Vertical stratification of plant-pollinator interactions in a temperate grassland

Jan Klecka[1], **Jiří Hadrava**[1,2]**, and Pavla Koloušková**[1]

[1]**Czech Academy of Sciences, Biology Centre, Institute of Entomology, České Budějovice, Czech Republic**
[2]**Department of Zoology, Faculty of Science, Charles University, Prague, Czech Republic**

Corresponding author:
Jan Klecka

Email address: jan.klecka@entu.cas.cz

ABSTRACT

Interactions between plants and their pollinators vary in time and space at different scales. A neglected aspect of small-scale variation of plant-pollinator interactions is the role of vertical position of flowers. We conducted a series of experiments to study vertical stratification of plant-pollinator interactions in a dry grassland. We observed flower visitors on cut inflorescences of *Centaurea scabiosa* and *Inula salicina* placed at different heights above ground in two types of surrounding vegetation: short and tall. Even at such a small-scale, we detected significant shift in total visitation rate of inflorescences in response to their vertical position. In short vegetation, inflorescences close to the ground were visited more frequently, while in high vegetation, inflorescences placed higher received more visits. Moreover, we found major differences in the composition of the pollinator community on flowers at different heights. In a second experiment, we measured flower visitation rate in inflorescences of *Salvia verticillata* of variable height. Overall flower visitation rate increased markedly with inflorescence height. We also detected a corresponding positive pollinator-mediated selection on increased inflorescence height using data on seed set of individual plants. Overall, our results demonstrate strong vertical stratification of plant-pollinator interactions at the scale of mere decimetres. This may be an important, albeit underappreciated, driver of plant-pollinator coevolution.

INTRODUCTION

Interactions between plants and their pollinators play an important role in the evolution (Grant and Grant, 1965; Bronstein et al., 2006; Suchan and Alvarez, 2015) and maintenance of biodiversity (Bascompte et al., 2003, 2006; Bascompte and Jordano, 2007) in terrestrial ecosystems. However, the presence and frequency of interactions between particular plants and pollinators vary in time (Olesen et al., 2008) and space (Espíndola et al., 2011; Newman et al., 2015). Spatial variation in plant-pollinator interactions operates across the range of spatial scales from variation at continental scales across the entire distributional range of a plant species (Espíndola et al., 2011), down to small habitat patches and individual plants (Ohashi and Yahara, 1998; Dupont et al., 2014; Akter et al., 2017). At the smallest scale, the position of an inflorescence in the context of the surrounding vegetation may affect the frequency and identity of flower visitors with consequences for plant reproduction.

Inflorescence height is a plant-level trait that may be particularly important in driving visitation of individual plants because insects and other flower visitors capable of flight usually prefer to fly at a certain height (Levin and Kerster, 1973; Gumbert and Kunze, 1999). Our understanding of vertical distribution of flower visiting insects is most advanced in forests, where the canopy and the understory harbour a very different set of flowers and the two microhabitats also differ in temperature, sun exposure and are physically separated by a distance of at least several meters (Roubik, 1993). Correspondingly, there is a number of studies which found differences in the abundance of various flower visitors along the vertical gradient from the ground up to the canopy (Roubik, 1993; Nagamitsu et al., 1999; Ramalho, 2004; Ulyshen et al., 2010).

The importance of inflorescence height is very little understood in grasslands, where the vertical distance between different flowers is rarely more than a few decimetres. However, there is evidence that inflorescence height may play an important role in plant-pollinator interactions even under these conditions. A few observational studies found that different bee species tend to visit flowers at different heights (Gumbert and Kunze, 1999; Hoehn et al., 2008). In addition, in a trait-based analysis of a plant-flower visitor network in a German grassland, Junker et al. (2013) found that inflorescence height was the most important trait after phenology to explain which plants were visited by which insects. There is also a few studies which found that inflorescence height is under significant pollinator-mediated selection (Sletvold et al., 2010; Jiang and Li, 2017; Trunschke et al., 2017). These studies unfortunately did not perform direct observations of flower visitors, but focused solely on fruit and seed set, or measured pollen transfer to stigmas as a proxy (Lortie and Aarssen, 1999). Nevertheless, these measurements of pollinator-mediated selection suggest that inflorescence height may play a role in coevolution of plants and pollinators. Indeed, recent evolutionary experiments demonstrated that pollinators can cause evolution of increased or decreased plant height within several generations (Gervasi and Schiestl, 2017; Zu and Schiestl, 2017), because plant height has a strong heritability (Andersson, 1991, 1996; Geber and Griffen, 2003; Zu and Schiestl, 2017).

Although our knowledge of vertical stratification of plant-flower visitor interactions in grasslands is limited, even less is known about how the relationship between pollination and inflorescence height is modified by other environmental factors such as the structure of the surrounding vegetation. For example, Sletvold et al. (2013) observed significant pollinator-mediated selection for tall *Dactylorhiza lapponica* plants in tall vegetation, while there was no significant selection on plant height in short vegetation. Similarly, in field experiments with *Primula farinosa*, Ehrlén et al. (2002) showed that short plants were more pollen-limited than tall plants and the difference was larger in a habitat with tall vegetation. However, Ågren et al. (2006) showed that removal of litter and pruning of vegetation around individual *Primula farinosa* plants increased their fruit and seed production apparently because of an increase in their nutritional status rather than increased pollination. The role of vegetation height for pollination thus remains unclear. These studies also looked at the topic entirely from the plant's point of view and did not measure the effects of vegetation height on visitation frequency or pollinator foraging behaviour. Apart from vegetation height, local density of the same or other plant species (Bartkowska and Johnston, 2014), distance from neighbours (Caraballo-Ortiz et al., 2011), as well as spatial variation in the proportion of different morphs (Toräng et al., 2006) can also modify the effects of plant height on its reproductive success.

We conducted a set of field experiments in a dry grassland in the Czech Republic to fill in some of these knowledge gaps. Specifically, our aim was to test whether total visitation rate and the composition of flower visitor assemblages depend on inflorescence height and whether the relationship is modified by the height of the surrounding vegetation. Another aim was to test whether inflorescence height is under pollinator-mediated selection in our system. Our field experiments with three species of plants common in dry grasslands in Central Europe showed that visitation rate varied with infloresence height, moreover the relationship differed between different flower visitor taxa and was modified by the height of the surrounding vegetation. We also detected significant pollinator-mediated selection on inflorescence height in *Salvia verticillata*.

METHODS

Field experiments

We conducted two field experiments in a dry grassland near Český Krumlov, in the southern part of the Czech Republic (48°49'28"N 14°18'59"E). The study site is a species rich calcareous grassland managed by occasional pasture by cows and sheep. The study site is a part of a state-owned publicly accessible area, where entry, collection of plant and invertebrate samples, with the exception of species protected by law, and similar activities are allowed without the need to apply for any permits.

In the first experiment, we observed visitation of inflorescences of two plant species, *Centaurea scabiosa* and *Inula salicina*, at different heights above ground. To avoid confounding factors, e.g. taller plants having a different size of inflorescences than shorter plants, we used inflorescences cut from plants in the local population. We selected inflorescences of a similar size and general appearance and placed them in 15 ml tubes with water. We attached each tube to a bamboo stick of different length and attached the stick to the ground. This way, we manipulated the height of the inflorescence between 5 cm and

105 cm above ground. We placed the inflorescences along two short transects, each containing seven inflorescences placed 50 cm apart. One transect was surrounded by short and the other by tall and dense vegetation; the transects were ca. 10 m apart. The area of short vegetation was grazed by cows in the spring, while the area of tall vegetation was not managed. Short vegetation was characterised by most plants <10 cm tall; the average height of inflorescences of all plants growing within 50 cm from the transect in all directions was 7.2 cm ($SD = 6.00$). Tall vegetation was composed of a dense layer of plants reaching ca. 50 cm; the average distance of flowers around the transect was 50.1 cm ($SD = 14.73$) above ground. We individually placed seven inflorescences of either *Centaurea scabiosa* or *Inula salicina* in each transect at 5, 15, 25, 45, 65, 85, and 105 cm above ground in a randomised order.

We observed visitation of the inflorescences by insects for 30 minutes and identified all visitors at the species level or classified them into taxonomical groups with the highest precision we could achieve without capturing the insects. Both transects were observed simultaneously, one person observed each transect. After the 30 minute period, we replaced the inflorescences and randomised the order of their vertical position along each transect and took another set of observations. In total, we measured inflorescence visitation in 20 transects in *Inula salicina*, 10 in short and 10 in tall vegetation, and 16 transects in *Centaurea scabiosa*, 8 in short and 8 in tall vegetation.

In the second experiment, we focused on the effect of inflorescence height for flower visitation rate and its consequences for seed set in *Salvia verticillata* at the same site. In this case, we did not cut the inflorescences so that we could test whether flower visitation rate varied between inflorescences within the natural limits of their height above ground and to test whether variation in flower visitation rate translated into differences in seed set; i.e. whether female fitness was affected by the vertical position of the inflorescence. We used the following approach to avoid confounding effects, such as taller plants having more resources, different display size, etc. We selected 17 plants of *Salvia verticillata* with multiple ramets of approximately the same size and with the first several flowers open or with buds ready to start flowering on 18 July 2017. We took advantage of the fact that the inflorescences grow on relatively long and flexible stems. We bent one of them close to the ground, where it was attached to a stick so that the bottom of the inflorescence was positioned just above ground. The second stem was attached to another stick so that it reached a maximum height and the third inflorescence was positioned at an intermediate height. This way, the only difference between the inflorescences was their vertical position.

We performed observations of flower visitation in individual *S. verticillata* plants at one of three dates (20 July, 21 July, and 2 August 2017), depending on when they reached the peak of flowering. The three manipulated ramets per plant were observed simultaneously during one 30 minute period and filmed using three digital cameras. Afterwards, we measured the height of each inflorescence as a distance of the highest open flower from the ground and counted the number of open flowers. We then watched the recordings and counted and identified all flower visitors. For each visitor, we also counted the number of flowers visited during each inflorescence visit.

We waited for the seeds of *S. verticillata* to ripen and then harvested them on 14 or 24 August 2017 depending on seed development in individual plants. We counted the number of developed seeds and the maximum potential seed set by multiplying the number of flowers by four which is the number of seeds the plant can produce per flower. We counted the flowers and seeds in individual whorls within each inflorescence separately to gain data on potential differences in percentage seed set along the inflorescence from the lowest to the highest whorl.

As already mentioned, we identified flower-visiting insects without capturing them. Naturally, we could not identify all individuals to the species level, so we classified some of them into higher taxa or categories, such as "small solitary bees". The most abundant flower visitors were bumblebees, *Bombus* sp., some of which are difficult to identify alive. Fortunately, we have extensive collections from the study site, so we know that there are three species, which we could not distinguish from *Bombus terrestris*, specifically *B. lucorum*, *B. cryptarum* and *B. magnus*. However, over 85% of individuals of this species group in our collections from this site belong to *B. terrestris*. Similarly, *Bombus lapidarius* could be confused with *B. confusus* and *B. ruderarius*, but they have been very rarely found on the site. The number of potential bumblebee misidentifications during the field observations was thus low.

Data analysis

We tested how the total number of visits and the number and proportion of visits by individual flower visitor taxa depended on inflorescence height using generalized additive models (GAM) to account for

the non-linear nature of these relationships. The identity of individual plants, each having three ramets manipulated and observed, was included as a random factor in analyses of data from the experiment with *Salvia verticillata*; i.e. generalized additive mixed models (GAMM) were used in this case. Poisson distribution with overdispersion (quasipoisson distribution) was used for the number of visits, while overdispersed binomial (quasibinomial) distribution was used for data on proportions. These analyses were perfomed using mgcv 1.8-17 package (Wood, 2006) in R 3.2.3 (R Core Team, 2015).

The analysis of relative fitness of individual ramets was performed using a generalized linear model with the number of flowers and the inflorescence height as predictors. We calculated the strength of selection on plant traits following Lande and Arnold (1983) using a generalized linear model (GLM) with relative female fitness (individual number of seeds divided by the mean number of seeds) as a response variable and the number of flowers and the inflorescence height as predictors (both standardised to have zero mean and unit variance). Linear selection gradients were estimated as partial regression coefficients from the GLM fitted in R 3.2.3 (R Core Team, 2015).

RESULTS

In the first experiment, we observed a strong dependence of the total visitation rate on inflorescence height in both *Centaurea scabiosa* and *Inula salicina* (Fig 1). Analysis using generalised additive models (GAM, Table 1) showed that the relationship was significant in *Centaurea scabiosa* as well as in *Inula salicina* in both short and tall vegetation (Table 1). There was also a shift in maximum visitation rate towards inflorescences higher above ground when the surrounding vegetation was taller (Fig 1). The difference in the shape of the relationship between total visitation and inflorescence height in short vs. tall surrounding vegetation was significant in both *Centaurea scabiosa* ($F = 19.27, P < 10^{-6}$) and *Inula salicina* ($F = 12.46, P = 3.10 \times 10^{-5}$). Analysis of visitation rate of the most abundant flower visitors showed that different insect species had contrasting height preferences modified by the height of the surrounding vegetation (Fig 2, Fig 3, and Table 1).

In *Centaurea scabiosa*, we observed a significant effect of inflorescence height on the number of inflorescence visits by *Bombus lapidarius*, which preferred mostly inflorescences close to the ground (Fig 2 A., Table 1), *Halictus quadricinctus*, which preferred inflorescence high above ground (Fig 2 C.), and small solitary bees, which visited mostly inflorescences at an intermediate height (Fig 2 D.). The relationship was not significant in *Bombus terrestris* (Table 1). Two species, *Bombus terrestris* and *Haliplus quadricinctus*, avoided the area of tall vegetation despite being frequently observed in transects surrounded by short vegetation. On the other hand, *Bombus lapidarius* was common in both habitats and showed a strong shift towards inflorescences higher above ground in the transects surrounded by tall vegetation (Fig 2 A. and E.); the relationship between visitation and inflorescence height was significantly different in short and tall vegetation ($F = 21.31, P < 10^{-6}$). On the contrary, small solitary bees did not shift their visitation (Fig. 2 D. and H.).

Inula salicina had a lower visitation rate than *Centaurea scabiosa* (Fig 1), and only two groups of flower visitors were abundant enough for analysis. Hoverflies (Diptera: Syrphidae) visited mostly inflorescences >40 cm above ground and the height of the surrounding vegetation had no effect on the relationship between the number of visits and inflorescence height (Fig 3 A. and C.; $F = 0.04, P = 0.95$). On the other hand, small solitary bees strongly favoured inflorescences close the the ground in short vegetation and shifted higher above ground in tall vegetation (Fig 3 B. and D.), the relationship of visitation with inflorescence height was significantly different in short and tall vegetation ($F = 15.39, P < 10^{-6}$; Table 1).

Inflorescences of both species experienced visitation by a very different community of potential pollinators depending on the height of the inflorescence and the height of the surrounding vegetation because different flower visitors responded to both factors in a species-specific way (Fig 4, Table 2). For example, inflorescences of *Centaurea scabiosa* positioned close to the ground were visited mostly by *Bombus lapidarius* when the surrounding vegetation was short, but mostly by small solitary bees when the surrounding vegetation was tall (Fig 4 A. and C).

In the second experiment, we found a strong effect of inflorescence height on visitation and seed set in *Salvia verticillata*. The total number of flower visitors (Fig 5A.) and the per-flower visitation rate (Fig 5B.) significantly increased with inflorescence height (GAMM; $edf = 1.91, F = 21.04, P = < 1 * 10^{-6}$ and $edf = 1.836, F = 21.62, P = < 1 * 10^{-6}$, respectively).

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Table 1. The effects of inflorescence height and surrounding vegetation height on the number of visits by different insects. Summary of results of generalized additive models testing the dependence of visitation of *Centaurea scabiosa* and *Inula salicia* on inflorescence height. Groups of flower visitors which had an insufficient number of observations for analysis were not analysed separately, but are included in the total visitation. edf = estimated degrees of freedom, which gives a measure of the complexity of the shape of the relationship (*edf* = 1 is a linear relationship). NA = cases when the number of observations was insufficient for analysis. The results are presented graphically in Figs 1, 2, and 3.

Response	Short vegetation			Tall vegetation			Short vs. tall vegetation	
	edf	F	P	edf	F	P	F	P
Visits of *Centaurea scabiosa*								
Total visitors	3.00	10.01	$3.77 * 10^{-6}$	3.55	15.21	$< 1 * 10^{-6}$	19.27	$< 1 * 10^{-6}$
Bombus lapidarius	2.80	8.38	$4.17 * 10^{-5}$	3.62	6.15	0.0005	21.317	$< 1 * 10^{-6}$
Bombus terrestris	1.69	1.92	0.1640	NA	NA	NA	NA	NA
Halictus quadricinctus	2.16	6.00	0.0028	NA	NA	NA	NA	NA
small solitary bees	2.62	8.16	$6.20 * 10^{-5}$	2.62	8.16	$6.20 * 10^{-5}$	0	1
Visits of *Inula salicina*								
Total visitors	1	5.38	0.0223	2.58	6.27	0.0005	12.46	$3.10 * 10^{-5}$
small solitary bees	1.32	17.12	$4.9 * 10^{-6}$	3.65	3.75	0.0072	15.39	$< 1 * 10^{-6}$
Syrphidae	1.94	9.54	0.0001	1.94	9.54	0.0001	0.04	0.9543

Different groups of flower visitors also showed distinct patterns in their preference for inflorescences of different heights. *Bombus terrestris* visited mostly the highest inflorescences, followed by *Bombus lapidarius*, while *Bombus sylvarum* showed no significant dependence of visitation on inflorescence height and small solitary bees visited mostly inflorescences close to the ground (Fig. 6, Table 3). When expressed as the proportion of visits attributed to individual pollinator groups, our results show that plants with inflorescences closest to the ground were visited equally by *Bombus terrestris* and small solitary bees (ca. 40% each), followed by *Bombus sylvarum* (almost 20%) (Figure 7, Table 3). On the other hand, visits to inflorescences high above ground were dominated solely by *Bombus terrestris* (Figure 7, Table 3). Different visitors also significantly differed in one aspect of foraging behaviour, namely in the proportion of flowers in an inflorescence probed during a visit (Table 3; GLM, $F = 5.24, P = 3.82 * 10^{-5}$). *Apis mellifera*, which was excluded from the previous analyses because it was too rare, visited on average over 60% of flowers during one inflorescence visit and the three bumblebee species over 40%. On the contrary, other visitors, which we classified as small solitary bees, Syrphidae, and other Diptera, visited less than 20% of the flowers per inflorescence visit (Figure 7).

Differences in visitation translated into differences in relative female fitness which significantly increased with both the number of flowers in an inflorescence (GLM, $F = 6.21, P = 0.0165$; Fig 8 A.) and with inflorescence height (GLM, $F = 6.09, P = 0.0175$; Fig 8 B.). Consequently, there was a positive pollinator-mediated selection on increased inflorescence height in *Salvia verticillata*. The strength of selection estimated by partial regression coefficients was very similar for the number of flowers ($\beta = 0.27600, SE = 0.09948$) and inflorescence height ($\beta = 0.25551, SE = 0.09948$). The importance of the vertical position of flowers is underscored by the fact that we found a significant increase in the proportional seed set in individual whorls within individual inflorescences when moving from the lowest to the highest whorl (GLMM, $\chi^2 = 228.01, P < 10^{-6}$; Fig 8 C.).

DISCUSSION

The effects of inflorescence and vegetation height on visitation by potential pollinators

In the first experiment, using *Centaurea scabiosa* and *Inula salicina* as focal species, total inflorescence visitation peaked approximately at or slightly above the level of the surrounding vegetation in transects surrounded by both short and tall vegetation. These results are consistent with observations that flower visiting bees tend to fly at a specific height and when they leave one inflorescence, they are more likely to fly to another one at a similar height compared to inflorescences lower or higher above ground (Levin and Kerster, 1973; Gumbert and Kunze, 1999). Flowers positioned above the level of a dense layer of vegetation are probably easier to detect and thus attract more visitors (Gumbert and Kunze, 1999). Height preferences of flower visitors can lead to vertical stratification of the plant-pollinator network if different

Table 2. The effects of inflorescence height and surrounding vegetation height on relative visitation by different insects. Summary of results of generalized additive models testing the dependence of the proportion of visits attributed to most abundant visitor taxa on inflorescence height in *Centaurea scabiosa* and *Inula salicina*. edf = estimated degrees of freedom, which gives a measure of the complexity of the shape of the relationship ($edf = 1$ is a linear relationship). NA = cases when the number of observations was insufficient for the analysis. The results are presented graphically in Fig 4.

Response	Short vegetation			Tall vegetation			Short vs. tall vegetation	
	edf	F	P	edf	F	P	F	P
Visits of *Centaurea scabiosa*								
Bombus lapidarius	1	30.60	$< 1 * 10^{-6}$	2.16	4.79	0.0073	14.22	$< 1 * 10^{-6}$
Bombus terrestris	1	1.28	0.2640	NA	NA	NA	NA	NA
Halictus quadricinctus	1	21.21	$3.62 * 10^{-5}$	NA	NA	NA	NA	NA
small solitary bees	1.72	1.18	0.3045	1	16.02	0.0002	11.871	0.0005
Visits of *Inula salicina*								
small solitary bees	1	35.25	$< 1 * 10^{-6}$	1	2.16	0.1450	14.78	0.0002
Syrphidae	1.93	15.14	$1.46 * 10^{-6}$	1.93	15.14	$1.46 * 10^{-6}$	1.48	0.2333

Table 3. The effect of inflorescence height in *Salvia verticillata* on inflorescence visitation. Summary of results of generalized additive mixed models testing the dependence of the number of visits and the proportion of visits by most frequent visitor taxa on inflorescence height in *Salvia verticillata*. edf = estimated degrees of freedom, which gives a measure of the complexity of the shape of the relationship ($edf = 1$ is a linear relationship). The results are plotted in Figs 6 and 7.

Response	No. of visits / 30 min.			Proportion of visits		
	edf	F	P	edf	F	P
Bombus lapidarius	1.912	8.56	0.0009	1.68	0.89	0.2640
Bombus terrestris	1.88	19.28	$1.66 * 10^{-6}$	1	6.90	0.0118
Bombus sylvarum	1.21	0.03	0.8700	1	9.93	0.0029
small solitary bees	1	10.08	0.0026	1	38.48	$< 1 * 10^{-6}$

241 species vary in their behaviour (Roubik, 1993; Gumbert and Kunze, 1999; Ramalho, 2004).

242 Different responses of individual species or taxonomic groups of flower visitors to inflorescence
243 height, which we observed, mean that inflorescences at different heights varied in the composition of
244 their flower visitor assemblages (Figs 4 and 7). We thus observed pronounced vertical stratification
245 of plant-pollinator interactions despite that fact that height differences between inflorescences were in
246 the order of mere decimetres. Previous studied on vertical stratification of pollinator communities were
247 conducted mostly in forests where the importance of the vertical dimension is more obvious. It seems
248 there is generally a major difference in the composition of flower visitor communities between the canopy
249 and the understory in tropical (Roubik, 1993; Nagamitsu et al., 1999; Ramalho, 2004) as well as temperate
250 forests (Ulyshen et al., 2010), probably related to vertical distribution of flowers preferred by different
251 species (Ramalho, 2004). However, vertical stratification of plant-pollinator interactions has been less
252 studied in grasslands where the vertical distances are limited usually to several decimetres. In one of
253 the few available studies, (Gumbert and Kunze, 1999) observed a clear differentiation between visitor
254 communities on flowers below and above the dominant grass layer in a tropical wetland. Similarly,
255 several species of bees visiting pumpkins in an agricultural landscape preferred flowers at different heights
256 (Hoehn et al., 2008). Our results show that vertical stratification of plant-flower visitor interactions may
257 be important also in common temperate grasslands.

258 An interesting observation is that small solitary bees were the dominant flower visitors close to the
259 ground in all three plant species. We noticed that unlike other flower visitors, they were frequently flying
260 among plant stems close to the ground even in dense vegetation and visiting flowers hidden there, such
261 as flowers of *Rubus* sp., which was growing in parts of the study site. The same pattern was observed
262 by (Gumbert and Kunze, 1999), who suggested that small bees, which are able to manoeuvre in dense
263 vegetation, benefit from the fact that most other flower visitors avoid this microhabitat, so flowers which
264 are found among dense vegetation close to the ground may be less depleted than flowers higher up. This
265 seems to be a likely explanation for our results as well. Behaviour of small solitary bees contrasted
266 with the behaviour of larger species, such as bumblebees, which were flying above the layer of dense

vegetation. For example, all observations of *Bumbus lapidarius* with one exception were at the height of >40 cm in tall vegetation (Fig 2E.).

The effect of flower visitation was thus modified by the height of the surrounding vegetation because most flower visitors avoided flowers within the layer of dense vegetation close to the ground. One bumblebee species, *Bombus terrestris*, also visited mostly inflorescences close to the ground in short vegetation (Fig 2 B.), but almost completely avoided the area with tall vegetation (Fig 2 F.), similarly to *Halictus quadricintus*, a solitary bee, which strongly favoured inflorescences >60 cm above ground(Fig 2 C.). Previous studies on the effects of the structure of the surrounding vegetation for flower visitation and plant reproductive success are rare and did not provide clear conclusions. For example, (Ågren et al., 2006) manipulated vegetation height and litter presence around individual plants of *Primula farinosa*, and found that litter removal and vegetation pruning increased seed set, especially in short plants. They did not report any data on visitation frequency of flowers in relation to vegetation structure. However, if we assume that higher visitation leads to higher fruit or seed production, our observations of higher visitation of inflorescences close to the ground in short vegetation exactly mirror these results. In tall vegetation, visitation of both *Centaurea scabiosa* and *Inula salicina* peaked higher above ground, which fits the results of (Sletvold et al., 2013), who observed pollinator-mediated selection for taller inflorescences in tall vegetation but not in short vegetation in a deceptive orchid, *Dactylorhiza lapponica*.

We did not measure the efficiency of different pollinators in the present study, so we cannot infer consequences of the variation of visitation at different heights for the reproductive success of *Centaurea scabiosa* and *Inula salicina*. However, data from detailed single visit experiments by other authors demonstrated that different flower visitor species vary in pollen deposition by several orders of magnitude (King et al., 2013). Hence, it is very likely that variation in total visitation rate together with the variation in visitor identity with inflorescence height affects reproductive success of plants in our system. We addressed this question in a second experiment with *Salvia verticillata*.

Consequences of inflorescence height for plant fitness

Observations on *Salvia verticillata* were constrained by the natural range of inflorescence heights. Unlike previous studies, we collected data both on flower visitation rates by pollinators and on fitness of individual ramets in relation to inflorescence height. We found a significant positive selection for inflorescence height as other authors demonstrated in several other plant species (Sletvold et al., 2010, 2013; Jiang and Li, 2017; Trunschke et al., 2017). However, we could also demonstrate that plants with inflorescences positioned higher above ground had higher total flower visitation rates, which points to pollinators being responsible for the dependence of plant fitness on inflorescence height.

Our experimental design allowed us to measure pollinator-mediated selection on inflorescence height, because we compared three similarly looking inflorescences per plant, whose height was adjusted by attaching them to wooden sticks. Vertical position was thus the only difference between the inflorescences. This is important because taller plants usually have higher percentage seed set even when they are hand-pollinated because they have more resources than shorter plants (Andersson, 1996; Červenková and Münzbergová, 2014). Testing for pollinator-mediated selection on inflorescence height thus requires specific experimental designs and is not possible by simply comparing plants of different height. The most frequent approach is to compare the selection coefficients for inflorescence height between open-pollinated and hand-pollinated plants (Sletvold et al., 2010; Červenková and Münzbergová, 2014; Jiang and Li, 2017; Trunschke et al., 2017). We used an alternative approach, which allowed us to skip the hand-pollination treatment. We took advantage of the morphology of *Salvia verticillata*, which creates multiple closely packed, relatively long, and flexible ramets, which can be easily pinned closer to the ground or straightened up without causing damage. For our observations, we selected three ramets with inflorescences of a similar length and general appearance per plant and randomly adjusted their vertical position, so there was no known confounding factor. So, the observed selection for increased inflorescence height corresponds to pollinator-mediated selection.

Flower visitation by different insect species can have different effects on plant fitness not only because different species differ in the number of pollen grains deposited per visit (King et al., 2013), but also because they differ in the relative frequency of movements between flowers on the same plant and between different plants (Paton, 1993). Our observations showed that honeybees (*Apis mellifera*) visited a majority of flowers within an inflorescence by moving along the inflorescence and probing one flower after another. The three bumblebee species exploited slightly lower percentage of flowers, while small solitary bees

and Diptera usually probed only a few flowers per inflorescence (Fig 7). Different pollinators thus have a different potential for geitonogamous pollination, because pollen from the previously visited plant is deposited mostly on stigmas of the first few flowers and receipt of foreign pollen exponentially decreases in each successive flower visit within an inflorescence (Thomson and Plowright, 1980; Gerber, 1985; Morris et al., 1994). High levels of geitonogamous pollination may negatively affect plant fitness (Gerber, 1985; Waser and Price, 1991; de Jong et al., 1993; Ruane et al., 2013). In our population of *Salvia verticillata*, we would expect higher level of geitonogamous pollination in inflorescences higher above ground because of shifts in the flower visitor community (see Fig. 7), perhaps also in individual whorls higher within an inflorescence. However, proportional seed set at the scale of entire inflorescences and individual whorls increased with height, apparently thanks to higher total visitation rate.

Inflorescences which are more attractive for pollinators may also attract higher numbers of florivores and seed predators (Sletvold and Grindeland, 2008). Seed set is thus driven by a balance between mutualistic and antagonistic interactions with flower visitors (Ehrlén et al., 2002; Schlinkert et al., 2016). We did not notice any conspicuous evidence of florivory during observations of flower visitors or seed predation when processing seeds of *Salvia verticillata*. However, in other plant species, florivory and seed predation can have a large negative effect on plant fitness (Ruane et al., 2014). For example, (Schlinkert et al., 2016) found that abundance of both pollinators and florivores increased with plant height and mutualistic and antagonistic interactions had contrasting effects on the number of seeds leading to seet set being independent of plant height. The role of inflorescence height may thus be species-specific and context-dependent, as shown also by our observations of inflorescence visitation in short and tall vegetation.

Conclusions

In conclusion, we experimentally demonstrated that both total flower visitation and the composition of the community of insect visitors changed with the vertical position of inflorescences in three common plant species growing in a dry grassland. Moreover, we found that the dependence of visitation rate on inflorescence height was mediated by the height of the surrounding vegetation. In one species, *Salvia verticillata*, we also measured seed set and demonstrated significant selection for increased inflorescence height. Hence, we detected pronounced vertical stratification of plant-pollinator interactions at a scale of mere decimetres in a temperate grassland.

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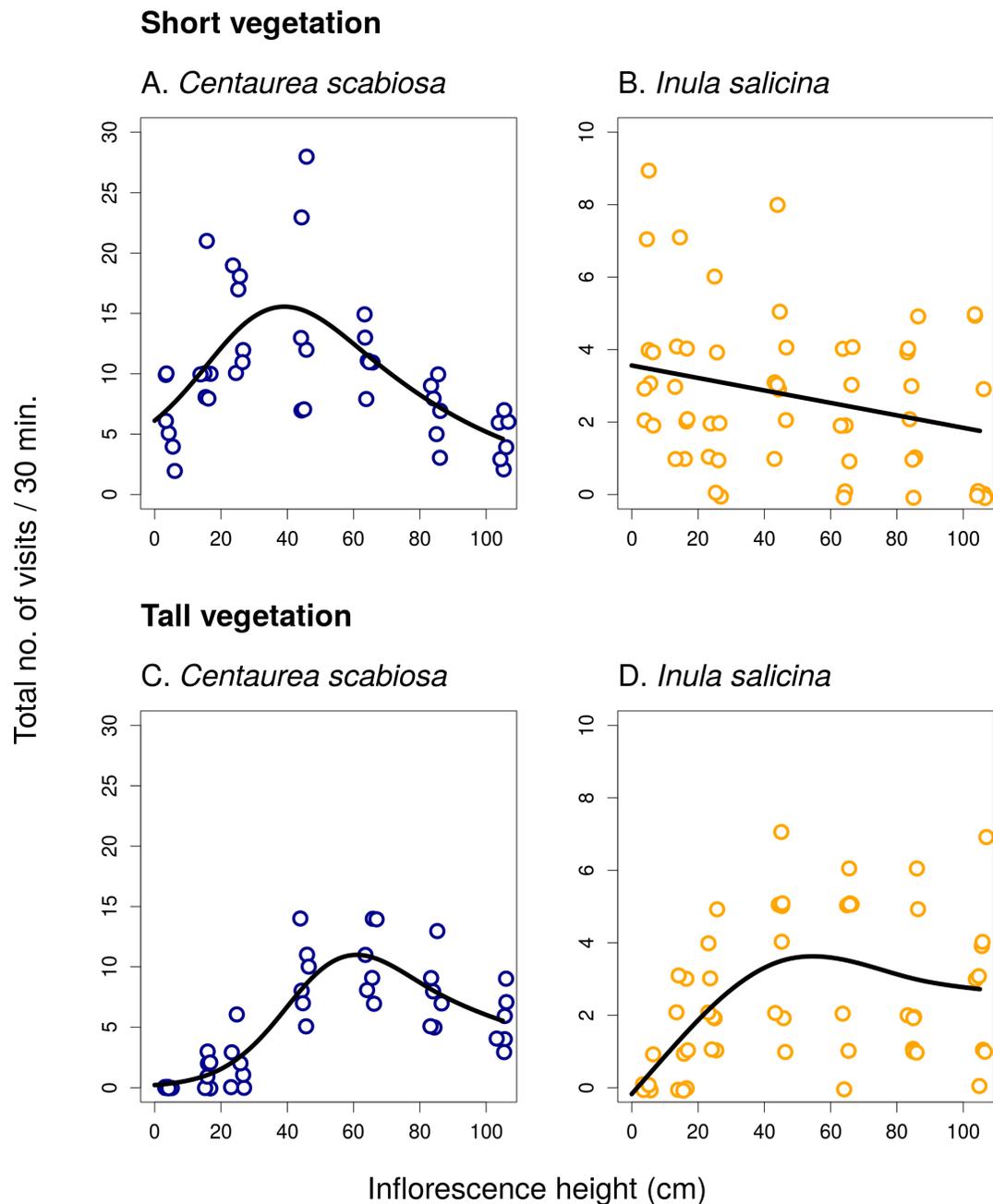


Figure 1. Inflorescence visitation in *Centaurea scabiosa* and *Inula salicina*. Visitation of inflorescences of *Centaurea scabiosa* and *Inula salicina* significantly depended on the vertical position of inflorescences above ground. This relationship was modified by the height of the surrounding vegetation as apparent from the comparison of data from transects surrounded by short (A. and B.) and tall (C. and D.) vegetation. A small amount of noise was added to the data in both x and y direction to make overlapping points visible. Summary of the statistical tests is shown in Table 1.

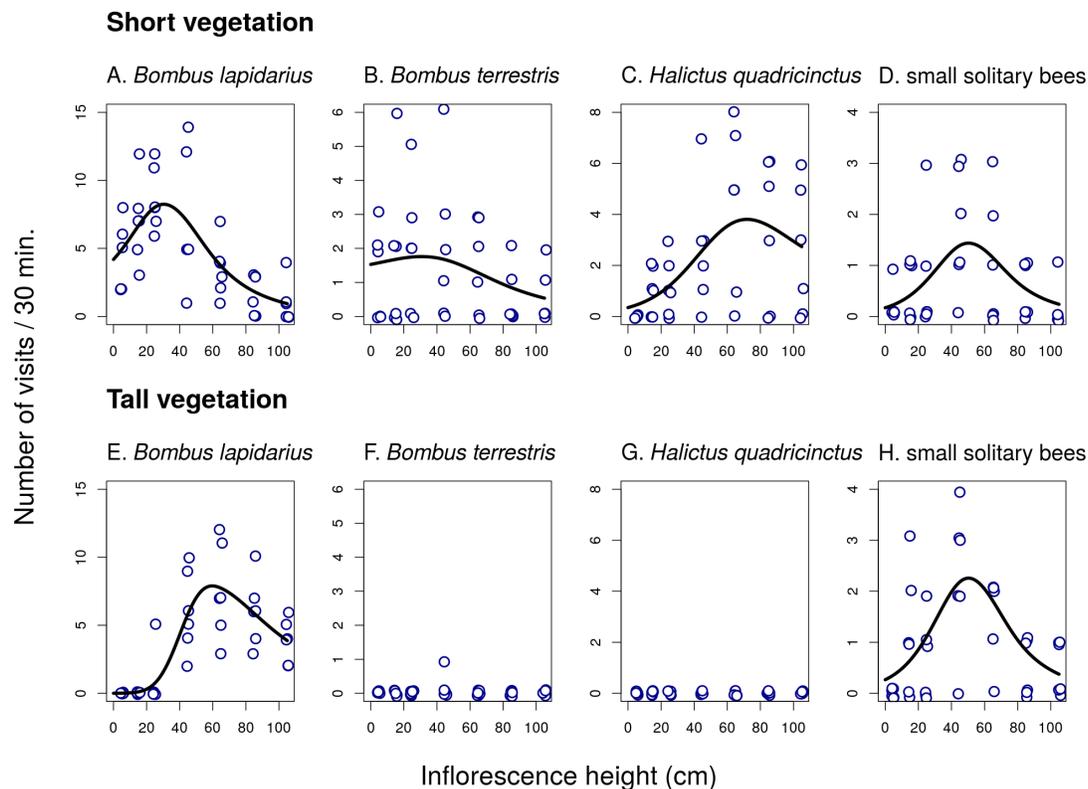



Figure 2. Inflorescence visitation of *Centaurea scabiosa* by the most frequent visitor taxa. The number of visits per 30 minutes in short (A. - D.) and tall (E. - H.) vegetation is plotted. A small amount of noise was added to the data in both x and y direction to make overlapping points visible. The relationship in *Bombus terrestris* is not statistically significant. Summary of the statistical tests is shown in Table 1.

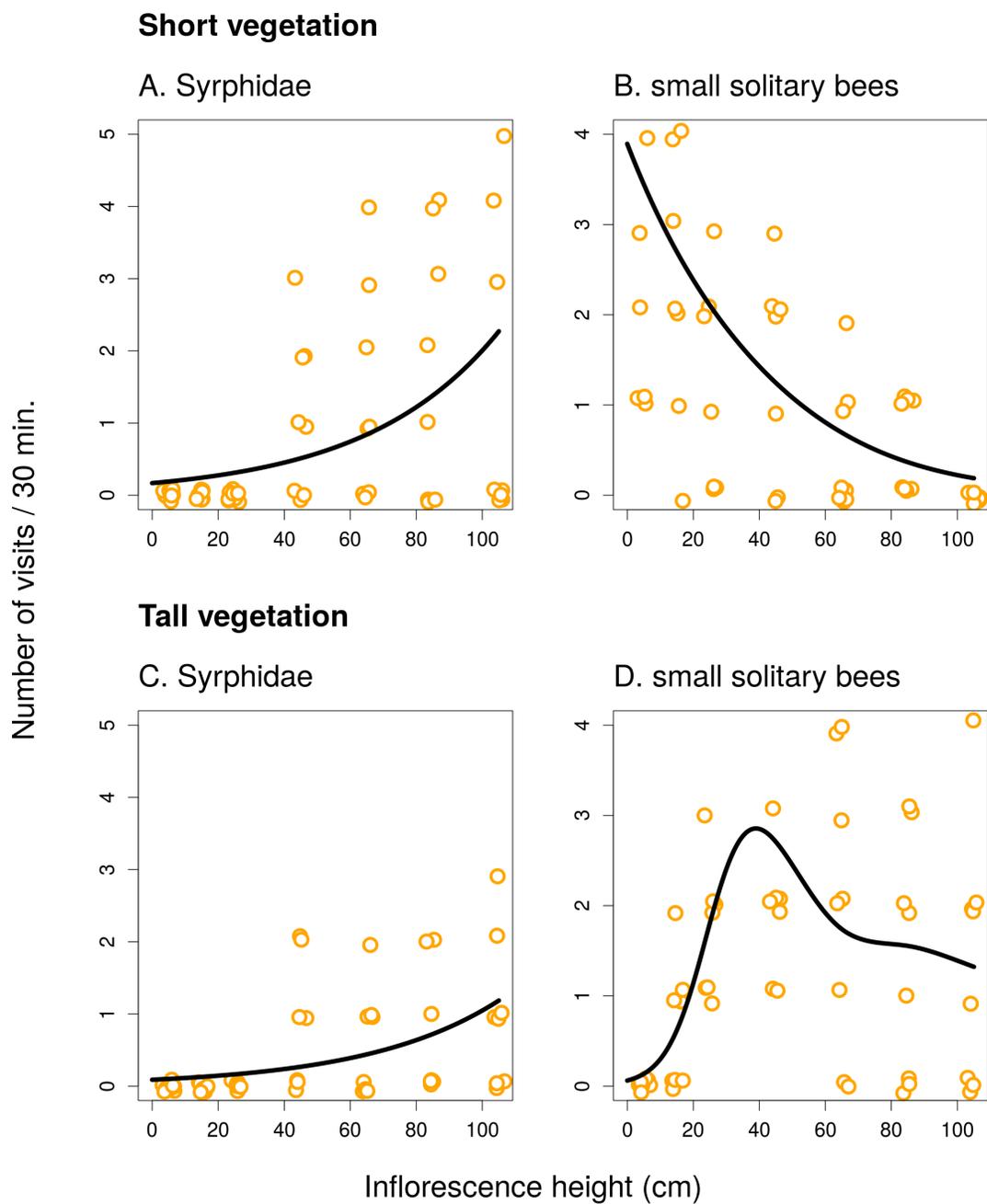
Short vegetation

Tall vegetation

Figure 3. Inflorescence visitation of *Inula salicina* by the most frequent visitor taxa. The number of visits per 30 minutes in short (A. and B.) and tall (C. and D.) vegetation is plotted. A small amount of noise was added to the data in both x and y direction to make overlapping points visible. Summary of the statistical tests is shown in Table 1.

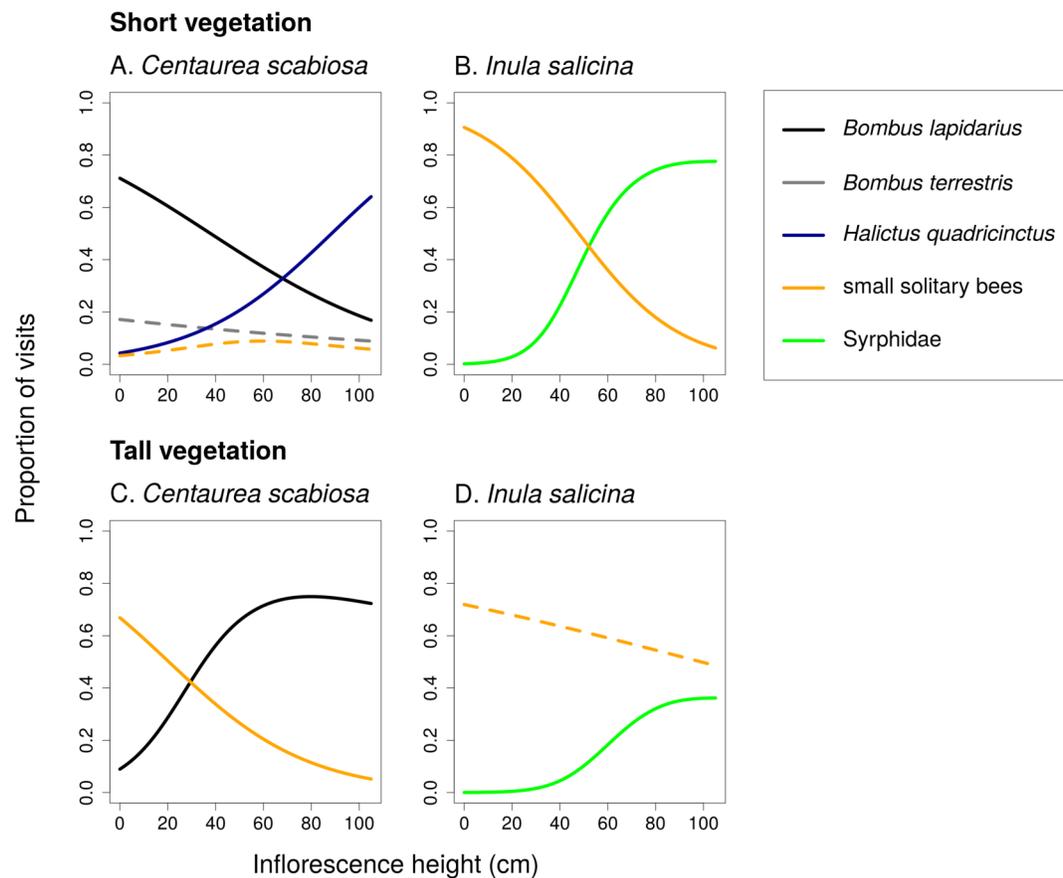



Figure 4. Changes in relative visitation by different insects depending on inflorescence height and vegetation height. Proportions of flower visits attributed to main groups of flower visitors of *Centaurea scabiosa* and *Inula salicina* in transects surrounded by short (A. and B.) and tall (C. and D.) vegetation. The relationships were estimated using generalised additive models. A small fraction of visitors belonged to other groups omitted from the analysis because they had very low abundance. Relationships which were not statistically significant are shown in dashed lines. Summary of the statistical tests is shown in Table 2.

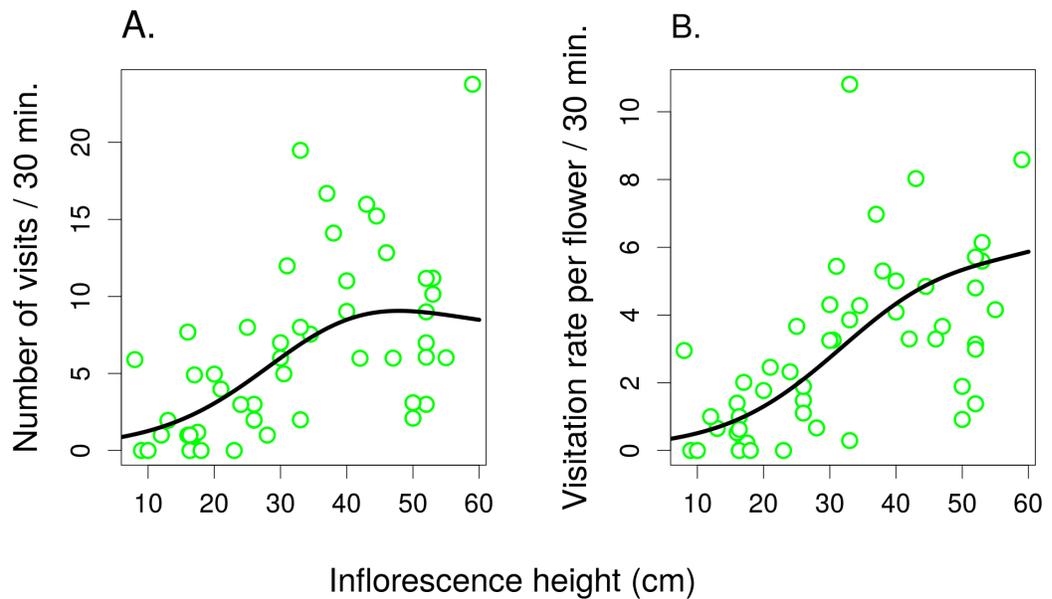



Figure 5. **The effect of inflorescence height on visitation of *Salvia verticillata*.** The number of visitors per inflorescence (A.) and the per-flower visitation rate (B.) in inflorescences of *Salvia verticillata* at different heights within the range of heights found naturally at the study site. The inflorescence height in cm refers to the top flower in each inflorescence.

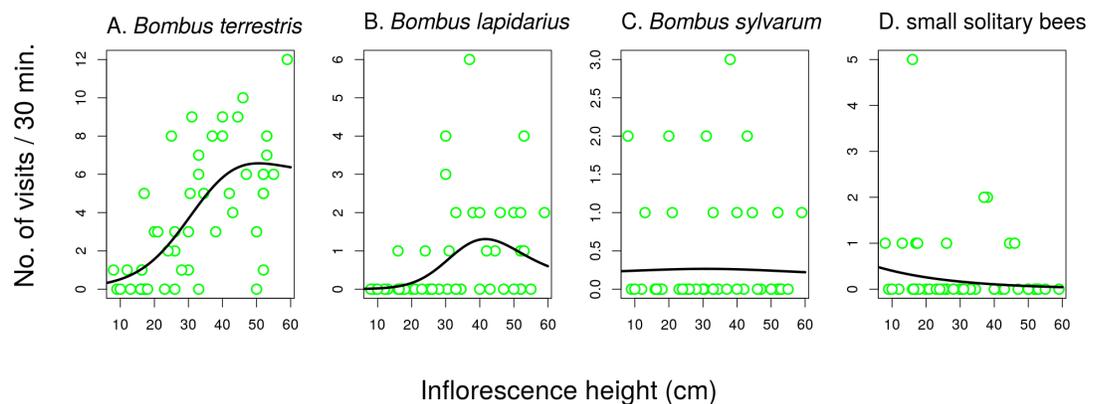



Figure 6. **The effect of inflorescence height on visitation of *Salvia verticillata* by different insects.** The inflorescence height in cm refers to the top flower in each inflorescence. The relationships are statistically significant except in *Bombus sylvarum*. Summary of the statistical tests is provided in Table 3.

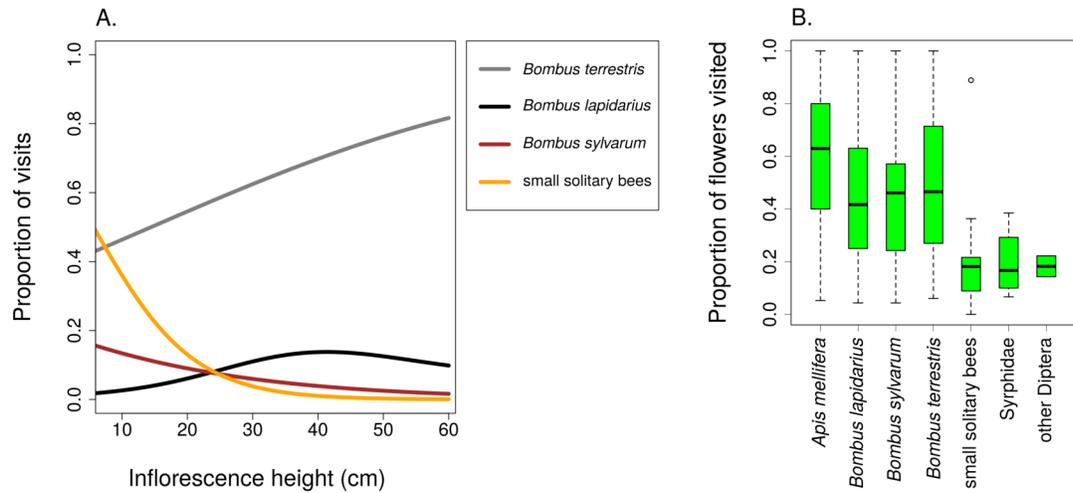



Figure 7. Different insects vary in their contribution to inflorescence visitation and visit different proportions of flowers per inflorescence. (A.) Proportions of inflorescence visits attributed to main groups of visitors of *Salvia verticillata* changed significantly in relation to inflorescence height. The relationships are statistically significant except in *Bombus lapidarius*. Summary of the statistical tests is provided in Table 3. (B.) Different groups of insects differed in the proportion of flowers visited during a visit to an inflorescence of *Salvia verticillata*. The box and whishers plot shows the median (horizontal line), interquartile range (box), and $1.5 * SD$ (whiskers) for each visitor group.

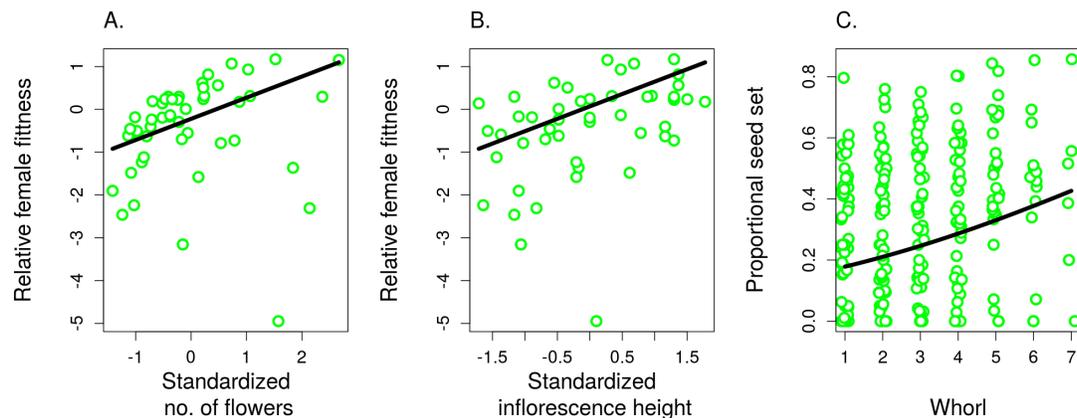



Figure 8. Seed set of *Salvia verticillata*. Relative female fitness of individual plants of *Salvia verticillata* increased with the number of flowers in the inflorescence (A.) and with the inflorescence height (B.). Relative female fitness was calculated based on the number of seeds produced by individual ramets. (C.) The proportion of seeds produced relative to the maximum potential seeds set in individual whorls within inflorescences of *Salvia verticillata* increased with the vertical position of individual whorls. Within each inflorescence, the whorl closest to the ground was numbered as 1 and increasing numbers refer to successive whorls higher above ground. Part of the variation around the fitted line was explained by differences in seed set between individual ramets (included in the fitted GLMM model, but not displayed in the plot).