RESEARCH PAPER

Foraging ecology of a local wild bee community in an abandoned Satoyama system in Kanazawa, Central Japan

Ramadhani Eka PUTRA[1] and Koji NAKAMURA[1,2]

1 Graduate School of Natural Science and Technology, Kanazawa University, Kanazawa, Japan
2 Institute of Nature and Environmental Technology, Kanazawa University, Kanazawa, Japan

Correspondence
Ramadhani Eka Putra, Graduate School of
Natural Science and Technology, Kanazawa
University, Kanazawa, Ishikawa 920-1192,
Japan. Email: ramadhaniputra@yahoo.com

Abstract

Satoyama is a traditional land management system in Japan that emphasizes the importance of a harmonious relationship between humans and their environment. It has been in a state of abandonment and destruction since the late 1960s. In 2000, the Japanese government initiated a new environment policy encouraging the use of Satoyama in biodiversity reservation areas. Before the initiation of active restoration works, an assessment of the potential of the Satoyama system is needed. To assess this potential, a study that focused on the foraging ecology of wild bees in a small abandoned Satoyama terraced paddy was carried out from June to October 2003. A total of 372 foraging bees belonging to 35 species in nine families was collected: two species of social bee (*Apis cerana* and *Bombus diversus*) and two of solitary bee (*Lasioglossum japonicum* and *Lasioglossum ohei*) dominated. The foraging activities of wild bees were highly influenced by the requirement of food for the colony and the active time of solitary bees. In the study, most wild bees showed a strong preference for abundant flowering plant species that produced a large number of flowers (*Achyranthes japonica* and *Polygonum thunbergii*). The results showed that an abandoned Satoyama system was an agricultural system that benefited pollinating bees. Careful and planned restoration practices to increase the diversity of foraging resources, microenvironment diversity and potential nesting areas for wild bees are needed to improve the ability of the Satoyama system to support more diverse and abundant wild bee populations.

Key words: flowering plant, pollination, Satoyama, wild bee.

Introduction

The intensification of agricultural practices coupled with habitat fragmentation are believed to be factors that have reduced the ability of agricultural landscapes to maintain high biological diversity (Saunders *et al*. 1991; Robinson & Sutherland 2002). Loss of biological diversity has detrimental consequences for ecosystems function and interaction between organisms (Schläpfer & Schmid 1999; Loreau *et al*. 2002; Kremen 2005; Schläpfer *et al*. 2005), which in an advanced state negatively affects important plant–animal interactions (Kremen 2005). To counter this, there have been attempts to create an environmentally friendly system that benefits biological

diversity and agriculture, the ecosystem service provided by them, that is, the Arable Stewardship Pilot Scheme (ASPS) in the UK (Pywell *et al*. 2005) and the Ecological Compensation Area in Switzerland (Albrecht *et al*. 2007).

Japan experienced a rapid loss of biodiversity since 1970, because of changes in agricultural systems and industrialization (Ministry of Environment 2006). To reduce and prevent loss of biodiversity, the Japanese government implemented a series of programs, with the Satoyama system as one of the main programs. Satoyama is a complete traditional rural ecosystem management system that covers not only agricultural areas but also forests, lakes and rivers connected with humans. All of these areas provide different habitats

that allow more plants and animals with different habitat requirements to co-exist (Kato 2001; Kobori & Primack 2003; Takeuchi *et al*. 2003). However, most remaining Satoyama areas have been in a state of abandonment or destruction due to lack of management and city expansion. In Satoyama areas, characterized by their small size (Tabata 1997; Kato 2001), these conditions have led to altered habitat mosaics that affect the flora and fauna, and interactions between them.

We chose to study, as a plant–animal interaction, the pollination relationship between flowering plants and foraging insects. Pollination by animals is ubiquitous in terrestrial habitats, involving approximately 67% of flowering plant species (Kearns & Inouye 1997) and a high diversity of insect species; this may act as a good bio-indicator of habitat change (Forup *et al*. 2007). Concern over the loss of pollinator diversity due to intensive agriculture (Rathcke & Jules 1993; Steffan-Dewenter & Tscharnke 1999) and the related ecological and economic consequences has been recently increasing (Allen-Wardell *et al*. 1998; Cane & Tepedino 2001; Kevan & Philips 2001; Biesmeijer *et al*. 2006).

In the present study, we selected wild bees as study subjects as they are considered the most important pollinators for many flowering plant species in various ecological regions (Bawa 1990; Michener 2000), and their communities can readily change due to changes in the plant community and habitat (Michener 2000). We aimed to investigate the potential of the abandoned Satoyama system as a conservation area for wild bees through observation of their foraging activities and interactions with local flowering plants biodiversity and impaired ecosystem service. The results are discussed in the context of (i) diversity of wild bees, (ii) foraging activities of wild bees and (iii) the interactions between flowering plants and wild bees.

Materials and methods

Study site

The study was carried in a small valley (0.5 ha, called Kitadan Valley) inside a Satoyama area (74 ha, 60–150 m altitude, 5 km south-east of central Kanazawa, Ishikawa) within Kanazawa University's Kakuma Campus (N36°32′ E136°42′) (Fig. 1). In Kanazawa, the average annual temperature is 14.8°C, with a monthly range from 3.5°C (January) to 26.8°C (August), and an annual rainfall of 2545 mm (for 30 years, 1977–2006: Japan Meteorological Agency 2007) (Fig. 1). Kakuma forest consists mainly of deciduous broad-leaved trees, dominated by two oak species (*Quercus serrata* and *Quercus variabilis*), patches of plantations of Japanese cedar (*Cryptomeria japonica*) and moso bamboo (*Phyllostachys* sp.). When local people

owned the forests in Kakuma, they managed them as Satoyama forests and used Kitadan Valley as terraced paddies. The forests and terraced paddies have been abandoned since the land was sold to Kanazawa University in the mid-1980s.

Census route

We carried out a census of the wild bee community over the season, following an adaptation of Pollard's method of butterfly surveying (Pollard 1977). A 200 m routine census route was established along the margin of the valley; it was comprised of footpaths previously used by farmers until 1986. The route was split into 40 segments, each 5 m, of which 37 were used in this study.

Flowering plants and bee census

The census was carried out once or twice a week from June to November on non-rainy days when the ambient temperature was 15°C or more. All observations were carried out between 07.00 and 15.00 hours, depending on the time of sunrise and sunset. All plants, except two orders, Graminales and Cyperales (Monocotyledoneae), which flowered during the census period, were identified into species following Yasaka (1989) and Chikara (1996). At the same time, the total number of flowers that opened at a particular time (FN) was counted directly for plants that produced a single flower. As for plants that produced inflorescence flowers, FN was counted as:

$$FN = AF \times I$$

where AF is the average number of flowers per inflorescence obtained from 10 samples or less and I is the number of inflorescences per plant.

The total number of opened flowers (FNO) that opened during the study period was derived by plotting FN as the y axis and sampling time on the x axis. FNO was then estimated as follows:

$$FNO = S/FL$$

where S is the area enclosed by the seasonal curve of FN and the x axis and FL is the average flower longevity, which was derived by marking 5–10 unopened flowers using small threads with different colors for different dates and following their daily changes until the withering of stamen and/or pistil.

While checking the plants, all bees that were found visiting flowers were collected with an insect net and were kept in separate vials, taken to the laboratory, and identified there or sent to specialists for identification to species level. Thus, the links between flowering plants and flower visiting bees were recorded at the species level.
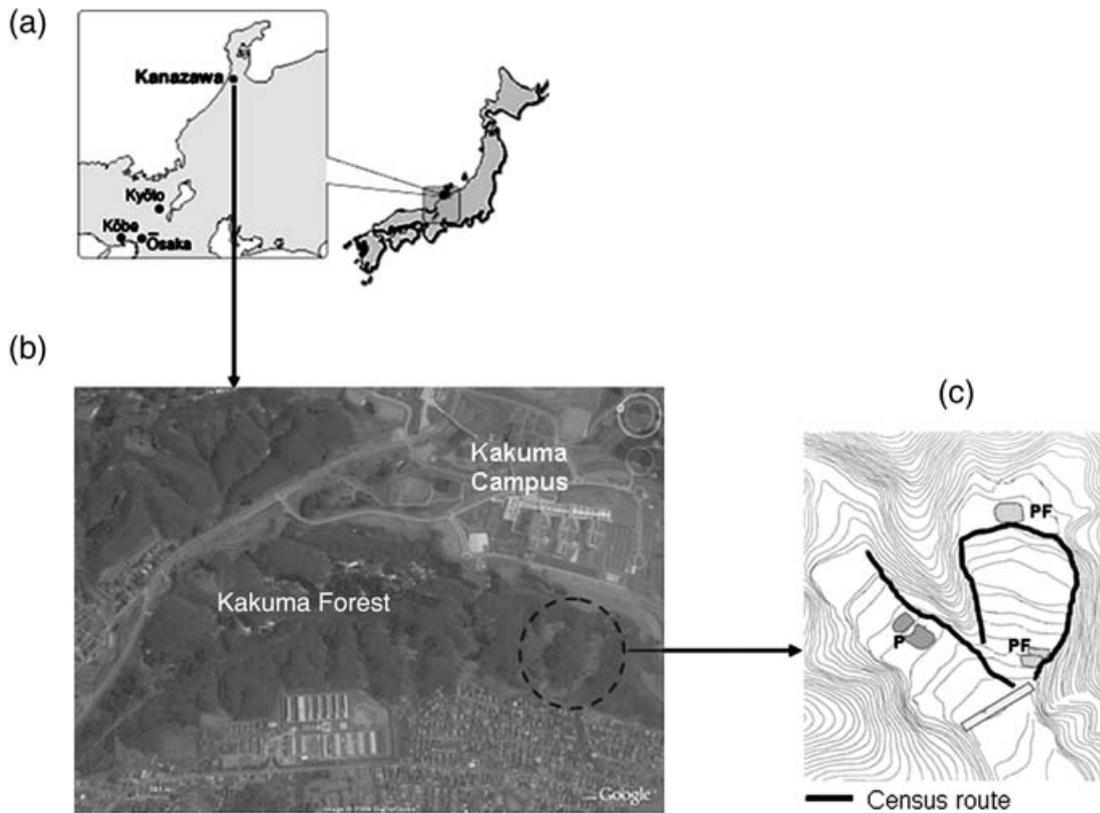
Figure 1 Map showing the location of (a) Kanazawa City, Ishikawa Prefecture, Japan and (b) Kitadan Valley in the Kakuma forest (approximately 60 ha, shown within the bold line). (c) An enlarged map of Kitadan Valley, with the census route (bold line) and locations of two ponds (P) dug up in 2002 and paddies (PF) that were restored in 2002 and 2003.

Wild bee population and diversity

We applied Simpson's indexes of diversity and species evenness to measure the potential of this abandoned Satoyama area to hold and maintain a high diversity of wild bees. Simpson's Index of Diversity (D) was calculated as

$$D = \frac{\sum_{i=1}^{S} n_i(n_i - 1)}{N(N - 1)}$$

with $0 < D < 1$, where the lower the value indicates the higher the diversity. For flowering plants, S is the number of species, while N is the total number of bees, and n_i is number of individuals of insect species i.

The stability of wild bee assemblages was measured by the Species Evenness Index (E), calculated as

$$E = \frac{H'}{H'_{max}}$$

where H' is the Shannon Diversity Index and H'_{max} is the maximum value of H',

$$H_{max} = -\sum_{i=1}^{S} \frac{1}{S} \ln \frac{1}{S} = \ln S.$$

S is the total number of species in the assemblage and $0 < E < 1$, where the higher the value indicates the higher the variation.

Results and discussion

Wild bee assemblage

We collected a total of 372 wild bee individuals from nine families and 35 species. The total number of species of wild bees we collected was similar to other results from biodiversity friendly agriculture areas, such as an organic farm in Germany (37 bee species in average study site size 400–500 km^2; Holzschuh et al. 2007) and an old field in Germany (36 bee species in average study site size 250–3000 m^2; Steffan-Dewenter et al. 2002), but it was lower than that in much larger ecological compensation areas in Switzerland (49 species in average study site size more than 0.05 ha; Knop et al. 2006). Of all insect families, the Halictidae and Apidae were the most dominant families: they accounted for 45.70 and 36.56%, respectively (82.26% combined), of the total number of collected wild bees. The dominance of the Halictidae has also been reported from other regions in Japan with a history of human disturbance, such

as Ibaraki (Hisamatsu & Yamane 2006), Sapporo (Sakagami & Fukuda 1973), Wakayama (Matsumura *et al*. 1974) and Kagoshima (Ikudome 1992): this shows that the Halictidae might characterize flowering plant–insect interactions in areas of human disturbance in Japan. However, we did not find clear dominance in terms of average abundance of each bee species, although it was slightly higher in the Apidae and Halictidae (one-way ANOVA: $F_{8,26} = 0.595$, $P = 0.773$).

In terms of species richness, the Halictidae and Apidae only accounted for 31.4 and 20.0%, respectively (51.4% combined), of the total wild bee species. Of the 35 species collected, there were four common ones (each being more than 10% of the total number of collected bees): *Bombus diversus* (Apidae, 17.7%), *Lasioglossum japonicum* (Halictidae, 16.7%), *Lasioglossum ohei* (Halictidae, 15.9%) and *Apis cerana* (Apidae, 11.8%).

The Simpson Diversity Index showed a high wild bee diversity in this abandoned Satoyama system ($D = 0.894$). High species diversity also showed at the family level, with the highest diversity recorded in the Megachilidae (and lowest in the Eumenidae). Species evenness in wild bees in our study area was quite low ($E = 0.263$), caused by the uneven number of individuals of each species. This situation can be easily observed in the Halictidae and Apidae, two families with the lowest species evenness. The Halictidae were largely dominated by *L. japonicum* and *L. ohei* (71.2% of the total Halictidae), while the Apidae were dominated by *B. diversus* and *A. cerana* (80.9% of the total Apidae) (Table 1).

Foraging activity

Foraging activity levels over the season closely followed resource availability (total number of flowers) (Fig. 2). There were three peaks found in the seasonality pattern of wild bees: early summer, late summer and mid autumn. However, only the late summer and autumn peaks were significantly greater than foraging levels over the rest of the season (one-way ANOVA: $F_{5,27} = 3.299$, $P = 0.019$).

We found that foraging activity was more influenced by the richness of flowering plant species ($r = 0.501$, $P = 0.003$) than by the total flower numbers ($r = 0.242$, $P = 0.175$). This finding is quite interesting because other studies have found that bees' foraging activity is highly correlated with the total number of flowers produced (Ginsberg 1983).

There were significant differences in seasonal foraging times between bee families ($\chi^2 = 472.26$, d.f. $= 256$, $P < 0.001$). In general, we found that there were three types of seasonality pattern of wild bees in our study area: (i) multiple peaks in summer and autumn for the Anthophoridae and Colletidae; (ii) low numbers in summer and a peak in autumn for the Apidae, Scollidae and Vespidae; and (iii) a peak period in summer and low numbers in autumn for the Halictidae, Eumenidae and Megachilidae (Fig. 2).

Table 1 Flower visiting wild bee species in Kitadan Valley, Kanazawa, Japan in 2003

Family	Species	No. individuals
Andrenidae	*Andrena brassicae*	1
	Andrena opacifovea	2
Anthophoridae	*Ceratina flavipes*	6
	Ceratina iwatai	8
	Ceratina japonica	8
	Xylocopa appendiculata	14
Apidae	*Amegilla florea florea*	1
	Apis cerana japonica	44
	Apis mellifera	12
	Bombus diversus	66
	Bombus hypocrita	4
	Bombus ignitus	8
	Eucera nipponensis	1
Colletidae	*Hylaeus floralis*	3
Eumenidae	*Eumenes micado*	6
	Stenodynerus chinensis	2
	Eumenes rubronotatus	1
Halictidae	*Lasioglossum apristum*	1
	Lasioglossum taeniolellum	1
	Lasioglossum japonicum	62
	Lasioglossum kansuense	1
	Lasioglossum kiautschouense	3
	Lasioglossum mutilum	21
	Lasioglossum nipponicola	1
	Lasioglossum occidens	17
	Lasioglossum ohei	59
	Lasioglossum pallilomum	3
	Lasioglossum proximatum	1
	Coelioxys yanonis	1
Megachilidae	*Megachile tsurugensis*	1
	Megachile humilis	2
	Campsomeris grossa	2
Scolliidae	*Campsomeris prismatica*	2
	Megacampsomeris prismatica	6
Vespidae	*Polistes japonicus*	1
Total		372

Common bee species also showed discrete seasonality patterns. First, *A. cerana* had a peak period and found forage heavily on two autumn species, *Impatiens textori* and *Polygonum thunbergii*, which grow in a large area and produce large numbers of flowers, thus providing valuable nectar and pollen resources. We conclude that *A. cerana* foragers were coming from colonies in surrounding secondary forest, as we did not find any *A. cerana* colonies in the study area, and there was no record of apiculture in surrounding areas. This finding showed that an unmanaged Satoyama area could provide an alternative foraging area for social insects, especially in autumn when most flowering plant in forests are already past their flowering time (R.E. Putra, pers. obs., 2003). Second, we found that *B. diversus* had two population peaks – in mid summer and late autumn – with differences
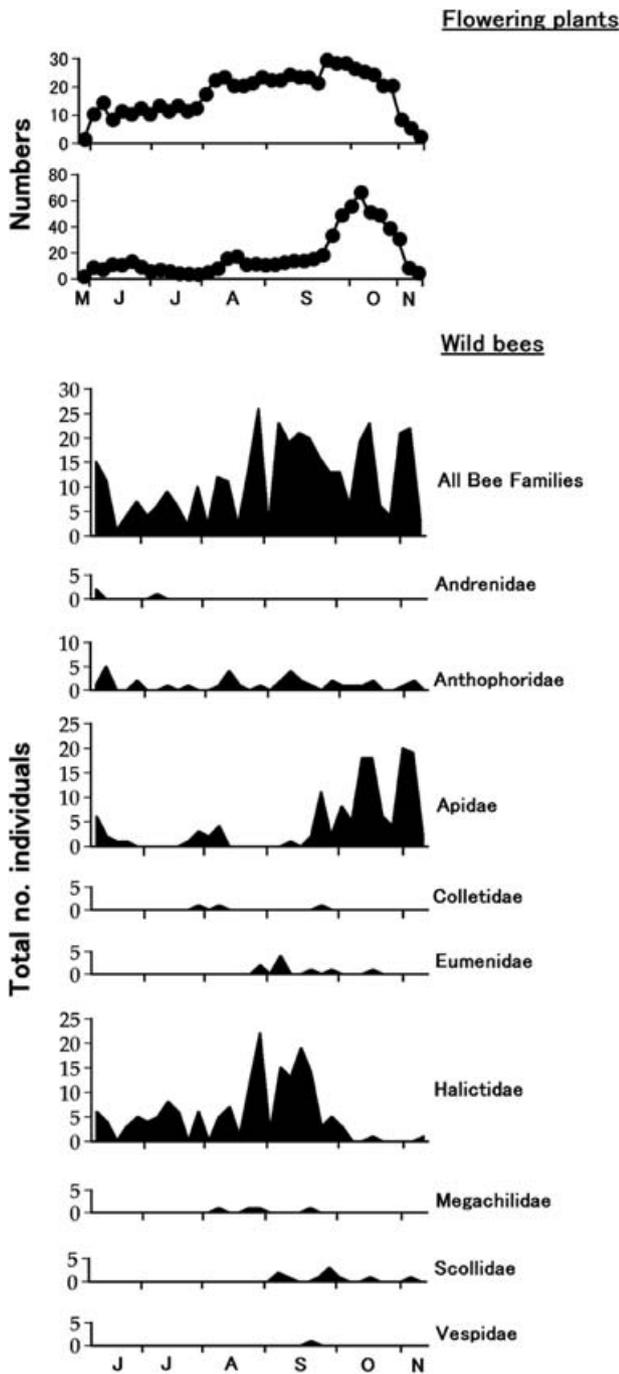
Figure 2 Seasonal changes in the total numbers of flowers (in thousands) (top), total numbers of flowering species (second from top), and wild bee individuals of different families in Kitadan Valley in 2003.

in the proportion of both populations. Spring and summer populations mostly consisted of young queens or workers, while more drones were found in autumn populations, which is due to the character of this social bee. Unlike honey bees, bumblebee colonies do not overwinter, thus new queens are

always produced in early spring while drones are mostly produced in autumn for reproduction purposes. Third, both *L. japonicum* and *L. ohei* had similar seasonality peak periods in mid summer, as expected for species of the same genus. Both of these highly similar bee species co-existed in relatively small valleys such as Kitadan Valley by having different active times (*L. ohei* in summer and *L. japonicum* in autumn; Fig. 3) and foraging plant species (Fig. 4).

Relationship between flowering plants and wild bees

A total number of 31 flowering plant species of 21 families (48.44% of total plants that produced flowers) was visited by wild bees. *P. thunbergii* was the most visited plant species, followed by *Achyranthes japonica*. Both of these species were visited by most wild bee individuals (40% of total) and species (15 and 14 species of 35 species, respectively) (Fig. 4) (R. E. Putra, unpubl. data, 2003). These species covered most of Kitadan Valley at different times of peak periods of insect populations (*A. japonica* produced flowers from mid-August to end-September, while *P. thunbergii* did so from end-September to end-October), which made these species preferred by many solitary bee species that have limited flight activity periods (Michener 2000) and by social insects that need a continuous supply of nectar and pollen.

Most of the visited flowering plant species belong to the Asteraceae (five species), Polygonaceae and Rosaceae (both with three species), and Caprifoliaceae and Umbelliferae (both with two species); other families are represented by only one species. Similar results showing strong preference of bees for Asteraceae were also reported by Hisamatsu and Yamane (2006).

Lasioglossum japonicum visited more flower species than other insects, followed by *L. ohei*, *Lasioglossum mutilum*, *B. diversus* and *Xylocopa appendiculata* (Fig. 4). Detailed observation revealed there was no significant difference in the number of specialized insect species (15 species) and oligolectic species (20 species).

We found that on average the Halictidae visited more diverse flowering plant species than other families (27 plant species visited), followed by the Anthophoridae (13 species) and Apidae (nine species). The Andrenidae and Megachilidae showed highly specialized foraging resources compared with other families. The three most abundant families, the Anthophoridae, Apidae and Halictidae, shared foraging resources with all families (Fig. 5).

Implications for future agro-environment schemes

The present study showed that the abandoned Satoyama system has great potential to provide an improved habitat for foraging bees. The limited number of flowering plant species
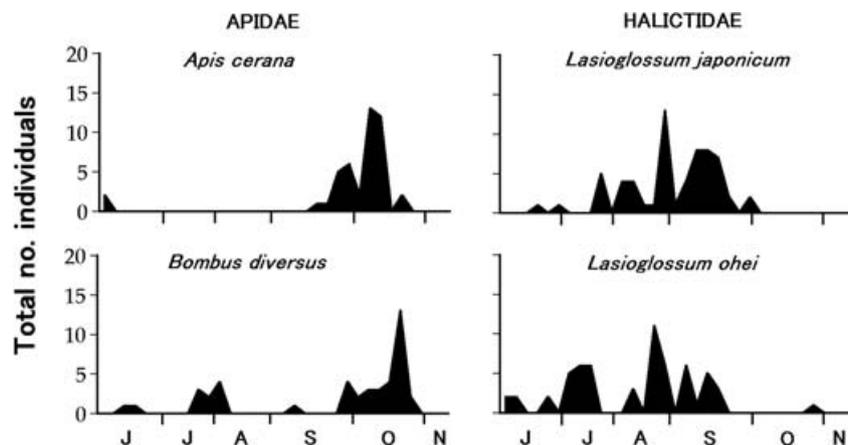
Figure 3 Seasonal changes in the number of individuals of major wild bee species in Kitadan Valley.
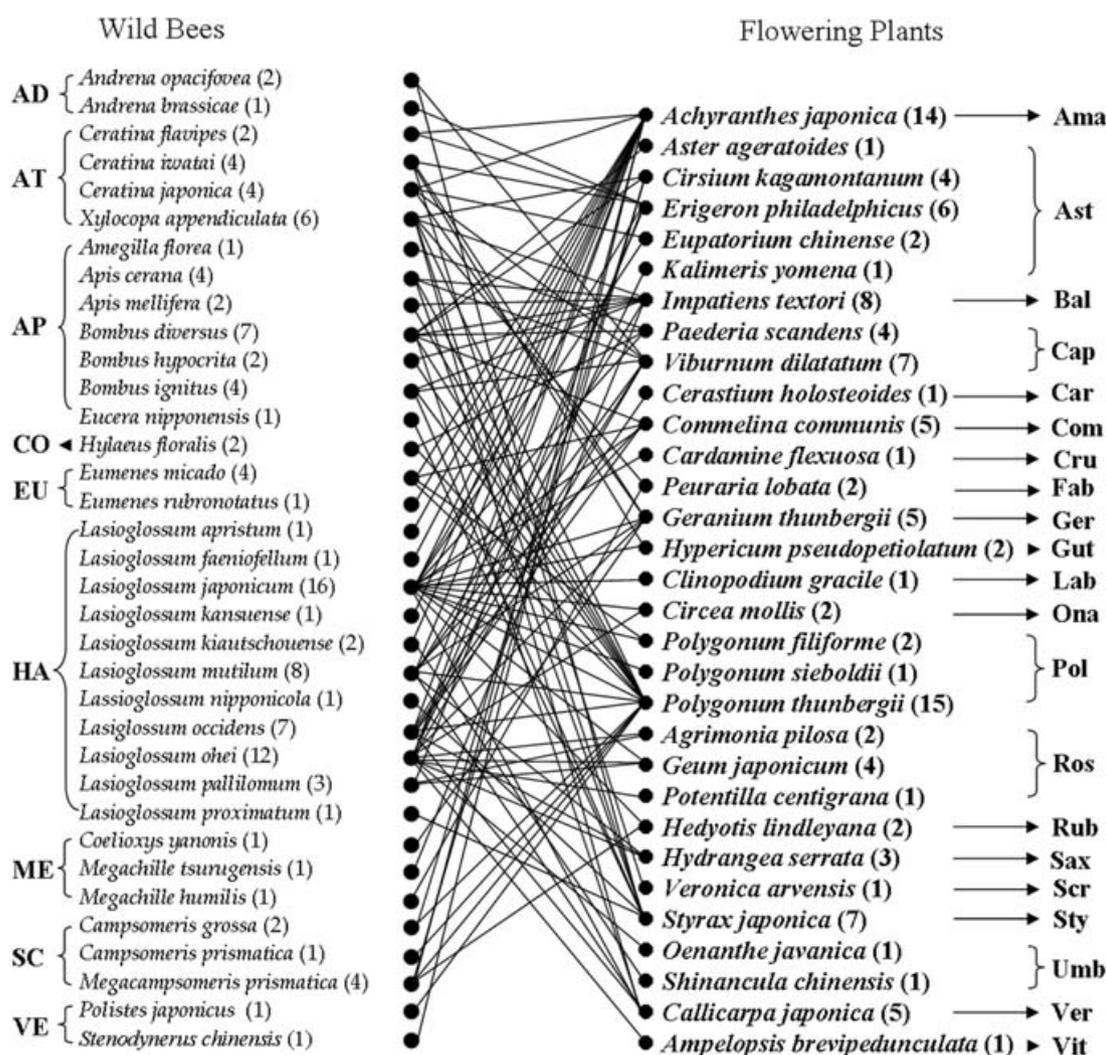
Figure 4 Interaction links between wild bee species and flowering plant species in Kitadan Valley in 2003. Numerals in parentheses are the total number of links for each flowering plant and flower-visiting insect species. Letters outside brackets are as follows. (i) Wild bee family: AD, Andrenidae; AT, Anthophoridae; AP, Apidae; CO, Colletidae; EU, Eumenidae; HA, Halictidae; ME, Megachilidae; SC, Scollidae; VE, Vespidae. (ii) Flowering plant family: Ama, Amaranthaceae; Ast, Asteraceae; Bal, Balsaminaceae; Cap, Caprifoliaceae; Car, Caryophyllaceae; Com, Commelinaceae; Cru, Cruciferae; Fab, Fabaceae; Ger, Geraniaceae; Gut, Guttiferae; Lab, Labiatae; Ona, Onagraceae; Pol, Polygonaceae; Ros, Rosaceae; Rub, Rubiaceae; Sax, Saxifragaceae; Scr, Scrophulariaceae; Sty, Styracaceae; Umb, Umbelliferae; Ver, Vervenaceae; Vit, Vitaceae.

	Andrenidae	Anthophoridae	Apidae	Colletidae	Eumenidae	Halictidae	Megachilidae	Scollidae	Vespidae
Andrenidae	(3)								
Anthophoridae	3/10	(13)							
Apidae	2/10	6/10	(9)						
Colletidae	5	1/13	2/7	(2)					
Eumenidae	7	2/13	4/9	1/4	(4)				
Halictidae	2/27	10/20	7/22	1/26	23	(27)			
Megachilidae	6	3/10	1/10	5	7	2/26	(3)		
Scollidae	7	11	9	1/4	2/4	3/25	7	(4)	
Vespidae	4	1/12	1/8	1	1/3	1/26	4	1/3	(1)

Figure 5 Diagram showing the overlap in the visited flowering plant species by wild bees of two different families in Kitadan Valley in 2003. Numerals in parentheses are the total number of flowering plant species visited by only one family. Numerals in gray and open parts in the circles are the total number of flowering plant species visited by the two families and by only one family, respectively.

might be the limiting factor for this system to hold more bee species, as shown by the high number of shared visited flowering plant species and low community stability. Increased numbers of possible forage resources or increased flower production of attractive but less disturbed species will be a necessity. Restoration and proper land management in a Satoyama area allow less competitive flowering plant species to grow and/or increase distribution of established flowering plants. This condition creates field margins containing great floral diversity (Marshall 1989; Wilson & Aebischer 1995; Kell *et al.* 2001), which provides foraging resources (Marshall 1989; Pywell *et al.* 2005) and nesting areas for solitary bee species (Hisamatsu & Yamane 2006), which maintain a continuous wild bee availability for crop pollination. Diverse flowering plant species might provide other benefits, such as (i) attracting more and varied pollinating insects (other than bees) to the vicinity of crops (Carreck & Williams 2002); (ii) attracting predatory insects such as adult syrphids (which were abundant in our Satoyama area [70% of total flower visiting insects; R.E. Putra and K. Nakamura, unpubl. data, 2003]) for aphid biological control (Hickman & Wratten 1996); (iii) providing nest material and food for game and farmland birds (Scott 1996); and (iv) the plants might have value as green manure used as either a traditional organic fertilizer or a cover crop.

Acknowledgments

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