2 Visits per plant for each plant species

For all plant species, the number of visits per plant increased with the number of floral units per plant (Table 2b, Fig. 3). For *D. carthusianorum* and *L. corniculatus*, the number of flower units was the only parameter influencing the number of visits (Fig. 3a and 3b.) For *H. maximum*, the number of visits increased with the number of floral units with the same slope for all treatments but the regression line for monocultures was above the one for mixtures: for the same number of floral units, monocultures always induced more visits (Fig. 3c). For *C. jacea* the number of visits increased with the number of flower units for all treatments and the slope of the relation was steeper for monocultures than for mixtures (Fig. 3d). For this species, we also found a substrate depth effect, with more visits per floral unit in the deep treatment. Within each vegetation type, the slope of the relation between visits and flower units was steeper for deep treatments than for shallow treatments. Overall, when depth or vegetation type affected the number of visits, monocultures and deep substrates were the most attractive treatments.

3.1.3 Composition of pollinator communities

Whatever the treatment, *C. jacea* was mostly visited by solitary bees (Fig. 4a), *D. carthusianorum* (Fig. 4b) and *H. maximum* (Fig. 4c) by honey bees. *L. corniculatus* was mostly visited by bumble bees except when grown in monocultures and deep substrate where a shift towards solitary bees and honey bees as the dominant visiting group was observed (Fig. 4d). Proportions of pollinators were affected by plant species, substrate depth, vegetation type and the substrate depth:vegetation type interaction (multinomial model, $P < 0.01$ in all cases). In the case of *C. jacea*, the most balanced composition was found for mixtures on deep substrate, as solitary bees accounted for about 43%, honey bees for 34 % and bumble bees for 23 % of the total number of visits (Fig. 4a). In the three other treatments, solitary bees were more dominant, accounting for 52 % (monoculture on shallow substrate) to 75% of the total number of visitors (mixture on shallow substrate). Monocultures of *D. carthusianorum*, either in deep or shallow substrate, were characterized by at least 75 % of honey bees (Fig. 4b). By comparison, *D. carthusianorum* grown in mixtures (whatever the substrate depth) led to more balanced communities, with the proportion of honey bees reduced to about 40% and a higher presence of bumble bees and syrphid flies. For *H. maximum*, the less diverse visiting community was found in mixtures grown on deep substrate, as honey bees accounted for almost 91 % of total pollinators (Fig. 4c). Both shallow treatments (mixture or monoculture) led to proportions of honey bees below 70 %. The shallow

mixture treatment presented the most balanced community, as bumble bees and solitary bees were almost equally represented (about 15 %), while monocultures were almost uniquely visited by solitary and honey bees. For *L. corniculatus*, the most balanced community was found for the monoculture treatment planted on deep substrate, with proportions of 29, 30 and 37 % of respectively bumble bees, honey bees and solitary bees (Fig. 4d). By comparison, bumble bees accounted for at least 60 % of total pollinators for all other treatments. However, syrphid flies accounted for 22 % of visitors in monocultures planted on shallow substrate, while this proportion was below 7 % for all other treatments.

3.2 Effect of substrate type and depth in mixture treatments

Only mixtures were grown on both substrate types. Here we focus on the influence of substrate type and depth on pollinator abundance and pollinator community composition in mixtures.

3.2.1 Number of floral units and visits per mesocosm and per plant

While no depth effect was found on the number of floral units per mesocosm, there were 2 times more floral units in artificial substrate than in natural soil at each depth (Table 3a, Fig. 5a). However, neither substrate type nor depth had an effect on the number of visits per mesocosm for mixtures (Table 3a, Fig. 5b). The number of visits per plant for *D. carthusianorum* and *H. maximum* was independent on the number of floral units, substrate type and substrate depth (Table 3b). The number of visits per plant was positively linked to the number of floral units for *C. jacea* (Fig. 6a) and *L. corniculatus* (Fig. 6b). This relationship was affected by substrate type: the number of visits increased with the number of flowers units quicker for the natural soil than for the artificial substrate

3.2.2 Composition of pollinator communities

Substrate type and depth had variable effects on pollinator communities according to plant species. There was a significant effect of substrate type, depth and their interactions on the proportion of visits received by *H. maximum* and *L. corniculatus* ($P < 0.05$ at the most), an effect of the Type:Depth interaction on visits received by *C. jacea* ($P < 0.01$) and no effect on visits received by *D. carthusianorum* ($P > 0.3$). For *C. jacea*, the most balanced visiting community was found for the deep artificial substrate treatment that was the only treatment where solitary bees did not reach 50% of total visitors (Fig. 7a). Only honey bees were observed on *H. maximum* grown in shallow natural soil (Fig. 7c) while on shallow artificial substrate, *H. maximum* received up to 15% visits by bumble bees and solitary bees. For *L. corniculatus*, distinct patterns were found for each substrate type. In the artificial substrate, bumble bees accounted for the majority of pollinators, while honey bees accounted for the majority of visitors in natural soil (Fig. 7d). Solitary bees and syrphid flies were more represented in the artificial substrate treatment, though differences were small.

4. Discussion

4.1 Functional diversity of pollinators

Given the short bloom time of *Sedum* species commonly used on green roofs, MacIvor, Ruttan & Salehi (2015) encouraged to plant green roofs with multiple species to provide resources for pollinators during a longer period of time. In our experiment, plants with diverse flower morphology and flowering phenologies were used, allowing the continuous presence of flowers and pollinators during at least two months. In particular, we have used species local to the Ile de France region so that these species should be well-adapted to climatic conditions (Van Mechelen et al, 2014) and their natural pollinators should be present. The choice of plant species had a strong role in determining the composition of the visiting community. *H. maximum* attracted almost exclusively honey bees while *C. jacea* was mostly visited by solitary bees and *L. corniculatus* attracted a high proportion of bumble bees. Overall, Syrphidae were rarely observed but neither Lepidopterae species nor Coleopterae species were found foraging during the two months observations. Apidae species are known to pollinate the selected plant species (Steffan-Dewenter et al. 2002; Arnold et al. 2010; Pellissier et al. 2012; Lundgren, Lazaro & Totland 2015). However, pollinators of *D. carthusianorum* include a large proportion of Lepidopterae in natural ecosystems (Bloch, Werdenberg & Erhardt 2006). The absence of Lepidopterae in our experiment might be linked to the overall decline of this group in cities (Bloch, Werdenberg & Erhardt 2006; Deguines et al. 2012), and more generally to biotic homogeneization favouring generalist taxa, that does not include Lepidoptera or Coleoptera (Desguines et al., 2016). Our results are consistent with other studies reporting that urban areas are profitable to bees (Winfree, Griswold & Kremen 2007; Carré et al. 2009; Fortel et al. 2014; Baldock et al. 2015) because of their ability to fly from patches to patches and forage on a large set of plant species (Biesmeijer et al. 2006; Geslin et al. 2013). Our results are also consistent with studies showing high bee abundance on green roofs (Colla, Willis & Packer 2009; Tonietto et al. 2011; Ksiazek, Fant & Skogen 2012). Effects of treatments on pollinator community composition were variable, plant species dependent and weak, confirming that the plant identity was the most important factor affecting the functional diversity. Moreover, in mixtures, pollinator communities were more balanced compared to monocultures, probably due to the fact that, as different plant species attract different pollinator communities, the visiting community of mixtures is more diverse but more similar. The artificial substrate was also associated with more balanced communities than the natural soil. In particular, the syrphid flies were more abundant on *L. corniculatus* grown in the artificial substrate than in the natural soil. The same number of floral units per plant led to more visits for the natural soil than for the artificial substrate, suggesting that a reduced competition between pollinators might have allowed more frequent syrphid flies visits for the artificial substrate. Future research should address more precisely the influence of soil-plant interactions on pollinator diversity. For instance, soil-plant interactions affect below-ground

competition for resources and consequently the floral display (Flacher *et al.* 2015) as well as habitat provision for arthropods and pollinating insects.

4.2 Abundance of pollinators

As expected, at the plant level, the more floral units, the greater the number of visits the plant received.

Overall monocultures produced more flowers, which induced more plant-pollinator interactions than mixtures. Competition for resources among the different species in mixtures could have led to a decrease in floral units numbers (Flacher *et al.* 2015), since producing flowers is costly (Snow, 1989). Increasing substrate depth had an effect on the number of floral units and visits per mesocosm only when plants were grown in monocultures and not in mixtures. Using the same soil, depth and plant species as in our experiment, Dusza *et al.* (2017) showed that the species grown in monoculture had a higher biomass in deep artificial substrate due to a higher nutrient content. Likewise, in our experiment, increasing depth in monoculture led to more floral units probably because of the higher nutrient content. This is consistent with several studies showing that increasing depth induces a higher plant development on green roofs (Dunnett, Nagase, & Hallam, 2008; Durhman, Rowe & Rugh, 2007; Lu *et al.*, 2015; Thuring *et al.*, 2010). In mixtures, interspecific interactions could have prevented the benefits of increasing substrate depth due to a lower investment in reproductive parts as suggested by Flacher *et al.* (2015). Besides, it has been shown that green roof substrate nitrogen availability lead to higher biomass on green roofs (Rowe, Getter & Durhman 2012; Clark & Zheng 2014; Kanechi *et al.* 2014). Studies in natural ecosystems have also shown that soils with more nitrogen could lead to more abundant flowers (Burkle & Irwin 2010). Likewise, the higher nitrogen availability in the artificial substrate probably explains the presence of more floral units per mesocosm as compared to the natural soil.

However, for the same number of floral units per plant, the number of visits per plant was higher for the natural soil than for the artificial substrate. Similarly, when we found depth effects, the same number of floral units for a plant grown in the deep substrate induced more visits than the shallow substrate. This suggests that the number of floral units is not the only characteristic that influences attractiveness when dealing with different soil compositions and depths. In particular, soil nutrient content could alter plant-pollinator interactions through nectar sugar content, as has been shown in experimental conditions and natural ecosystems (Baude *et al.* 2011; Cardoza, Harris & Grozinger 2012). There is evidence that increasing depth on green roofs increases the amount of water retained in the soil and limits the impact of drought episodes on plants in the absence of watering system (Durhman *et al.* 2007; Getter & Rowe 2008; Van Mechelen, Dutoit & Hermly 2015). This could in turn impact plant attractiveness to pollinators through increased nectar production (Petanidou, Goethals & Smets 1999). Similarly, although the artificial substrate had a higher water retention

capacity, it dried out faster than the natural soil (Dusza et al., 2017). Possibly, drier conditions in artificial substrate, as green roofs often experience (VanWoert *et al.* 2005a), might have led to a reduced production of nectar and a reduced number of visits per plant. Alternatively, substrate type and depth may also affect pollinator abundance through soil habitat. For instance, deeper substrates may provide more suitable habitats for ground-nesting species or solitary bees. Likewise, the high macro-porosity of the artificial substrate might have reduced the capacity of ground-nested species or solitary bees to create a suitable habitat, preventing them to forage on the mesocosm.

4.3 Designing green roofs to enhance plant-pollinator interactions

In many urban environments, measures to promote pollination mainly focus on a single generalist pollinator species, the domesticated honey bee *Apis mellifera* (Geslin *et al.* 2017). In the city of Paris, where the experiment was carried out, more than 1000 hives have been installed since the first one in 1856, making a mean of 10 hives per km² (Ville de Paris, 2017). However, there are growing concerns and controversies about promoting honey bees instead of wild pollinators (Aebi *et al.* 2012; Ollerton *et al.* 2012), even though there is evidence that wild pollinators can ensure efficient pollination (Garibaldi *et al.* 2013; Garantonakis *et al.* 2016). Because honey bees were strongly represented and have the ability to forage from ground to roofs and from patches to patches (Braaker *et al.* 2013), treatments that reduce the proportion of honey bees might be preferred. Favouring a plant community with diverse flowering phenologies and characteristics to a monoculture could have two benefits: extending pollination services for a longer period and attracting a more diverse community of pollinators (Nagase, Dunnett & Choi 2017; Tonietto *et al.* 2011; Braaker *et al.* 2013; MacIvor, Ruttan & Salehi 2015). In addition, there is growing evidence that increasing plant species diversity when designing a green roof results in improved ecosystem multifunctionality and services (Lundholm 2015; Dusza *et al.* 2017).

Overall, we found that a trade-off occurred between promoting a high number of visits using monocultures and promoting more diverse pollinator communities with mixtures. We suggest that mixing on the same roof patches of monocultures and patches of mixtures of species should help mitigating this trade-off. Testing more plant mixtures and roof configurations is needed to verify this hypothesis. In France, increasing green roof substrate depth is a current trend. Some regional or local agencies have fixed the minimum of substrate depth at 10 cm (Ville de Paris 2012; Natureparif 2013) in contrast to older green roof systems (2-4cm, Monterusso, Rowe & Rugh 2005; VanWoert *et al.* 2005b; Getter & Rowe 2008). Besides, most new green roofs are currently installed on new buildings, which allow deeper substrates for a reduced economic cost compared to retrofitting. When possible, we suggest that increasing substrate depth will result in higher attractiveness to pollinators. More research is required to evaluate the effect of substrate on floral traits, such as nectar or floral display, but also on the production of fruits and seeds that are the final product of pollination. Similarly, as

green roofs are expected to support biodiversity in cities, a future direction would be testing at a larger scale the effect of diverse green roof designs on the surrounding abundance and diversity of pollinators.

5. Conclusion

In this study, we showed that the choice of substrate type, substrate depth and vegetation type has an impact on both abundance and functional diversity of pollinators. Enhancing functional diversity of pollinators requires mixing plants with diverse flower morphologies and phenologies. Promoting a more abundant community of pollinators on green roofs could be achieved with deeper substrates, although we found an effect only on monocultures. We showed that although plants grown on a natural soil had less floral units, they attracted as many pollinators as plants grown on a typical green roof substrate. Further investigation is necessary to determine the mechanisms underlying the effects we found, e.g. to determine how substrate composition influences floral traits and in turn plant-pollinator interactions. This study was a first step to analyse the impact of various green roof characteristics on the attractiveness to pollinators. Future research should address the influence of these characteristics on whole green roof sustainability, the dynamics of plant diversity and the pollination of surrounding plant populations on the ground. On the long term, this line of research should allow designing rules to optimize various aspects of the impact of green roofs on pollination and pollinating communities.

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Conflict of Interest:

The authors declare that they have no conflict of interest.

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Table 1. Substrates characteristics (mean \pm SE).

Soil characteristics	Natural soil	Artificial substrate
<i>Type</i>	Sandy-loam	Pozzolan-peat
<i>Dry bulk density (kg.m^{-3})</i>	1.6 \pm 0.01	1.1 \pm 0.02
<i>Saturated bulk density (kg.m^{-3})</i>	2.1 \pm 0.03	1.5 \pm 0.03
<i>Water retention (% of dry soil)</i>	33 \pm 2.13	41 \pm 2.99
<i>C content (g.kg^{-1})</i>	9.71 \pm 0.26	51.14 \pm 0.39
<i>N content (g.kg^{-1})</i>	0.74 \pm 0.03	4.97 \pm 0.04
<i>pH</i>	7.7 \pm 0.09	7.4 \pm 0.18

Table 2. Anova/Ancova tables for artificial substrate treatments. **(a)** Number of floral units and visits per mesocosm as a function of depth and vegetation type. **(b)** Number of visits per plant for each plant species as a function of the number of floral units, vegetation type and substrate depth. Missing factors or values correspond to factors and interactions removed from the complete models after the simplifications using the Akaike Information Criterion. “R²” stands for the squared R of the fitted model. “FL” stands for the number of floral units and “Veg” for Vegetation type.

a.

Plant	Model		ANOVA df/F value/p-value			
	R ²	p-value		Depth	Veg	Depth*Veg
Number of floral units	0.87	1.48 10 ⁻⁵	DF	1	1	1
			F value	14.82	49.24	14.62
			p-value	0.002	1.4 10 ⁻⁵	0.002
Number of visits	0.91	2.01 10 ⁻⁶	DF	1	1	1
			F value	28.67	71.68	14.54
			p-value	1.72 10 ⁻⁴	2.10 10 ⁻⁶	0.002

b.

Plant species	Model		ANCOVA df/F value/p-value			
	R ²	p-value		FL	Veg	FL* Depth
<i>Centaurea jacea</i>	0.22	4.90 10 ⁻⁷	DF	1	1	1
			F-value	18.01	5.13	13.09
			p-value	4.11 10 ⁻⁵	0.025	4.22 10 ⁻⁴
<i>Dianthus carthusianorum</i>	0.31	5.51 10 ⁻¹⁰	DF	1		
			F-value	46.66		
			p-value	5.51 10 ⁻¹⁰		
<i>Hylotelephium maximum</i>	0.61	9.97 10 ⁻⁷	DF	1	1	
			F-value	28.88	17.33	
			p-value	8.98 10 ⁻⁶	2.56 10 ⁻⁴	
<i>Lotus corniculatus</i>	0.36	4.91 10 ⁻¹³	DF	1		
			F-value	66.188		
			p-value	4.91 10 ⁻¹³		

Table 3. Anova/Ancova tables for mixture treatments. **(a)** Number of floral units and visits per mesocosm as a function of substrate depth and substrate type. **(b)** Number of visits for each plant species as a function of the number of floral units, substrate type and substrate depth. Missing factors and values correspond to factors removed from the complete models after the simplification using the Akaike Information Criterion. “R²” stands for the squared R of the fitted model. “FL” stands for the number of floral units, and “S” for substrate type. In table b, the model did not fit for *D. carthusianorum* and *H. maximum* (p<0.05).

a.

Plant species	Model		ANOVA degrees of freedom/F-value/p-value			
	R ²	p-value		Depth	Substrate type	Depth*S
Number of floral units	0.65	0.004	DF	1	1	1
			F-value	0.290	21.869	0.193
			p-value	0.600	5.36 10 ⁻⁴	0.667
Number of visits	0.37	0.022	DF	1	1	1
			F-value	2.810	1.203	1.133
			p-value	0.120	0.294	0.308

b.

Plant species	Model		ANCOVA degrees of freedom/F-value/p-value			
	R ²	p-value		FL	Substrate type	FL*S
<i>Centaurea jacea</i>	0.37	1.25 10 ⁻¹²	DF	1		1
			F value	2.56		66.23
			p-value	0.11		3.36 10 ⁻¹³
<i>Lotus corniculatus</i>	0.30	3.47 10 ⁻⁸	DF	1	1	1
			F value	18.86	25.07	7.69
			p-value	3.00 10 ⁻⁵	1.97 10 ⁻⁶	0.006

Fig.1 Schematic representation of the experimental design

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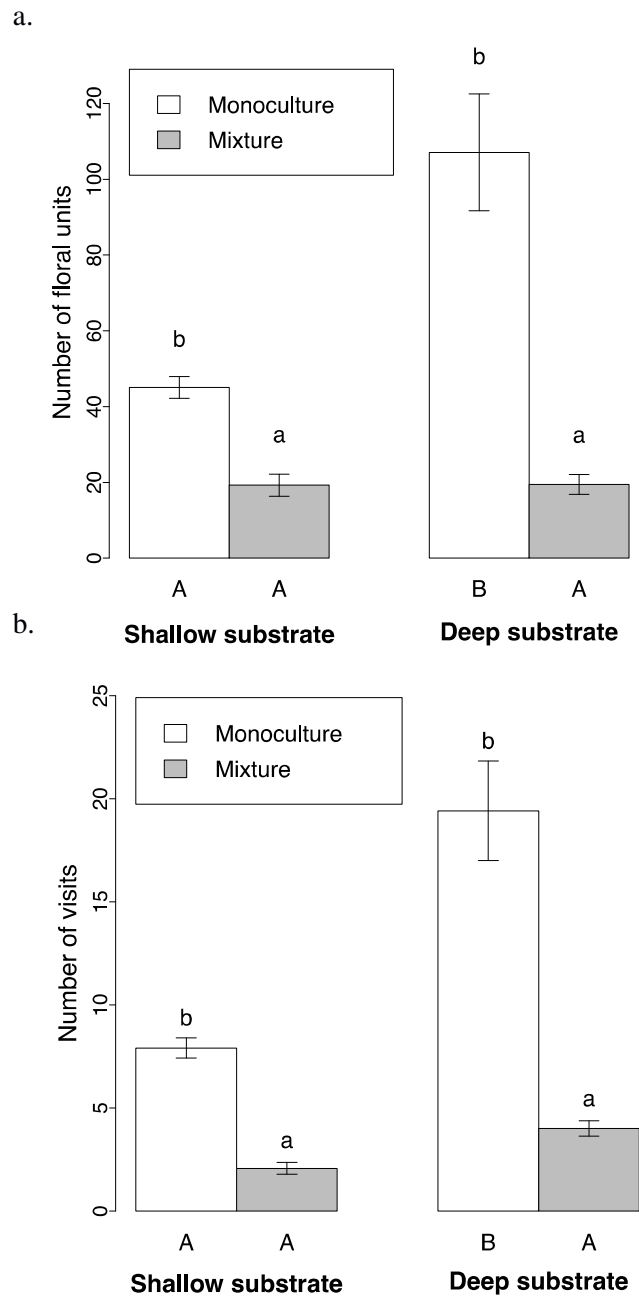


Fig.2 Average number of floral units (a) and visits (b) per mesocosm as a function of vegetation type and substrate depth for artificial substrate treatments (\pm SE). Lower case letters indicate differences ($p<0.05$) between vegetation types within each substrate depth. Capital letters indicate differences ($p<0.05$) between substrate depth within each vegetation type.

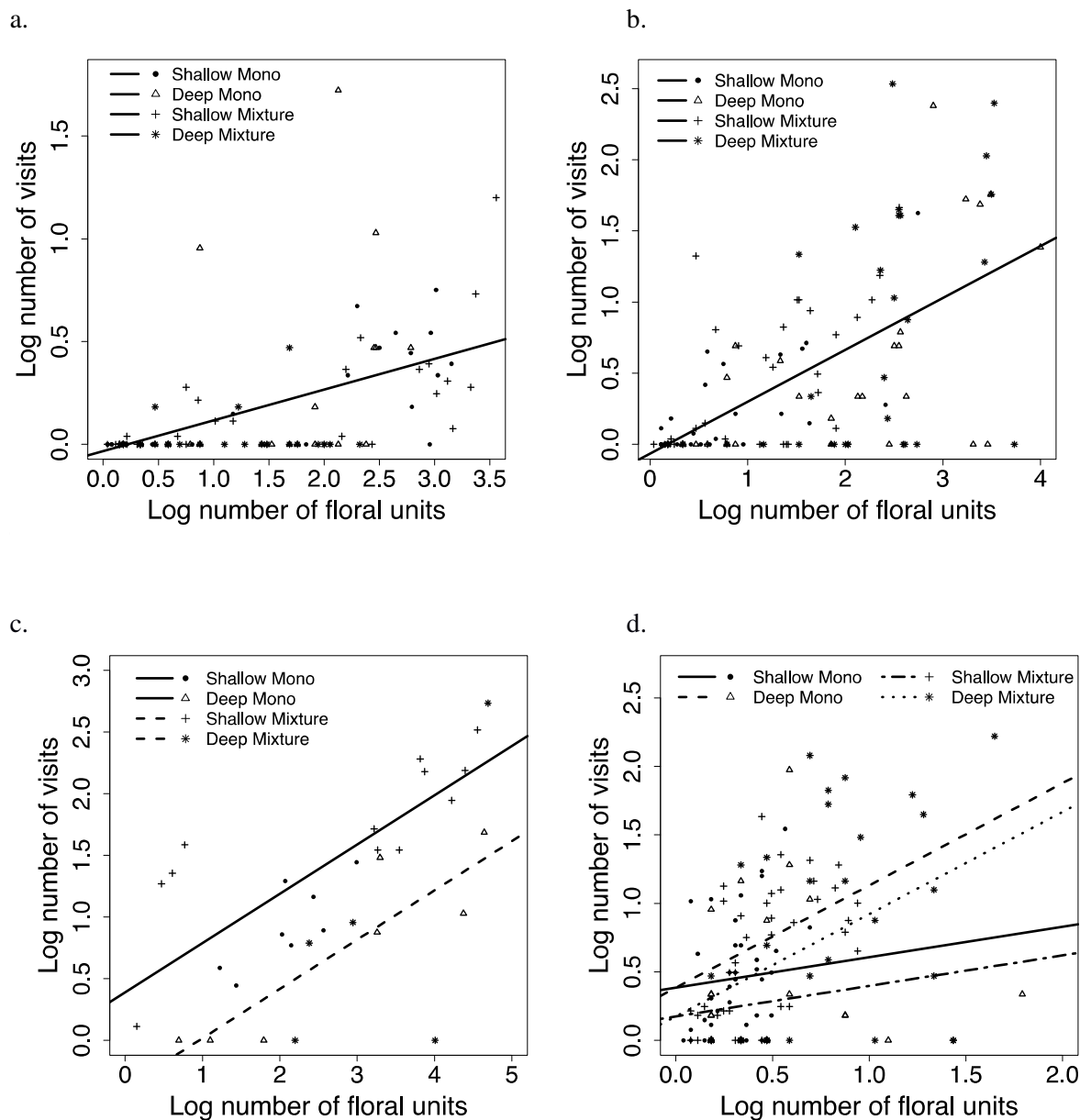


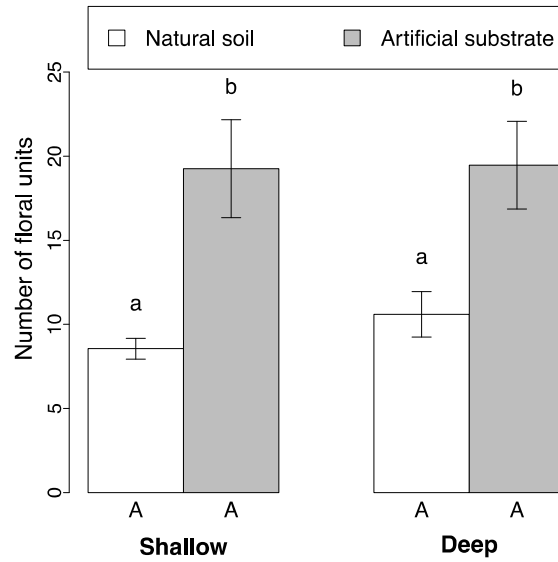
Fig.3 Number of visits per plant against the number of floral units for each plant species grown on artificial substrate as a function of vegetation type and substrate depth. a = *Dianthus carthusianorum*; b = *Lotus corniculatus*; c = *Hylotelephium maximum*; d = *Centaurea jacea*. Regressions lines are based on ANCOVA results. The different number of lines between plant species is due to the removal of factors that did not influence the relation between number of visits and number of floral units, based on the simplification of the complete ANCOVA model using the Akaike Information Criterion (Table 2.b). “Mono” stands for “monoculture”.

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a.



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b.

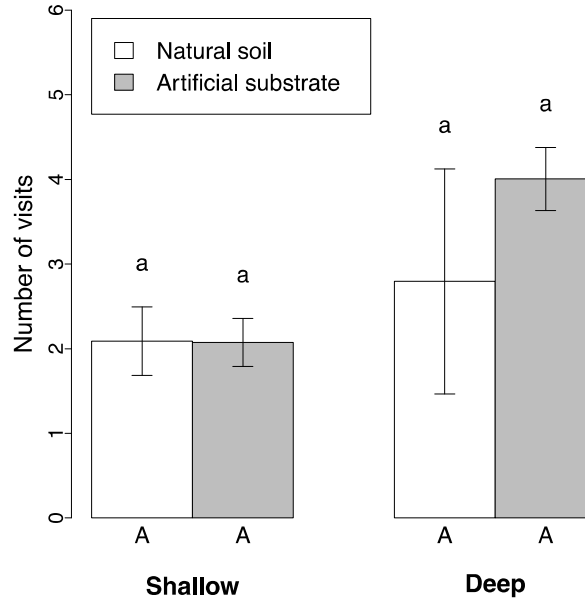


Fig.5 Average number of floral units(a) and visits (b) as a function of substrate depth and substrate type for mixture treatments (\pm SE). Lower case letters indicate differences ($p < 0.05$) between substrate type within each substrate depth. Capital letters indicate differences ($p < 0.05$) between substrate depths within each substrate type.

850

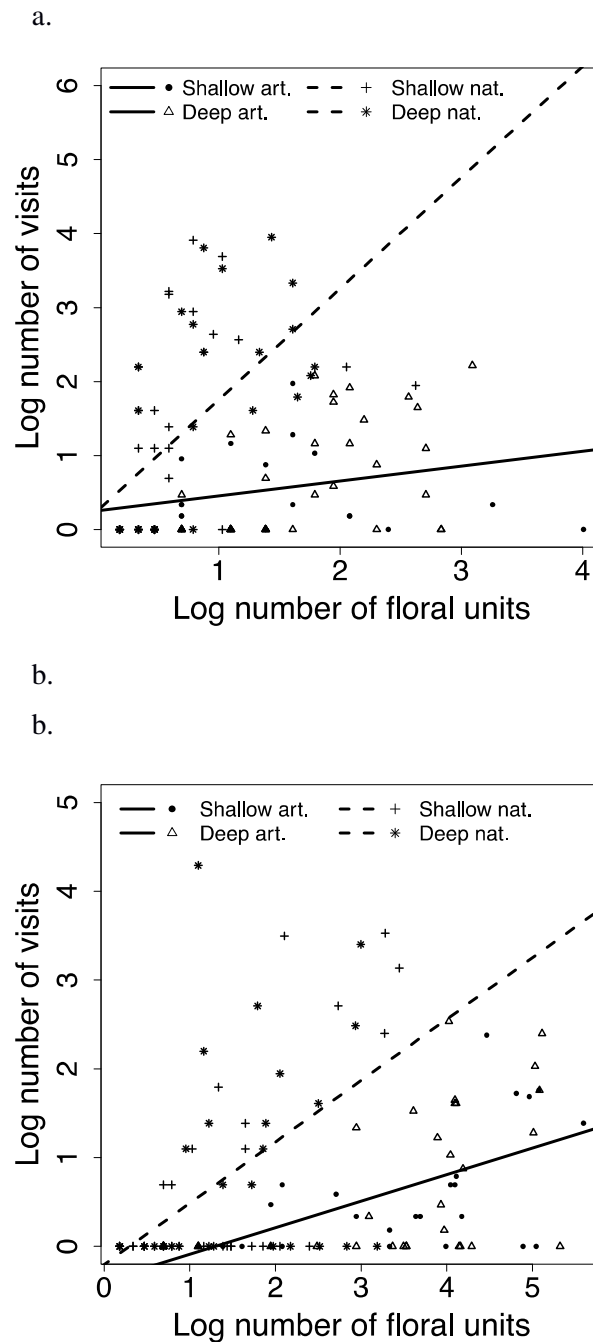


Fig.6 Number of visits per plant against the number of floral units for each plant species grown in mixture as a function of substrate type and substrate depth. a = *Centaurea jacea*; b = *Lotus corniculatus*. Regressions lines are based on ANCOVA results. The different number of lines between species is due to the removal of factors that did not influence regressions, based on the simplification of the complete ANCOVA model using the Akaike Information Criterion (Table 3.b). “art.” stands for “artificial substrate” and “nat” stands for “natural soil”.

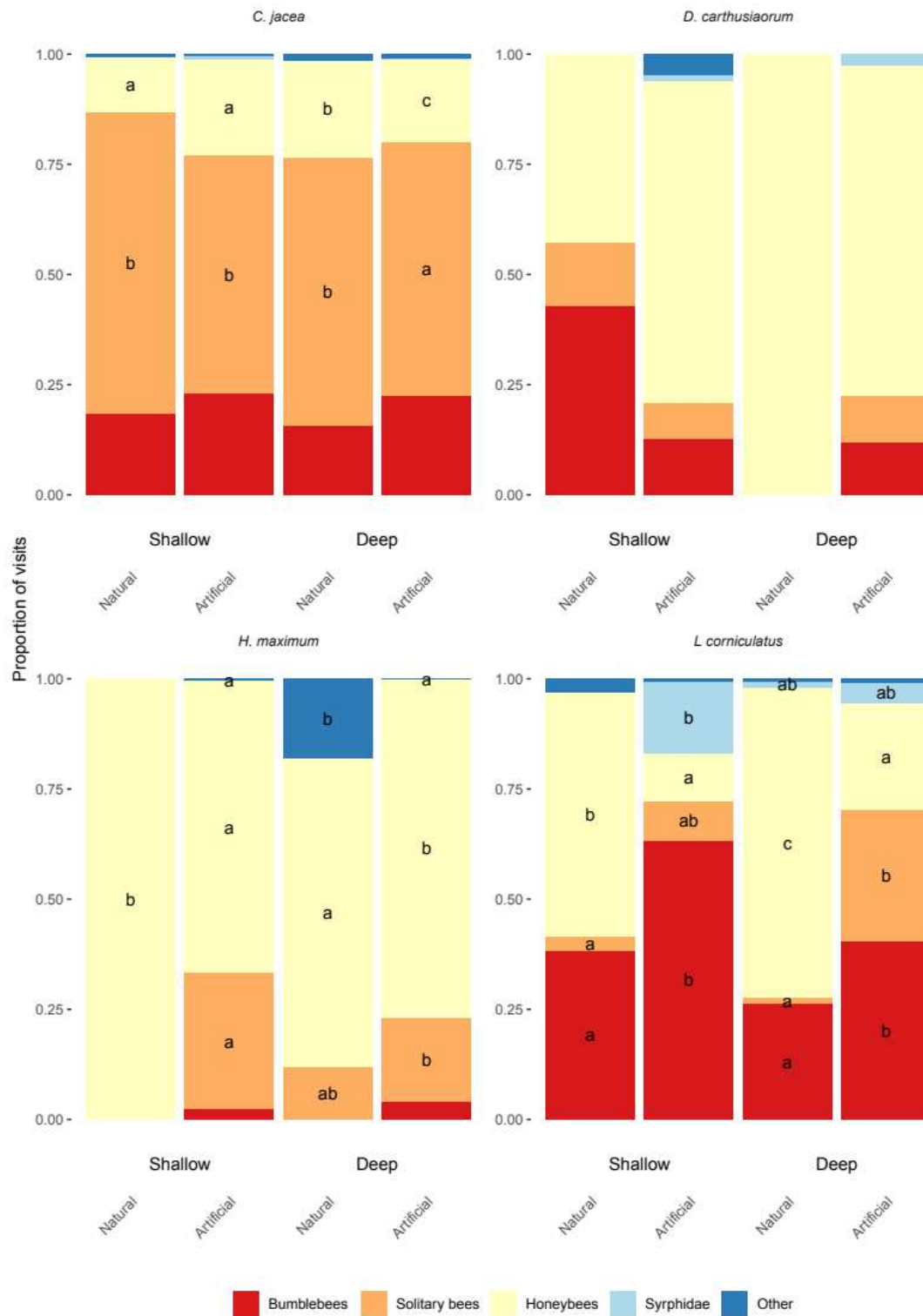


Fig.7 Proportion of visits on each plant species grown on artificial substrate as a function of substrate type and substrate depth. Within each group of pollinators, letters indicate difference in proportions ($p < 0.05$) between treatments. Letters are only shown when there are differences between treatments.