



Extrapolating from Honeybees to Bumblebees in Pesticide Risk Assessment

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Abstract. Bumblebees are important pollinators of many crops and wild flowers and there are both conservation and economic reasons for taking action to assess the impact of pesticides on bumblebees. Pesticide risk assessments for honeybees are based on hazard ratios which rely on application rates and toxicity data and are unlikely to be appropriate for bumblebees. Bumblebees are active at different times and on different crop species and are, therefore, likely to have different exposure profiles. Unlike honeybees, deaths of bumblebees due to pesticides are unlikely to be reported, since the bees are not kept domestically and will die in small numbers. This paper highlights the differences in the potential risk posed by pesticides to bumblebees from that of honeybees. This is based on their exposure through use of crops and flowering weeds and on available data on toxicity of pesticides. This information is also intended as a source document for information on the foraging behavior and phenology of bumblebees for use in risk assessment for pesticides.

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Recently, there has been concern about the potential impact of pesticides on both long-tongued and short-tongued species of bumblebee (*Bombus*). There has been a severe decline in the abundance of bumblebees in the last thirty years, particularly in southern Britain, and it is possible that this is due in part to the use of certain pesticides. Bumblebees are important pollinators of many crops and wild flowers and, therefore, there are both conservation and economic reasons for taking action to assess the impact of pesticides on bumblebees.

Pesticide risk assessments for honeybees are based on hazard ratios which rely on application rates and toxicity data and are unlikely to be appropriate for bumblebees. Bumblebees are active at different times and on different crop

species and are, therefore, likely to have different exposure profiles. Unlike honeybees, deaths of bumblebees due to pesticides are unlikely to be reported, since the bees are not kept domestically and will die in small numbers.

This paper highlights the differences in the potential risk posed by pesticides to bumblebees from that of honeybees. This is based on their exposure through use of crops and flowering weeds and on available data on toxicity of pesticides. This information is also intended as a source document for information on the foraging behaviour and phenology of bumblebees for use in risk assessment for pesticides.

1. The use of crops by bumblebees in the UK

A review of literature was carried out to collate currently available information on the use of crop

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plants by bumblebees. All insect-pollinated crops known to be grown in the UK were included and cereal crops were considered as a single group. Table 1 below summarises British insect-pollinated crop species known to be used by bumblebees.

Honeybees regularly collect honeydew from aphid-infested cereal crops. No records of bumblebees collecting honeydew from aphids on cereal crops were found. However, *Bombus lucorum* and other species have been reported to collect honeydew, usually on trees, in Russia, Finland, USA and the UK (Brian, 1957; Bishop, 1994; Teras, 1985). Bumblebees have also been observed to collect pollen from grasses and other wind-pollinated plants and so they may also do so from cereal crops. Therefore it is likely that bumblebees use cereal crops to some extent.

Bumblebees were recorded as frequent on most of the crop species listed. There were only nine crop species known to be visited by bumblebees to which they are recorded as occasional visitors. This probably reflects that fact that bumblebees are often at low population densities, can have small colonies and are also likely to be displaced in many of these experiments by domestic honeybees, with hives kept close to the crop in question. It seems reasonable to suggest that bumblebees actually use the majority of our insect-pollinated crop plants to a large extent (taking their often low and very variable population densities into account).

2. Use of wild flowers by bumblebees

Bumblebees will also be exposed to pesticides if they are foraging on wild flowers that grow under crops or in field margins. Wild flowers associated with crops are divided into two groups—weeds (mostly annuals) which grow in ploughed fields with crops; and field margin species (mostly perennials) which grow in unploughed field boundaries and hedgerows. Bumblebees using the former group, arable weeds, are likely to be more exposed to pesticides than bumblebees foraging on field margins, because farmers try to avoid spraying the field margins and hedgerows with pesticides.

2.1. Arable weeds

The arable weed flora consists of plants growing underneath crops and often up to the field edge. Due to the annual disturbance of ploughing, perennial plants are unable to establish here, with the exception of those which can regenerate from broken root fragments such as field bindweed (*Convolvulus arvensis*). The flora is therefore made up predominantly of annual species, most of which are not favoured by bumblebees. However, any bees foraging on these species will be directly exposed to pesticide sprays.

2.1.1. Arable weed survey methods. Thirteen papers were found from the last ten years which list common arable weed species (Acker and Lutman, 1995; Barr *et al.*, 1996; Clarke *et al.*, 1993; Firbank, 1990; Glasgow *et al.*, 1976; Gwynne and Murray, 1985; Knott *et al.*, 1995; Lutman *et al.*, 1995; Marshall, 1989; Mortimer, 1990; Olgivy *et al.*, 1993; Pallutt, 1993; Watkinson and Bo, 1993). Species lists from each of these papers were compiled and the most frequently mentioned species were interpreted as the most common, although there are likely to be other species, less commonly found, that are also used by bumblebees.

All the papers except one (Firbank, 1990) dealt primarily with weeds under broadleaved crops. This is because broad-leaved weeds are a much greater proportion of the weed flora than grasses, under broad-leaved crops, due to the use of graminicides. Broadleaf crops surveyed in the papers included sugar beet, oilseed rape, field bean, potatoes, carrots, peas and linseed. Firbank (1990) dealt with weeds under cereal crops and mentioned no species that were not included in several of the other papers concerned with the broadleaf weed flora, indicating that there is little difference in broadleaf weed flora under broadleaf and cereal crops.

The results of the literature survey of bumblebee use of arable weeds are given in Table 2. Weed species are presented in rank order (column 2), according to how many of the 13 reviewed papers they appeared in. These weed species are so common that they are likely to be found under any crop.

Table 1. Crop species known to be used by *Bombus* spp.

Family	Species	Common name	Flowering season	Visits by <i>Bombus</i> ^b	References
Alliaceae	<i>Allium ampeloprasum</i> ^a	Leek	July–Aug	+	Macgregor, 1976
	<i>Allium cepa</i> ^a	Onion	June–Sept	f*	Free, 1993; Williams and Free, 1974
Boraginaceae	<i>Allium schoenoprasum</i>	Chives	June–Aug	+	Free, 1993; Fussell and Corbet, 1992
	<i>Borago officinalis</i>	Borage	May–Sept	f*	Osborne, 1994
Compositae	<i>Helianthus annuus</i>	Sunflower	Aug–Oct	f*	Free, 1993; Banaszak, 1984
	<i>Lactuca sativa</i> ^a	Lettuce	July–Aug	o	Free, 1993
Cruciferae	<i>Brassica napus / campestris</i>	Oilseed rape	Apr–Aug	f*	Free, 1993; Williams, 1985; Delbrassine and Rasmont, 1988
	<i>Brassica oleracea</i> ^a	Cabbage, etc.	May–Sept	+	Free, 1993; Doorn, 1993
Cucurbitaceae	<i>Raphanus sativus</i> ^a	Radish	May–Sept	f*	Free, 1993; Patten <i>et al.</i> , 1993
	<i>Sinapis alba</i>	White mustard	April–Oct	+	Free, 1993
Ericaceae	<i>Cucurbita</i> sp.	Pumpkins, squashes		+	Free, 1993; Hurd, 1964
	<i>Vaccinium</i> sp.	Blueberry/bilberry	April–July	f	McGregor, 1976; Free, 1993
Grossulariaceae	<i>Vaccinium macrocarpon</i>	Cranberry	June–Aug	f*	Patten <i>et al.</i> , 1993; Reader, 1977; McGregor, 1976
	<i>Ribes nigrum</i>	Blackcurrant	April–May	f*	Free, 1968b; Free, 1993
Labiatae	<i>Ribes rubrum</i>	Redcurrant	April–May	o	Free, 1993; Wilson, 1929
	<i>Ribes uva-crispa</i>	Gooseberry	March–May	f*	Free, 1993; Wilson, 1929
Leguminosae	<i>Lavandula latifolia</i>	Lavender	July–Sept	o*	Fussell and Corbet, 1992; Herrera, 1990
	<i>Ocimum</i> sp. ^a	Basil	June–Sept	f	Voloshin, 1995
Leguminosae	<i>Origanum</i> sp. ^a	Marjoram	July–Sept	+	Williams <i>et al.</i> , 1993; Fussell and Corbet, 1992
	<i>Coronilla varia</i>	Crown vetch	June–Aug	o	Free, 1993
Leguminosae	<i>Lotus corniculatus</i>	Birdsfoot	May–Sept	f*	Fussell and Corbet, 1992; Williams, 1997; Patten <i>et al.</i> , 1993
	<i>Lupinus angustifolius</i>	Trefoil	May–July	o	Williams <i>et al.</i> , 1990; Fussell and Corbet, 1992; Williams, 1987
Leguminosae	<i>L. albus</i>	Lupins	June–Oct	f*	Holm, 1966; Bohart, 1957; Free, 1993
	<i>Medicago sativa</i>	Lucerne/alfalfa	June–Oct	f*	Fussell and Corbet, 1992
Leguminosae	<i>Melilotus alba / officinalis</i>	Sweet clover	June–Oct	+	Richards and Edwards, 1988
	<i>Onobrychis viciifolia</i>	Sainfoin	June–Sept	f*	Free, 1968a; Kendall and Smith, 1976
Leguminosae	<i>Phaseolus coccineus</i>	Runner bean	June–July	+	Bohart, 1960
	<i>Trifolium incarnatum</i>	Crimson clover	June–July	+	Teras, 1976; Macfarlane <i>et al.</i> , 1983, 1991; Gurr, 1975; Free, 1993
Leguminosae	<i>Trifolium pratense</i>	Red clover	May–Oct	f*	Free, 1993; Michaelson-Yates <i>et al.</i> , 1997; Fussell and Corbet, 1992
	<i>Trifolium repens</i>	White clover	May–Oct	f*	Free, 1993; Stoddard and Bond, 1987; Legeun <i>et al.</i> , 1993; Fussell <i>et al.</i> , 1991
Leguminosae	<i>Vicia faba</i>	Field/broad bean	June–July	f*	Fussell and Corbet, 1992
	<i>Vicia sativa</i>	Fodder vetch	Apr–Sept	+	Bohart, 1960; Free, 1993; Fussell and Corbet, 1992
Leguminosae	<i>Vicia villosa</i>	Hairy vetch	June–Nov	+	Wilson, 1929; Fussell and Corbet, 1992
	<i>Pisum sativum</i>	Peas		+	Free, 1993

Table 1. Crop species known to be used by *Bombus* spp.

Family	Species	Common name	Flowering season	Visits by <i>Bombus</i> ^b	References
Linaceae	<i>Linum usitatissimum</i>	Linseed/flax	June–Oct	o	Williams, 1988; Gubin, 1945
Rosaceae	<i>Fragaria x ananassa</i>	Strawberries	April–July	o*	Free, 1968b, 1993; Wilson, 1929; Nye and Andersen, 1974
	<i>Malus</i> sp.	Apples	March–May	o*	Free, 1993; Wilson, 1929; Kendall and Solomon, 1973; Mayer, 1983
	<i>Prunus</i> sp.	Cherries/plums	April–May	o*	Wilson, 1929; Walton, 1927; Bhalla <i>et al.</i> , 1983
	<i>Pyrus</i> sp.	Pears	April	f	Emmett, 1971
	<i>Rubus fruticosus</i>	Blackberry	May–Nov	f*	Fussell and Corbet, 1992; Wilson, 1929; Gyan and Woodell, 1987
Solanaceae	<i>Rubus idaeus</i>	Raspberry	May–Aug	f*	Willmer, 1994
	<i>Capsicum annuum</i>	Sweet pepper		f	Free, 1993; Griffiths and Roberts, 1996; Shipp <i>et al.</i> , 1994
	<i>Lycopersicon esculentum</i>	Tomato	May	f*	Free, 1993; Pincham <i>et al.</i> , 1978; Kevan <i>et al.</i> , 1993
	<i>Solanum tuberosum</i>	Potato		+	Free, 1993; Sanford and Hannemann, 1981; Batra, 1993

^a Denotes crops which do not produce flowers during commercial production. They will only be used by bumblebees when grown for seed.

^b Frequency of visits:

f = frequent: This indicates that bumblebees have been recorded, by at least one observer, to be frequent visitors. 'Frequent' is defined as > 0.1 bees/m². This threshold is arbitrary. It is often not comparable between different studies, due to variations in the densities of plants, flowers and other pollinators, and in the timing of fieldwork. However, the threshold, based on the findings of various studies, is felt to be useful in this context because it highlights those crops on which bumblebee populations might be seriously at risk from pesticides.

o = occasional: This indicates that no records have been found of bumblebees at > 0.1 bees/m², under any circumstances.

+ = unknown: This means that bumblebees have been recorded visiting the species, but no quantitative records of their density have been found.

* = known to be visited by long-tongued bumblebees species (*Bombus hortorum* and *B. pascuorum* in the UK).

Table 2. The use of common arable weeds by bumblebees

Species	Common name (frequency rank)	Flowering season	Number of studies recording bumblebee visits (total of 12)	Do bumblebees show a preference for this family or species?
<i>Stellaria media</i> ^a	Chickweed (1)	All year	1	No
<i>Veronica</i> sp. (mostly <i>V. persica</i>) ^a	Speedwells (2)	All year	2	Family—Scrophulariaceae—exhibits bee pollination syndrome. These flowers are blue, but they are small and almost actinomorphic, not typical of the family.
<i>Matricaria</i> / <i>Tripleurosperum</i> spp. (mostly <i>T. maritima</i>) ^a	Mayweeds (3)	April–Oct	3	Family—Compositae—contains some bee pollinated flowers, but these species, with tiny yellow disc florets, are not of that type.
<i>Capsella bursa-pastoris</i> ^a	Shepherd's purse (4)	All year	1	No
<i>Polygonum</i> sp. (mostly <i>P. aviculare</i>)	Knotgrass/reds hank, etc. (4)	June–Nov	2	No
<i>Sinapis arvensis</i> ^a	Charlock (4)	April–Oct	1	No
<i>Viola arvensis</i> ^a	Field pansy (4)	April–Nov	3	Yes. Family—Violaceae—typical of bee pollinated flowers.
<i>Galium aparine</i> ^a	Cleavers (4)	May–Sept	0	No
<i>Convolvulus arvensis</i>	Field bindweed (5)	June–Sept	7*	Yes. Large, nectar-rich trumpet shaped flowers. This species is perennial. Important to <i>B. lucorum</i> , <i>B. terrestris</i> and other short-tongued species.
<i>Lamium purpureum</i> / <i>plexicaule</i> ^a	Red/henbit deadnettle (5)	All year, March–Oct	9*	Yes. Family—Labiatae—is typical of bee pollinated flowers. Nectar-rich, zygomorphic, purple. Especially important to <i>B. Pascuorum</i> .
<i>Papaver rhoeas</i>	Common poppy (5)	June–Oct	2	Yes. Open flowered, pollen abundant species. Most likely to be used by <i>B. lucorum</i> .

^aWeed species that was amongst the top 10 broadleaf weeds found in cereal crops (Firbank, 1990).

This table lists the weed species that emerged as the most commonly found and gives information about the use of each of those species by bumblebees. References used in this review are given in the text. The plant species are ranked according to the number of papers reviewed in which they were listed as common weeds. Eleven studies were considered (Teras, 1985; Fussell and Corbet, 1992; Patten *et al.*, 1993; Fussell and Corbet, 1991; Walton, 1927; Prys-Jones, 1982; Saville, 1993; Barrow, 1983; Dramstad and Fry, 1995; Fussell and Corbet, 1993). Any species that has been recorded by at least one author to be 'important' to bumblebees is indicated (*) in the table.

Bumblebees have been recorded to forage on all but one of the ten species or groups of species identified as the most common arable weeds in the UK. Four of the weed species—field pansy (*Viola arvensis*), field bindweed (*Convolvulus arvensis*), red deadnettle/henbit (*Lamium* sp.), and common poppy (*Papaver rhoeas*)—exhibit features common to bumblebee pollinated flowers. Two of these—red deadnettles and field bindweed—are considered to be important to

certain types of bumblebee in the seasonal succession of forage plants.

Ellenberg (1988) lists red deadnettle and henbit (*Lamium purpureum* and *L. amplexicaule*) as characteristic species of 'summer crop weed communities,' which indicates that they are more likely to be found growing under crops that are spring planted, as opposed to under winter planted cereals. Field bindweed (*Convolvulus arvensis*), however, is not listed as characteristic of any

particular arable weed community, suggesting that it is ubiquitous.

2.2. *Field margin and hedgerow flowers*

The flora of field margins and hedgerows is much more variable than the arable weed flora. It can depend on land use, both current and historical, soil type, boundary feature and climate and it is also drawn from a far greater pool of species which are able to thrive in the field margin habitat (Barr *et al.*, 1996; Mountford *et al.*, 1994). Therefore, it was not possible to treat the survey of bumblebee use in the same way as for arable weeds. A short list of 'most common' species, apart from being very difficult to compile, would be unlikely to represent any given field margin, verge or hedge. Therefore, those plant species found in field margins that are known to be frequently¹ visited by bumblebees have been listed. Farmers with these species in their margins or hedgerows risk causing damage to bumblebees if they allow spray drift, or spray pesticides in the field margins or hedgerows.

Fussell and Corbet's (1992) national survey of flowers used by bumblebees was used as a basis for compiling a list of field margin and hedgerow flowers. Flowering plant species found in field margins and hedgerows were extracted from the lists for each colour group. These species are shown in Table 3 below, along with which bumblebee colour group(s) they are frequently used by. Woody species that make up hedges, such as hawthorn, have not been included in this list, because the flowers are less likely to be exposed to pesticides.

The studies of flowers visited by bumblebees used in the previous section (Acker and Lutman, 1995; Barr *et al.*, 1996; Clarke *et al.*, 1993; Firbank, 1990; Glasgow *et al.*, 1976; Gwynne and Murray, 1985; Knott *et al.*, 1995; Lutman *et al.*, 1995; Marshall, 1989; Mortimer, 1990; Olgivy *et al.*, 1993; Pallutt, 1993; Watkinson and Bo, 1993) have also been reviewed with respect to field margin species common in the UK. Plant species which have been suggested to be **important** to bumblebees by other authors are indicated (*). If they are species not mentioned in the Fussell and Corbet survey, they are also listed in the table.

2.2.1. *Results—field margin and hedgerow flowers of importance to bumblebees.* Thirty-one plant species are listed (Table 3), all of which are common in the field margin/hedgerow in at least some parts of the country (Stace, 1997). They are all perennial or biennial, with the exception of borage, and some species of vetch and geranium. All of them are considered **important** forage for bumblebees and are visited frequently by at least one of the colour groups. The only surprising inclusions in the table are angelica and hogweed, both of which are in family Umbelliferae and have relatively small, white flowers.

It must be pointed out that while these thirty-one species are used a lot by bumblebees, there are many other species that are also used by bumblebees.

One of the species in Table 3, *Lamium album*, white deadnettle, is of particular importance. It is an early flowering species and it is used extensively in the early Spring by foraging queens of long-tongued species (Fussell and Corbet, 1992; Prys-Jones, 1982).

3. **Bumblebee ecology and activity patterns**

There are 19 species of true bumblebee (*Bombus* sp.) present in the UK (for further information see Williams (1985), Prys-Jones and Corbet (1991)). Bumblebee diversity in Britain has declined in recent decades and only six species remain widespread and common: *Bombus lapidarius*, *B. lucorum*, *B. terrestris*, *B. pratorum*, *B. pascuorum* and *B. hortorum* (the first four are short-tongued species and the latter two long-tongued, see Table 4 for common names). These six species will be considered in detail in this section, along with two other species which are known to visit crops in the UK—*B. ruderarius* and *B. ruderatus*. However, it must be considered that all the bumblebee species have similar habits. As members of the same genus, they have similar physiological, morphological and behavioural characteristics. Because the length of their season exceeds that of most flowering plant species, they are almost all generalists in terms of forage plants.

Most species are likely to be found close to arable farmland, which accounts for approxi-

Table 3. Field margin/hedgerow flowers important to bumblebees

Flower species	Common name	Flowering season	Bumblebee colour groups/ species showing high preference for this species ^a
Species indicated by the national survey (Fussell and Corbet, 1992) to be important:			
<i>Borago officinalis</i>	Borage	May–Sept	2BWT
<i>Campanula</i> spp.	Bellflowers	June–Sept	BBRT
<i>Centaurea</i> spp.*	Knapweeds	June–Sept	2BWT; BBRT; BRT
<i>Cirsium / Carduus</i> spp.*	Thistles	June–Sept	BBRT; BRT
<i>Digitalis purpurea</i> *	Foxglove	June–Sept	3BWT
<i>Epilobium / Chamerion</i> spp.*	Willowherbs	June–Aug	2BWT
<i>Geranium</i> spp.	Cranesbills	June–Sept	BRT
<i>Lamium album</i> *	White deadnettle	March–Nov	Br; 3BWT
<i>Lonicera</i> spp.	Honeysuckle	June–Oct	3BWT
<i>Lotus corniculatus</i> *	Birdsfoot trefoil	May–Sept	BBRT
<i>Ranunculus</i> spp.	Buttercups	April–Oct	BBRT
<i>Rubus fruticosus</i> *	Bramble	May–Nov	2BWT
<i>Senecio jacobaea</i>	Ragwort	June–Nov	BRT
<i>Stachys</i> spp.*	Woundworts	April–Oct	Br; 3BWT
<i>Symphytum</i> spp.*	Comfrey	May–June	2BWT; BRT; Br
<i>Trifolium pratense</i> *	Red clover	May–Oct	Br; 3BWT
<i>Trifolium repens</i> *	White clover	May–Oct	BBRT
<i>Vicia</i> spp.*	Vetches	April–Sept	Br
Species considered important by other authors:			
<i>Angelica sylvestris</i> (Saville, 1993; Dramstad and Fry, 1995)	Angelica	July–Sept	
<i>Ballota nigra</i> (Fussell and Corbet, 1991; Saville, 1993)	Black horehound	June–Sept	
<i>Clinopodium vulgare</i> (Saville, 1993)	Wild basil	July–Sept	
<i>Dipsacus fullonum</i> (Saville, 1993)	Teasel	July–Sept	
<i>Galeopsis tetrahit</i> (Saville, 1993)	Hemp nettle	July–Sept	
<i>Heracleum sphondylium</i> (Fussell and Corbet, 1991)	Hogweed	April–Nov	<i>B. terrestris / lucorum</i> (Fussell and Corbet, 1993)
<i>Lamium galeobdolon</i> (Barrow, 1983)	Yellow archangel	May–June	
<i>Linaria vulgaris</i> (Saville, 1993)	Toadflax	June–Oct	
<i>Knautia arvensis</i> (Saville, 1993)	Field scabious	June–Oct	<i>B. pascuorum</i> (Brian, 1957)
<i>Solanum dulcamara</i> (Brian, 1957; Saville, 1993)	Bittersweet	May–Sept	
<i>Solidago virgaurea</i> (Saville, 1993)	Golden-rod	June–Sept	
<i>Taraxacum officinale</i> (Barrow, 1983)	Dandelion	April–June	
<i>Teucrium scorodonia</i> (Williams, 1985)	Wood sage	July–Sept	<i>B. terrestris, B. lapidarius</i> (Williams, 1985)

^a Colour groups: 2BWT = 2-banded white tails; 3BWT = 3-banded white tails; BBRT = black-bodied red tails; BRT = banded red tails; Br = browns.

Species in the table are presented in alphabetical, rather than rank order, because the latter is different for each colour group. Species in the first half of the table are all from the 'top ten' for the colour groups mentioned in Fussell and Corbet's list (1992). Species only mentioned in other surveys are shown in the second half of the table. Species considered important by at least one other author are indicated (*) (see text for references).

Table 4. Phenologies of eight bumblebee species^a

Species	Queen emergence	Emergence of first workers	Emergence of first males	Total season	Peak worker numbers and size ^a	Regional differences
<i>B. terrestris</i> : buff-tailed bumblebee	Late Feb–early Apr	Late Apr–end June	Mid-June–mid-July	End Feb–end Oct (long cycle)	End July 200–300	Whole cycle earlier in WL; much later in Kent colony over early in SW (by mid-Aug in 1980)
<i>B. lucorum</i> : common white-tailed bumblebee	Early Mar–mid-Apr	Early May–early July	Mid-June–start July	Early Mar–end Sept (long cycle)	Mid-July–Aug 200–300	First queens to emerge in SW; whole cycle later in Kent
<i>B. pratorum</i> : meadow bumblebee	Mid-Mar–mid-Apr	Mid–late April	Early May–end July	Mar–mid-Sept (short cycle) ^b	Early–mid June usually approx 30, sometimes up to 200	First queens to emerge in C1 Colony over in July in WL 2nd worker peak in Aug, C2 ^b
<i>B. ruderatus</i> : Small red-tailed bumblebee	Mid-Mar–late May	Late May–end June	Mid–late July	Mar–early Sept (short cycle)	Early July–late Aug ?	Last species to emerge in SW, but colony over in Aug
<i>B. lapidarius</i> : Large red-tailed bumblebee	Mid-Mar–start May	Mid-May–mid-June	Early June–early Aug	Mar–mid-Sept (medium cycle)	Mid June–Aug 200–300	Whole cycle later in Kent, worker peak Aug in C1, June in C2
<i>B. ruderatus</i> : Ruderal bumblebee	Early May	Late June	Early July	?	?	Only recorded in Kent
<i>B. pascuorum</i> : Common carder bee	Late Mar–mid-May	Early May–mid-June	Late June–mid July	Late-Mar–mid-Oct (long cycle)	Aug Less than 200	Whole cycle early in WL, late in Kent, length of time queens–first workers variable, longest in C1, but males emerging similar time at all sites
<i>B. hortorum</i> : garden bumblebee	End Mar–mid June	Early May–mid-July	End May–mid July	End Mar–mid-Oct (short cycle) ^b	Late May–late July 30–80	Whole cycle much later in Kent, early queen emergence in WL and S, season ends late July–early Sept in K, S and WL

The information in this table has been collected from several detailed studies (Prys-Jones, 1982; Saville, 1993; Williams, 1985; Goodwin, 1995; Barrow, 1983)—these were carried out in Cambridgeshire (C1 and C2), Kent (K), West London (WL), south Wales (SW) and north-west Scotland (S) respectively. Species are presented in approximate order of emergence in Spring, although this does not entirely agree between different studies. Dates given are the range across all of the studies for each species. Any notable discrepancies between the different studies are described in the final column, Regional Differences.

^aData from (Prys-Jones and Corbet, 1991; Alford, 1975)

^bSignifies evidence for bivoltinism—for example, where a short cycle species has been recorded late in the year, but not at all sites, or where a second peak in worker numbers has been recorded late in the season.

mately 20% of land cover across the UK (MAFF, 1997). Even *Bombus monticola*, which is considered a moorland species (Alford, 1975) has been shown to rely on arable field margin and verge flowers at certain times of year (Yalden, 1982).

3.1. Natural history

All bumblebee species form colonies which are small in comparison to honeybee colonies. A colony of several hundred workers is considered large in bumblebees (Prys-Jones and Corbet, 1991) compared to a full colony size of around 30,000 individuals, for honeybees (Seeley, 1985).

The life cycle of bumblebees in temperate regions differs from that of honeybees in that only the queens over-winter. The rest of the colony—workers and males—only survive for a single season. In Spring, mated queens emerge, feed and establish a new colony alone. They must collect pollen and nectar to feed their first batch of worker larvae, as well as feeding themselves. Often the queen works alone for more than a month, before her first workers appear.

New gynes (reproductive females) and males are produced in late summer to early autumn. Once emerged, males do not return to the nest. They forage for themselves, “patrol” for mates and usually spend the night on flower heads. At the end of the season, mated queens search for sites to hibernate underground. The rest of the colony dies.

Bumblebees, then, are much more vulnerable than honeybees, in that there is a month every year when the entire population depends upon the success of the queens in establishing colonies. This makes the colony particularly susceptible to pesticides applied early in the year. In addition, as they have smaller colonies, a single bumblebee worker is more important to the survival of the colony than a single honeybee worker.

3.2. Phenology

Phenology is the annual, or seasonal, pattern of activity, which is specific to each bumblebee species. It varies according to parameters such as colony cycle length and forage requirements, as well as external factors like climate. Prys-Jones (1982) and Goodwin (1995) both showed that the

timing of queens emerging from hibernation correlates with temperature—a maximum soil temperature of 6–9°C in the former study and air temperature of 11°C in the latter. In general, the bumblebee season runs from mid-March to mid-October, with a peak in numbers during the summer. Table 4 presents available information on the timing of the annual cycle, for the eight species of bumblebee that have been recorded to visit crops in the UK.

The order in which the species emerge from hibernation is relatively predictable, although there was disagreement between the studies over the order of the first three species to emerge. It is worth noting that the two long-tongued species in the list (*B. pascuorum* and *B. hortorum*) are the last species to emerge. This means that foraging queens of these species in the process of founding colonies can be vulnerable to the effects of pesticides later in the year than those of other species.

3.3. Diel activity patterns

The foraging and flying activity of bumblebees during the day has been recorded by many authors. Normally, the pattern observed is that the number of foragers peaks in the early morning and evening, with a drop in numbers in the middle of the day (Plowright and Lavery, 1984; Alford, 1975). Peaks are usually recorded before 10:00h and after 16:00h. Bumblebees also tend to start foraging earlier in the day than honeybees, and finish later in the evening (Fussell and Corbet, 1991; Corbet *et al.*, 1993). This is very different from the activity pattern for honeybees, in which the number of foragers peaks in the middle of the day.

Two reasons are thought to combine to account for this difference in foraging activity between bumblebees and honeybees—the effects of ambient temperature and the effects of exploitative competition with honeybees.

3.3.1. Temperature. Most bumblebees are able to fly at lower air temperatures than honeybees (Corbet *et al.*, 1993; Lundberg, 1980; Stone and Willmer, 1989). This is because bumblebees have better thermoregulatory ability and they are able to warm up their wing muscles to a temperature considerably higher than ambient (Heinrich,

1993). These data confirm that generally, bumblebees can be active at lower temperatures than honeybees, with the possible exception of *B. lapidarius*. Bumblebees may be limited by higher temperatures, because they are large and black and at risk of overheating (Willmer, 1983). This may partly explain the observed drop in foraging activity during the middle of the day, in the summer months.

3.3.2. Competition from honeybees. A second, and complementary, explanation for the diel activity pattern of bumblebees is that they confine their foraging to times when honeybees are less numerous. Honeybees can be present in very large numbers, especially since they are known to communicate the whereabouts of resources to one another (Seeley, 1985) and they often congregate at a good foraging site. They can deplete the quantity of nectar in each flower to a level which may be below that required for bumblebees to forage profitably.

3.4. Bumblebee foraging behaviour in relation to that of honeybees

Bumblebees almost always forage faster than honeybees. They generally spend a shorter time per flower and visit more flowers per minute than honeybees (Williams, 1997). For both types of bee, flower handling time can be expected to increase as the quantity of available nectar in each flower increases (Williams, 1997). Long-tongued bumblebees tend to forage even faster than short-tongued bumblebees (Alford, 1975).

Unlike honeybees, which use information from other foragers, bumblebees learn where to forage by their own initiative (Prys-Jones and Corbet, 1991). They are not known to communicate information about food sources and each individual bases foraging decisions on its own experience (Plowright and Laverty, 1984). Bumblebees exhibit a behaviour pattern called 'trap-lining,' in which an individual worker visits the same sequence of flowers on each foraging trip (Saville, 1993). They are less 'flower constant' (faithful to one plant species) than honeybees (Plowright and Laverty, 1984) and they regularly sample flowers of minority plant species, or newly opened flowers (Heinrich, 1979).

Bumblebees are thought not to forage very far away from their nests. Many authors have suggested that they will not exceed 250 m from home (Saville, 1993). However, in a study of bumblebee dispersal in an arable habitat, Saville (1993) discovered at least one individual more than 300 m from the nest and found many marked bees could not be located in the study area once they had left the nest to forage. The exact range of foraging bumblebees, then, remains uncertain.

The quantity of nectar which a bumblebee drinks from a flower has been investigated by Prys-Jones (1982). He tempted bees into a glass tube, in the field and fed them sugar solution from a syringe. Only *B. hortorum* could not be persuaded to participate, and so for that species, measurements were made by feeding the colony in a nest box. Uptake rate and total volume of sugar solution imbibed were found to vary according to body weight and concentration of the sugar solution.

The ranges of nectar uptake rate and total quantity taken are given in Table 5 below for the four species studied. The uptake rate is positively correlated to body size, such that larger bees can drink faster—in general, a doubling of body weight led to a 30–40% increase in uptake rate. In real flowers long-tongued bees have been recorded to be faster drinkers than short-tongued bees of similar body size (Harder, 1983).

The way in which these observations affect the potential exposure of bumblebees to pesticides depends on whether pesticides become dissolved in the nectar of flowers, and if so, exactly how that happens. If pesticides enter nectar immediately by direct contact with the flowers, then to spray in humid conditions may be a disadvantage to bumblebees because they may be drinking faster at the time. On the other hand, if pesticides are absorbed by the plant and secreted in the nectar, then bumblebees will receive a higher dose if the nectar is more concentrated, in dry conditions.

3.5. Preferences in flower use

3.5.1. General bumblebee preferences. There are several sets of flower characteristics particularly associated with bee pollination (bee pollination syndromes) (Proctor *et al.*, 1996) including one

Table 5. Nectar uptake in different bumblebee species

Bumblebee species/caste	Nectar uptake rate ($\mu\text{l/s}$)	Total volume nectar taken (μl)	Range of unfed mass (mg)
<i>B. hortorum</i> :			
workers/gynes	0.9–3.0		
<i>B. pascuorum</i> : workers		36.0–65.1	74–165
<i>B. pratorum</i>			
Workers	0.3–1.8		83–160
Gynes	0.5–3.1		325–425
<i>B. terrestris</i>			
Workers	0.5–2.0	41.1–111.9	109–300
Gynes		104.0	
<i>A. mellifera</i>		50 ^a	100 ^b

This table shows the uptake rates and total volumes of nectar of varying concentrations, taken by different bumblebee species. It also gives the range of mass measured, to give an indication of sizes (modified from Prys-Jones (1991)).

^aCrane (1990).

^bNBU data.

peculiar to bumblebees. However, bumblebees are opportunists and will visit a wide variety of species including some families that characterise different pollination syndromes such as Umbelliferae (largely fly-pollinated) (Corbet *et al.*, 1991). Bumblebees tend to pollinate the larger flowers (Proctor *et al.*, 1996). In addition, many authors have shown that bumblebees prefer to forage on perennial flowers, as opposed to annual species (Fussell and Corbet, 1992; Prys-Jones, 1982; Saville, 1993; Dramstad and Fry, 1995). This preference can be largely explained by the fact that perennial species often produce more nectar per flower or per plant than annual species (Fussell and Corbet, 1992).

Some bumblebees have been observed to collect pollen from non-insect pollinated plant species, such as grasses or salt-marsh plants (Pojar, 1973). At certain times of year, when reproductives are being reared, for example (mid-summer), it is possible that pollen is a limiting resource for bumblebees, forcing them to move to plants that produce copious pollen (Plowright and Laverty, 1984).

3.5.2. Interspecific differences in flower preference.

It has often been said that bumblebee species are able to coexist because they have different flower preferences and different species of bee forage on different species of plant. This may be at least partly attributable to differences in tongue length between the species.

Preferences are shown in Table 6 below for each of the six common species (only these species have been studied in any detail). The table also gives estimates for the average tongue length of workers of each species, as calculated by Saville, from a variety of sources (Saville, 1993). This serves to demonstrate the morphological difference which is partly responsible for species specific flower preferences.

4. Toxicity and repellency of pesticides to bumblebees

4.1. Toxicity, repellency and sub-lethal effects data

Van der Steen (1994) showed that the acute contact and oral toxicity of dimethoate is correlated with the size of the bumblebee (*B. terrestris*). This reported the toxicity of dimethoate to five size classes of bumblebees ranging from 0.162 g to 0.297 g. When corrected for weight bees in the mid-range (0.168–0.285 g) have similar LD₅₀ values, 33–37 $\mu\text{g/g}$ bee, but small bees (0.162 g) have a lower LD₅₀ of 25 $\mu\text{g/g}$ bee and large bees (0.297 g) have a higher LD₅₀ of 44 $\mu\text{g/g}$ bee. Therefore although correcting for size can reduce the variability in the mid-range of size significantly smaller, presumably younger, and significantly larger, probably older, bees have differing LD₅₀s in terms of weight. It is therefore important that toxicity data for bumblebees are quoted

Table 6. Suggested flower preferences and tongue lengths for six common bumblebee species

Bumblebee species	Flower preferences	Average tongue length (mm) ^a
<i>B. lucorum</i>	<ul style="list-style-type: none"> • Wide range of short tubed and open flowers (Brian, 1957) • Often collecting only pollen (Brian, 1957; Fussell and Corbet, 1992; Macdonald, 1998) • Clustered flowers for nectar only (Prys-Jones, 1982) 	7.06
<i>B. pratorum</i>	<ul style="list-style-type: none"> • Open flowers, prefers to forage in shady habitats (Brian, 1957) • Makes good use of pendulous flowers—due to small size and agility? (Prys-Jones, 1982; Macdonald, 1998) • Actinomorphic^b flowers (Fussell and Corbet, 1992) 	7.60
<i>B. lapidarius</i>	<ul style="list-style-type: none"> • Composites or clustered flowers (Fussell and Corbet, 1992; Prys-Jones and Corbet, 1991; Prys-Jones, 1982) • Preference for yellow flowers (Fussell and Corbet, 1992) • Flowers facing upwards (Fussell and Corbet, 1992) 	7.77
<i>B. terrestris</i>	<ul style="list-style-type: none"> • Clustered flowers for nectar only (Prys-Jones, 1982) 	8.29
<i>B. pascuorum</i>	<ul style="list-style-type: none"> • Upwards facing flowers (Prys-Jones, 1982) • Flowers of intermediate corolla length; prefers sheltered habitats (Brian, 1957) • Horizontal facing flowers, like Labiates (Prys-Jones and Corbet, 1991) • Prefers zygomorphic flowers (Fussell and Corbet, 1992; Macdonald, 1998) 	8.94
<i>B. hortorum</i>	<ul style="list-style-type: none"> • Flowers with long corolla tubes (Brian, 1957; Fussell and Corbet, 1992) • Deep, nectar rich flowers (Prys-Jones and Corbet, 1991) • Zygomorphic flowers, especially with spurs (Fussell and Corbet, 1992) 	12.87

^aPrementum and glossa together.

^bRadially symmetrical.

in terms of weight of the bees tested as, unlike honeybees, their weight can vary significantly between individuals.

Table 7 shows the contact and oral toxicity of a range of pesticides to honeybee and bumblebee species both in terms of per bee and per g bee. There are very limited data for bumblebee species other than *B. terrestris* although the data available shows the toxicity on a weight basis to be similar. It can be seen that the toxicity of the pesticides, for which data are available, are generally lower to bumblebees than honeybees when expressed on a weight basis. However, it should also be remembered that the data are limited in

terms of number and type of insecticide. There is a need to increase the amount of toxicity data available for bumblebees in order to support the assumption that they are less susceptible than honeybees.

5. Likelihood of exposure of queens and workers to pesticides

Overlaying the annual patterns of emergence of queens and workers for the most common bumblebee species with seasonal uses of insecticides on crops shows that there are a number of classes

Table 7. Contact and oral toxicity of a range of pesticides to honeybee and bumblebee species (24 hr unless otherwise stated)

Pesticide	Contact LD ₅₀ <i>A. mellifera</i> µg ai/bee (µg/g bee) ^a	Oral LD ₅₀ <i>A. mellifera</i>	Contact LD ₅₀ <i>B. terrestris</i>	Oral LD ₅₀ <i>B. terrestris</i>	Contact LD ₅₀ <i>B. lucorum</i>	Contact LD ₅₀ <i>B. agrorum</i> (Pascuorum)	Oral LD ₅₀ <i>B. lapidarius</i>
	Acetate		0.2 ^c (2.0)		135.5 ^c (645) 3.93, 72 hr ^c (19) 0.52 ^g (2.5)		
Alpha + cypermethrin	0.03 ^c (0.3) 0.05 ^g (0.5)	0.06 ^c (0.6)	0.17 ⁱ (0.81) 0.15, 72 hr ⁱ (0.71)	0.36, 72 hr ^g (1.7)			
Chlorpyrifos	0.059 ^g (0.59)		2.39 ⁱ (11.4) 1.58, 72 hr ⁱ (7.5)				
Deltamethrin	0.05 ^c (0.5)		0.9, 48 hr Decis CE in acetone ^f (4.3)	0.6 Decis ^b (2.7)			
Demeton methyl	0.5 ^h (5.0)				Workers 1-2 ^h Queens 6-24 ^h	Workers 1-3 ^h (8-25) Queens 10-24 ^h	
Demeton S methyl	0.26 ^g (2.6)		3.27 ⁱ (15.6) 2.68, 72 hr ⁱ (13)				
Dimethoate	0.4 ^d (4.0)	0.12, 24 & 48 hr ⁱ (1.2)	4.1-13 ^c (19-62)	4.7, 24-72 hr ⁱ (22)	Workers 2-5 ^h Queens 5-20 ^h	Workers 0.5-2 ^h (4-17) Queens 1-5 ^h	
Disulfoton	0.12, 24 & 48 hr ^g (1.2) 0.1 ^h (1.0) 5.0 ^h (50)						
Methomyl		0.08 ^c (0.8)		3.2 ^c , (15) 2.6, 72 hr ^c (12) 0.75 Metastox R ^b (3.6)	Workers 2-10 ^h Queens > 40 ^h	Workers 1-4 ^h (8-33) Queens 5-10 ^h	2.78 ^c , 2.4, 48 hr ^c , 2.18, 72 hr ^c
Oxydemeton methyl	0.54 ^g (5.4)						
Permethrin	0.1 ^c (1.0)	0.03 ^c (0.3)	0.81 ⁱ (3.9) 0.82, 72 hr (3.9)				
Phorate	0.3 ^h (3.0)				Workers 1-2 ^h Queens 6-23 ^h	Workers 1-2 ^h (8-17) Queens 1-5 ^h	
Phosalone	8.9 ^g (89)			60 ^b Rubitox (286)			
Pirimicarb	> 54 ^g (> 540)			8.5 Pirimor Granulat ^b (40)			

^a Calculated av *A. mellifera* = 0.10 g, *B. terrestris* = 0.21 g, *B. pascuorum* = 0.12 g; ^b (Gretenkord and Drescher, 1993); ^c (Drescher and Geusen-Pfister, 1991); ^d (van der Steen, 1994); ^e (Inglesfield, 1989); ^f (Tasei *et al.*, 1994); ^g (Greig-Smith *et al.*, 1994); ^h (Stevenson and Racey, 1996); ⁱ unpublished NBU data.

of insecticide applied to crops during the periods when queens are emerging and establishing colonies.

Of particular concern is that pyrethroids can be applied to oilseed rape crops in full flower at times of day when, although honeybees are less active, bumblebees are likely to be foraging on the crop. There are recommendations that pyrethroid sprays are applied early morning or late evening to avoid honeybee exposure. However, as shown above, these are the peak activity times for bumblebee species. Therefore direct overspray of foraging bumblebees by pyrethroids is likely to occur.

Although the application of these pesticides to the remainder of these crops is not of immediate concern, as there are label restrictions to prevent applications to flowering crops, there are likely to be flowering weeds around many of these crops which are attractive to bumblebees. Generally queens can be seen to emerge between February and mid-June depending on species and during this period many of the common weed species are in flower. Flowering weeds are unlikely to be visited by significant numbers of honeybees and therefore are likely to be overlooked by spray operators. Therefore the presence of flowering weeds in and around agricultural crops on which bumblebee species may forage is important in determining the exposure of bumblebees.

6. Quantitation of exposure of bumblebees relative to honeybees

6.1. Oral exposure

Oral exposure by uptake of nectar from treated crops and oversprayed weeds depends on the number of flowers visited, the level of transfer of pesticide to nectar and the capacity of the honey stomach of the bee. In addition, oral exposure may occur during the collection of contaminated pollen and is related to the number of flowers visited. On average honeybees undertake 7–13 foraging trips per day (Crane, 1990) whereas bumblebees undertake 17–27 foraging trips per day (Alford, 1975). Bumblebees visit an average of 2.5 more flowers per minute than honeybees and have a nectar carrying capacity per trip of up

to 112 μl compared to 50 μl in a honeybee. Therefore bumblebees have the potential to take up to 5 times the level of contaminated nectar in a day as honeybees. There are no data available on the levels of pesticides in pollen.

6.1.1. Secretion of pesticides into nectar. There are two possible routes of exposure of bumblebees to pesticides, through uptake of nectar into which the pesticide has been secreted or through contact with treated foliage or flowers. Systemic pesticides are most likely to occur in nectar and their concentrations depends on both the amount and method of nectar secretion. Investigations with dimethoate and carbofuran in *Ajuga reptans*, *Brassica napus* and *Vicia faba* showed an apparent selective transport of the insecticides into the nectar as the concentration in nectar often exceeded that in the solution in which the excised flowers were exposed, i.e. it is more than passive movement with water (Davis and Shuel, 1988).

Barker *et al.* (1980) showed that one day after application of dimethoate to an alfalfa crop at 340 ppm active ingredient residues of dimethoate in pollen were 0.5 ppm but were 16 ppm in nectar of uncovered florets and 5 ppm in the nectar from covered florets. After one week the residues in nectar had declined to 3 ppm and after 2 weeks 1 ppm. These values for dimethoate in the nectar of alfalfa are similar to the levels reported for fuschia, nasturtium and field beans by Lord *et al.* (1968). Pesticides in nectar are not thought to harm honeybees as they are diluted with stores within the colony. Bumblebees do not build up such high levels of stores and therefore are likely to consume higher levels.

There are several reports that it is not only the truly systemic pesticides which can be detected in nectar but chemicals such as parathion can result in toxic nectar for up to 24 hours (Jaycox, 1964). Even systemic granular insecticides can penetrate sufficiently into nectar to kill bees (Jaycox, 1964).

Lord *et al.* (1968) showed that 6 days after nasturtium and fuschia plants watered with 25 mg dimethoate resulted in 741 ± 259 ng/ml dimethoate in nasturtium nectar and 2890 ± 550 ng/ml in fuschia nectar (0.05 ml nectar). 50 mg dimethoate applied to compost in which field bean plants were growing resulted in 130–136

ng/6 mg in nectaries whereas 100 mg of phorate resulted in only 0.042–0.052 ng/6 mg in nectaries.

6.1.2. Assessment of exposure. The transfer of pesticide to nectar may be by direct overspray or by translocation within the plant. Using the data of Barker *et al.* (1980) a 340 ppm ai dimethoate spray resulted in 16 ppm ($\mu\text{g}/\text{ml}$) in nectar from uncover alfalfa florets, i.e. a 5% recovery. Therefore with an oral LD_{50} of 4.7 μg ai/bee a bumblebee must consume 293 μl nectar to obtain a lethal dose and a honeybee 7.5 μl (LD_{50} 0.12 $\mu\text{g}/\text{bee}$). If a flower contains 50 μl nectar this equates to 6 flowers visited for bumblebees and only 1 flower for a honeybee. Given that bumblebees undertake twice as many foraging trips during a day and 2.5 times as many flower visits then the level of risk is similar for the two species when based on their behaviour and the toxicity of the pesticides.

6.2. Contact exposure

Obviously, when it comes into direct contact with a pesticide, the residue on a bumblebee is greater than that on a honeybee due to its larger surface area. Assuming that there is not a significant difference in density of bee species then the weight of the species is related to surface area, i.e. bumblebees are approx twice the weight and twice the surface area of honeybees. Therefore differences due to size are taken into account in data relating toxicity as $\mu\text{g}/\text{g}$ bee and residues as $\mu\text{g}/\text{g}$ bee. However, *Bombus* species tend to be more active foragers visiting more flowers per min (on average 2.5 times) and undertaking approx twice as many foraging trips in a day than *Apis mellifera* which will increase their exposure level, i.e. the exposure of bumblebees to residues on flowers may be up to 5 times that of honeybees based on their behaviour.

6.2.1. Assessment of exposure. Koch and Weiber (1997) reported the results of a field study using a fluorescent tracer to assess the exposure of honeybees to pesticides applied to crops. The only route which could be assessed in this manner is contact exposure but it provides information

which may be extrapolated to other species with similar behaviour patterns. Assessments of the levels of tracer on bees returning to the hive were undertaken for 20–30 minutes after the spray application. The mean deposit per bee for approx. 100 bees sampled at 5 minute intervals over the 20–30 minutes was 1.62–20.84 ng in apple orchards and 6.34–35.77 ng in *Phacelia* following applications at 20 g/ha. The maximum residue detected following the orchard application was 35 ng and following the *Phacelia* application 48 ng. This was despite the potential for prolonged exposure of bees in orchards to be greater than in arable crops due to the time required for spray application (20 min/ha in fields, 75 min/ha in orchards). The residues detected declined to low levels (less than 10 ng) within 30 minutes of finishing the application. Therefore, an application rate of 20 g/ha results in a mean residue of 18 ng per bee in *Phacelia* crops. Given the surface area of a bumblebee is approx. 2.5 times that on a honeybee, under similar circumstances the residue of tracer on the surface of a bumblebee would be in the order of 46 ng.

6.3. Risk assessment

Risk assessments are routinely based on the dose available (mg/kg) and the toxicity of the compound (mg/kg). However, for honeybees an empirical approach (hazard ratio) has been developed (EPPO, 1993) based on the application rate of the pesticide (g ai/ha) and the toxicity to the bee ($\mu\text{g}/\text{bee}$). These approaches are reviewed below together with other methods of assessing exposure which may be more readily adapted for use with bumblebees.

6.3.1. Hazard ratio. A hazard ratio (application rate (g ai/ha)/ LD_{50} ($\mu\text{g}/\text{bee}$)) of < 50 is used to define a pesticide as harmless to honeybees, 50–2500 as slight to moderately toxic and > 2500 as dangerous to bees. An application rate of 15 g ai/ha for alphacypermethrin gives a hazard ratio of 88 for bumblebees and 500 for honeybees. However, this use of a hazard ratio does not take into account the differences in the foraging behaviour and thus the exposure of bumblebees.

6.3.2. *Insect residue based data.* Pesticide residues on large insects (mg/kg) are calculated by Kenega as 2.7 times the application rate in kg/ha. Therefore, at an application rate for alphacypermethrin of 0.015 kg/ha the residue on a large insect would be 0.041 $\mu\text{g/g}$. Taking the toxicity of alphacypermethrin to bumblebees as 0.81 $\mu\text{g/g}$ bee this gives a dose/toxicity (D/T) of 0.05 and a medium risk classification. The classification for honeybees would be D/T 0.13, a high risk classification.

6.3.3. *Bee residue data.* Using the data produced by Koch and Weiber (1997) based on actual residues following a field application of a marker to produce a D/T is another method for assessing the risk (D/T). At 15 g ai/ha the Koch and Weiber (1997) data gives a residue of 35 ng/bee (0.175 $\mu\text{g/g}$ bee) for bumblebees and for alphacypermethrin a D/T of 0.22. For honeybees the same data gives a residue of 13.5 ng/bee (0.135 $\mu\text{g/g}$ bee) and D/T of 0.45 for alphacypermethrin. These are both high risk classifications. This method allows the larger surface area of the bumblebee to be taken into account in the risk assessment. However, further data are required to determine the scale of difference in contact exposure between bumblebees and honeybees based on their behaviour, e.g. number of foraging trips and number of flowers visited which would allow extrapolation of the risk assessment.

7. Possible role of pesticides in decline of bumblebees

7.1. *Non-Pesticide causes of bumblebee decline*

As is the case with butterflies (Longley and Sotherton, 1997) there are two main potential causes of bumblebee decline on farmland, a decrease in suitable habitats and/or the toxicological effects of insecticides.

The potential for indirect effects on bumblebees through the loss of nectar producing plants, e.g. perennial weeds, as a consequence of herbicide use is significant. In addition the use of

nitrogen fertilisers can reduce floral diversity in field boundaries and thus essential nectar bearing plants. The removal of hedgerows and ploughing of headlands will also result in the loss of nest sites, hibernation sites, male patrolling and mating sites.

7.2. *Pesticide effects*

Bumblebees may be exposed to pesticides by direct overspray, spray drift or vapour drift through contact with treated flowering crops or small patches of flowering weeds. In addition there are a number of sublethal effects of pesticides which may impact on colonies from the effects of insect growth regulators on brood development to effects of pyrethroids on memory and ability to return to the colony.

Bumblebees are likely to be more attracted than honeybees to small, isolated areas of flowering perennial weeds. These are likely to be overlooked when decisions are made about spray application as they may not be considered important for honeybees particularly if they are feeding on a nearby flowering crop which is more attractive to honeybees. Bumblebees tend to forage on a trackline, i.e. a regular foraging route, and on an individual basis rather than communicating good forage in the way honeybees do. Therefore they tend to visit a relatively small number of flowers on a regular basis. Bumblebees also tend to forage far closer to the nest than honeybees; 250–300 metres rather than up to 3 km and therefore are more likely to forage on flowering weeds close to their nest.

7.3. *Pesticide incidents*

The submission of bumblebees to the Wildlife Incident Investigation Scheme may provide information on the scale of any problem. Only 3 incidents involving bumblebees have been reported in which pesticides were detected, one each in 1995, 1996 and 1997.

1. In 1995 the incident involved dimethoate (0.29 $\mu\text{g/bee}$ dimethoate, 0.12 $\mu\text{g/bee}$ omethoate)

and may have been linked to an application to oilseed rape in full flower (misuse of the pesticide) but this could not be confirmed. The bumblebees (described as numerous) were found dead and dying in a nearby garden; obviously they are more likely to be detected in a garden than in the field situation.

2. In 1996 0.033 $\mu\text{g}/\text{bee}$ lambda cyhalothrin was detected in 15 bumblebees after an application to field beans in full flower (a misuse of the pesticide). Although honeybee colonies were situated nearby no deaths occurred. The bumblebees were detected by an observant beekeeper who was concerned about the use of the pesticide on a flowering crop.
3. In 1997 alphacypermethrin (0.0044 $\mu\text{g}/\text{bee}$) was detected in bumblebees which had been foraging on oilseed rape which had been sprayed whilst in flower. The numbers of bumblebees found dead was not stated. The spray was applied at 1915 and 1930 (i.e. evening) and contained a mixture of alphacypermethrin, carbandazim and iprodione. Again the bumblebees were detected two days after the spray application by an observant beekeeper whose apiary was unaffected. Further dead bumblebees were collected 2 weeks after the the spray application.

Therefore of the three incidents reported in which pesticides were detected two were apparent misuse (spray application to a flowering crop) and only one followed normal use. The latter demonstrates the potential for exposure of bumblebees at the time when spraying is recommended as no honeybee colonies were affected.

It is difficult to gauge the scale of the problem from the level of incidents reported. It is unlikely that bumblebee deaths would normally be detected unless they are on a large scale, unlikely due to the small size of many colonies. Certainly it is likely that when incidents involving honeybees are reported deaths of bumblebees are also likely to have occurred but have not been detected (except in the case of feral colony treatment). However, applications of sprays to flowering crops or weeds at times when honeybees are less active are likely to result in unreported bumblebee deaths. Therefore it is likely that there are

far more bumblebee deaths than the levels reported through the Scheme.

8. Conclusions

This review has shown that the exposure of bumblebees to pesticides is likely to be at least that of honeybees. Of particular concern are insecticide applications to flowering crops, such as oilseed rape, at times which, although posing less risk to honeybees, are likely to coincide with foraging bumblebees. In addition, contamination of flowering weeds in and around sprayed crops is likely to pose a greater risk to bumblebees than honeybees due to their differing foraging habits and smaller colony size. Therefore, it is important that these differences in foraging behaviour, and thus exposure, are considered in the risk assessment process.

The potential for exposure of the queen bumblebee early in the season when she is establishing her colony is likely to have a greater impact on a bumblebee colony than exposure of workers later in the season, although this is also of concern due to the relatively small colony size. Indirect effects of pesticides, e.g. herbicides, on bumblebees are also important through loss of perennial weed forage, nesting sites etc.

Given the wide range of plant species dependent on bumblebees for pollination impacts on colonies are also likely to have effects on the populations of dependent plant species resulting in less forage. To more closely assess the direct risk posed by pesticides to bumblebees more detailed information on their exposure to pesticides applied to crops is required than the hazard ratio currently used for honeybee risk assessment. In addition further information is required to confirm the limited data suggesting that generally bumblebees are less sensitive to pesticides than honeybees.

Note

1. This does not refer to the threshold used in section 3. There was not enough quantitative information available to use the same threshold for this part of the work, and more qualitative criteria have been used instead.

References

- Acker, R.C.V. and Lutman, P.J.W. (1995). Weed interference in autumn-sown field beans (*Vicia faba* L.). In *Proceedings of the Brighton Crop Protection Conference—Weeds, 20–23 November 1995*, pp. 907–12. Farnham: BCPC.
- Alford, D.V. (1975). *Bumblebees*. London: Davis-Poynter Ltd.
- Banaszak, J. (1984). The occurrence and number of bees (Apodea) on some cultivated crop plants in the Wielkopolska region (W. Poland). *Entomologiczne* **53**, 623–31.
- Barker, R.J., Lehner, Y. and Kunzmann, M.R. (1980). Pesticides and honeybees: nectar and pollen contamination in alfalfa treated with dimethoate. *Arch. Environ. Contam. Toxicol.* **9**, 125–33.
- Barr, C.J., Bunce, R.G.H., Clarke, R.T., Fuller, R.M., Fuse, M.T., Gillespie, M.K., Broom, G.B., Hallam, C.J., Hornung, M., Howard, D.C. and Ness, M.J. (1996). *The Countryside Survey—Main Report*. London: Department of the Environment.
- Barrow, D.A. (1983). Ecological Studies on Bumblebees in South Wales with Special Reference to Resource Partitioning and Bee Size Variation. PhD Thesis, University College, Cardiff.
- Batra, S.W.T. (1993). Male-fertile potato flowers are selectively buzz-pollinated only by *Bombus terricola* Kirby in upstate New York. *J. Kansas Entomol. Soc.* **66**, 252–4.
- Bhalla, O.P., Verma, A.K. and Dhaliwal, H.S. (1983). Foraging activity of insect pollinators visiting stone fruits. *J. Entomol. Res.* **7**, 91–4.
- Bishop, J.A. (1994). Bumblebees (*Bombus hypnorum*) collect aphid honeydew on stone pine (*Pinus pumila*) in the Russian far-east. *J. Kansas Entomol. Soc.* **67**, 220–2.
- Bohart, G.E. (1957). Pollination of alfalfa and red clover. *Annu. Rev. Entomol.* **2**, 355–80.
- Bohart, G.E. (1960). Insect pollination of forage legumes. *Bee World* **41**, 51–64.
- Brian, A.D. (1957). Differences in the flowers visited by four species of bumblebees and their causes. *J. Animal Ecol.* **26**, 69–96.
- Clarke, J.H., Bowerman, P., Young, J.E.B., Cook, S.K., Jones, A.E., Groves, S.J. and Green, M. (1993). Effects of recommended and reduced rate herbicides on weed number, yield and gross margin in TALISMAN: report on the first two years. In *Proceedings of the Brighton Crop Protection Conference—Weeds, 22–25 November 1993*, pp. 1009–14. Farnham: BCPC.
- Corbet, S.A., Williams, I.H. and Osborne, J.L. (1991). Bees and pollination of crops and wild flowers in the European Community. *Bee World* **72**, 47–59.
- Corbet, S.A., Fussell, M., Ake, R., Fraser, A., Gunson, C., Savage, A. and Smith, K. (1993). Temperature and pollinating activity of social bees. *Ecol. Entomol.* **18**, 17–30.
- Crane, E. (1990). *Bees and Beekeeping; Science Practice and World Resources*. Oxford: Heinemann Newnes.
- Davis, A.R. and Shuel, R.W. (1988). Distribution of carbofuran and dimethoate in flowers and their secretion in nectar as related to nectary vascular supply. *Can. J. Bot.* **66**, 1248–55.
- Delbrassinne, S. and Rasmont, P. (1988). Contribution à l'étude de la pollinisation du colza *Brassica napus* L. var. *oleifera* (Moench) Delle, en Belgique. *Bull. Rech. Agron. Gembloux* **23**, 123–52.
- Doorn, A.V. (1993). Bumblebees breaking through as crop pollinators. In *Pollination in Tropics*, pp. 195–201. IUSI.
- Dramstad, W. and Fry, G. (1995). Foraging activity in bumblebees in relation to flower resources on arable land. *Agric. Ecosystems Environ.* **53**, 123–35.
- Drescher, W. and Geusen-Pfister, H. (1991). Comparative testing of the oral toxicity of acephate, dimethoate and methomyl to honeybees, bumblebees and syrphidae. *Acta Horticulturae* **288**, 133–6.
- Ellenberg, H. (1988). *Vegetation Ecology of Central Europe*, 4th ed. Cambridge: Cambridge University Press.
- Emmet, B.J. (1971). Insect visitors to pear blossom. *Plant Pathol.* **20**, 36–40.
- EPPO (1993). Decision making scheme for the environmental risk assessment of plant protection products—honeybees. *Bull. OEPP/EPPO Bull.* **23**, 151–65.
- Firbank, L.G. (1990). Interactions between weeds and crops. In: Firbank, L.G., Carter, N., Darbyshire, J.F. and Potts, G.R. (eds) *The Ecology of Temperate Cereal Fields*, pp. 469. Oxford: Blackwell Scientific Publications.
- Free, J.B. (1968a). The behaviour of bees visiting runner beans (*Phaseolus multiflorus*). *J. Appl. Ecol.* **5**, 631–8.
- Free, J.B. (1968b). The foraging behaviour of honeybees (*Apis mellifera*) and bumblebees (*Bombus* spp.) on blackcurrant (*Ribes nigrum*), raspberry (*Rubus idaeus*) and strawberry (*Fragaria x ananassa*) flowers. *J. Appl. Ecol.* **5**, 157–68.
- Free, J.B. (1993). *Insect Pollination of Crops*, 2nd ed. London: Academic Press.
- Fussell, M., Osborne, J.L. and Corbet, S.A. (1991). Seasonal and diurnal patterns of insect visitors to winter sown field bean flowers in Cambridge. *Aspects Appl. Biol.* **27**, 95–9.
- Fussell, M. and Corbet, S.A. (1991). Forage for bumblebees and honeybees in farmland; a case study. *J. Apic. Res.* **30**, 87–97.
- Fussell, M. and Corbet, S.A. (1992). Flower usage by bumblebees: a basis for forage plant management. *J. Appl. Ecol.* **29**, 451–65.
- Fussell, M. and Corbet, S.A. (1993). Bumblebee (Hym. Apidae) forage plants in the United Kingdom. *Entomologists Monthly Magazine* **129**, 1–14.
- Glasgow, J.L., Dicks, J.W. and Hodgson, D.R. (1976). Competition by, and chemical control of, natural weed populations in spring-sown field beans (*Vicia faba*). *Ann. Appl. Biol.* **84**, 259–69.
- Goodwin, S.G. (1995). Seasonal phenology and abundance of early-, mid- and late-season bumblebees in Southern England 1985–1989. *J. Apic. Res.* **34**, 79–89.
- Greig-Smith, P.W., Thompson, H.M., Hardy, A.R., Bew, M.H., Findlay, E. and Stevenson, J.H. (1994). Incidents of poisoning of honeybees (*Apis mellifera*) by agricultural pesticides in Great Britain 1981–1991. *Crop Protection* **13**, 567–81.
- Gretenkord, C. and Drescher, W. (1993). Effects of four pesticides (Decis, Metasystox, Pirimor, Rubitox) on the bumblebee *Bombus terrestris* L.: determination of the oral LD50 and preliminary results with semi-field tests. *Apiologie* **24**, 519–20.

- Griffiths, D. and Robberts, E.J. (1996). Bumblebees as pollinators of glasshouse crops. In Matheson, A. (ed.) *Bumblebees for Pleasure and Profit*, pp. 33–9. Cardiff: IBRA.
- Gubin, A.F. (1945). Cross-pollination of fibre flax. *Bee World* **26**, 30–1.
- Gurr, L. (1975). The role of bumblebees as pollinators of red clover and lucerne in New Zealand; a review and prospect. *Proc. N.Z. Grassland Association* **36**, 111–22.
- Gwynne, D.C. and Murray, R.B. (1985). *Weed Biology and Control in Agriculture and Horticulture*. London: Batsford Technical.
- Gyan, K.Y. and Woodell, S.R.J. (1987). Analysis of insect pollen loads and pollination efficiency of some common insect visitors of woody Rosaceae. *Functional Ecol.* **1**, 269–74.
- Harder, L.D. (1983). Functional differences of the proboscides of the short- and long-tongued bees (Hymenoptera, Apoidea). *Can. J. Zool.* **61**, 1580–6.
- Heinrich, B. (1979). “Majoring” and “minoring” by foraging bumblebees, *Bombus vagans*; an experimental analysis. *Ecology* **60**, 245–55.
- Heinrich, B. (1993). *The Hot-Blooded Insects*, Berlin: Springer-Verlag.
- Herrera, C. (1990). Daily patterns of pollinator activity, differential pollinating effectiveness and floral resource availability in a summer flowering Mediterranean shrub. *Oikos* **58**, 277–88.
- Holm, N. (1966). The utilization and management of bumblebees for red clover and alfalfa seed production. *Annu. Rev. Entomol.* **11**, 155–77.
- Hurd, P.D. (1964). The pollination of pumpkins, gourds and squashes (genus *Cucurbita*). *Bee World* **47**, 97–8.
- Inglesfield, C. (1989). Pyrethroids and terrestrial non-target organisms. *Pestic. Sci.* **27**, 387–428.
- Jaycox, E.R. (1964). Effect on honeybees of nectar from systemic insecticide-treated plants. *J. Econ. Entomol.* **57**, 31–5.
- Kendall, D.A. and Smith, B.D. (1976). The pollinating efficiency of honeybee and bumblebee visits to flowers of the runner bean *Phaseolus coccineus* L. *J. Appl. Ecol.* **13**, 749–52.
- Kendall, D.A. and Solomon, M.E. (1973). Quantities of pollen on the bodies of insects visiting apple blossom. *J. Appl. Ecol.* **10**, 627–34.
- Kevan, P.G., Straver, W.A., Offer, M. and Laverty, T.M. (1993). Pollination of greenhouse tomatoes by bumblebees in Ontario, Canada. *Proc. Entomol. Soc. Ontario* **3**, 4–6.
- Knott, C.M., May, M.J. and Ward, J.T. (1995). Weed control in potatoes, oilseed rape, pulses and sugar beet—trends and prospects. In *Proceedings of the Brighton Crop Protection Conference—Weeds, 20–23 November 1995*, pp. 1193–202. Farnham: BCPC.
- Koch, H. and Weiber, P. (1997). Exposure of honeybees during pesticide application under field conditions. *Apidologie* **28**, 439–47.
- Legeun, J., Mesquida, J., Pierre, J.S., Morin, G., Tasei, J.N. and Carre, S. (1993). Efficiency of pollinating treatments on 2 lines of spring faba bean (*Vicia faba* L. var *equina* Steudel) with different levels of self fertility and using three species of *Bombus* Latr. (Hymenoptera, Apidae). *Apidologie* **24**, 129–45.
- Longley, M. and Sotherton, N.W. (1997). Factors determining the effects of pesticides upon butterflies inhabiting arable farmland. *Agric. Ecosystems Environ.* **61**, 1–12.
- Lord, K.A., May, M.A. and Stevenson, J.H. (1968). The secretion of the systemic insecticides dimethoate and phorate into nectar. *Ann. Appl. Biol.* **61**, 19–27.
- Lundberg, H. (1980). Effects of weather on foraging flights of bumblebees (Hymenoptera, Apidae) in subalpine/alpine area. *Holarctic Ecol.* **3**, 104–10.
- Lutman, P.J.W., Bowerman, P., Palmer, G.M. and Whytock, G.P. (1995). A comparison of the competitive effects of eleven weed species on the growth and yield of winter oilseed rape. In *Proceedings of the Brighton Crop Protection Conference—Weeds, 20–23 November 1995*, pp. 877–82. Farnham: BCPC.
- Macdonald, M.A. (1998). The feeding ecology of some *Bombus* and *Psithyrus* bees in North Scotland and the importance to them of native and exotic plants. In preparation.
- Macfarlane, R.P., Griffin, R.P. and Read, P.E.C. (1983). Bumblebee management options to improve “Grasslands Pawera” red clover seed yields. *Proc. N.Z. Grassland Association* **44**, 47–53.
- Macfarlane, R.P., Ende, H.J. and Griffin, R.P. (1991). Pollination needs of “Grasslands Pawera” red clover. *Acta Horticulturae* **288**, 399–404.
- MAFF (1997). <http://www.maff.gov.uk> (General Agricultural Statistics Section).
- Marshall, E.J.P. (1989). Distribution patterns of plants associated with arable field edges. *J. Appl. Ecol.* **26**, 247–57.
- Mayer, D.F. (1983). Behaviour of pollinators on *Malus*. In *Proceedings of the 5th International Pollination Symposium, Versailles*, pp. 387–390.
- McGregor, S.E. (1976). *Insect Pollination of Cultivated Crop Plants*. Washington DC: Agricultural Research Service, USDA.
- Michaelson-Yeates, T.P.T., Marshall, A.H., Williams, I.H., Carreck, N.L. and Simpkins, J.R. (1997). The use of isoenzyme markers to determine pollen flow and seed paternity mediated by *Apis mellifera* and *Bombus* spp. in *Trifolium repens*, a self-compatible plant species. *J. Apic. Res.* **36**, 57–62.
- Mortimer, A.M. (1990). The biology of weeds. In Hance, R.J. and Holly, K. (eds) *Weed Control Handbook: Principles*, 8th ed, pp. 582. Farnham: BCPC/Blackwell.
- Mountford, J., Parish, T. and Sparks, T.H. (1994). The flora of field margins in relation to land use and boundary features. In Boatman, N. (ed) *Field Margins; Integrating Agriculture and Conservation*, Monograph 58, pp. 105–10. Farnham: BCPC.
- Nye, W.P. and Andersen, J.L. (1974). Insect pollinators frequenting strawberry blossoms and effect of honeybees on yield and fruit quality. *J. Amer. Soc. Hortic. Sci.* **99**, 40–4.
- Olgivy, S.E., Green, M.R., Groves, S.J. and Jones, A.E. (1993). SCARAB—the impact of less intensive herbicide use on the diversity and distribution of weed species in three arable rotations. In *Proceedings of the Brighton Crop Protection Conference—Weeds, 22–25 November 1993*, pp. 1241–6. Farnham: BCPC.

- Osborne, J.L. (1994). Evaluating a Pollination System: *Borago officinalis* and bees. PhD Thesis, University of Cambridge.
- Pallutt, B. (1993). Population dynamics and competition of weeds depending on crop rotation and mechanical and chemical control measures in cereals. In *Proceedings of the Brighton Crop Protection Conference—Weeds, 22–25 November 1993*, pp. 1197–204. Farnham: BCPC.
- Patten, K.D., Shanks, C.H. and Mayer, D.F. (1993). Evaluation of herbaceous plants for attractiveness to bees for use near cranberry farms. *J. Apic. Res.* **32**, 73–9.
- Pinchinat, B., Bilinski, M. and Ruszkowski, A. (1979). Possibilities of applying bumblebees as pollen vectors in tomato F1 hybrid seed production. In *Proceedings of the 4th International Symposium on Pollination, Maryland*, pp. 73–90.
- Plowright, R.C. and Laverty, T.M. (1984). The ecology and sociobiology of bumblebees. *Annu. Rev. Entomol.* **29**, 175–99.
- Pojar, J. (1973). Pollination of typically anemophilous salt marsh plants by bumblebees, *Bombus terricola occidentalis* Grne. *Amer. Midland Naturalist* **89**, 448–51.
- Proctor, M., Yeo, P. and Lack, A. (1996). *The Natural History of Pollination*. London: Harper Collins.
- Prys-Jones, O.E. (1982). Ecological Studies of Foraging and Life History in Bumblebees. PhD Thesis, Cambridge University.
- Prys-Jones, O.E. and Corbet, S.A. (1991). *Bumblebees*, 2nd ed. Slough: Richmond Publishing.
- Reader, R.J. (1977). Bog ericad flowers: self compatibility and attractiveness to bees. *Can. J. Botany* **55**, 2279–87.
- Richards, K.W. and Edwards, P.D. (1988). Density, diversity and efficiency of pollinators of sainfoin, *Onobrychis viciifolia* sp. *Can. Entomologist* **120**, 1085–100.
- Sanford, J.C. and Hannemann, R.E. (1981). The use of bees for the purpose of inter-mating in potato. *Amer. Potato J.* **58**, 481–5.
- Saville, N.M. (1993). Bumble Bee Ecology in Woodlands and Arable Farmland. PhD Thesis, Cambridge University.
- Seeley, T.D. (1985). *Honeybee Ecology*, Princeton NJ: Princeton University Press. Shipp, J.L., Whitfield, G.H. and Papadopoulos, A.P. (1994). Effectiveness of the bumblebee, *Bombus impatiens* Cr. (Hymenoptera, Apidae) as a pollinator of the greenhouse sweet pepper. *Scientia Horticulturae* **57**, 29–39.
- Stace, C.A. (1997). *New Flora of the British Isles*, 2nd ed. Cambridge: Cambridge University Press.
- Stevenson, J.H. and Racey, P.A. (1966). Toxicity of Insecticides to Bumblebees. Report Rothamsted Experimental Station 176.
- Stoddard, F.L. and Bond, D.A. (1987). The pollination requirements of the faba bean. *Bee World* **68**, 144–52.
- Stone, G.N. and Willmer, P.G. (1989). Warm-up rates and body temperature in bees; the importance of body-size, thermal regime and phylogeny. *J. Exp. Biol.* **147**, 303–28.
- Tasei, J.N., Sabik, H. and Pirastru, L. (1994). Effects of sublethal doses of deltamethrin (Decis ce) on *Bombus terrestris*. *J. Apic. Res.* **33**, 129–35.
- Teras, I. (1976). Bumblebees, *Bombus* Latr. (Hymenoptera, Apidae) on red clover in South Savo, Finland. *Ann. Agric. Fenniae* **15**, 116–27.
- Teras, I. (1985). Food plants and flower visits of bumblebees (*Bombus*: Hymenoptera, Apidae) in Southern Finland. *Acta Zool. Fennica* **179**, 1–120.
- van der Steen, J.J.M. (1994). Method development for the determination of the contact LD50 of pesticides to bumblebees (*Bombus terrestris* L.). *Apidologie* **25**, 463–5.
- Voloshin, M., Voloshina, T. and Valter, V. (1995). Use of wild bees for alfalfa pollination. In Banaszak, J. (ed) *Changes in Fauna of Wild Bees in Europe*, pp. 220. Bydgoszcz: Pedagogical University.
- Walton, C.L. (1927). Note on the activities of bumblebees (*Bombus*) in North Wales. *Ann. Appl. Biol.* **14**, 465–9.
- Watkinson, A.R. and Bo, L. (1993). Patterns of abundance in the weed seed bank. In *Proceedings of the Brighton Crop Protection Conference—Weeds, 22–25 November 1993*, pp. 293–298. Farnham: BCPC.
- Williams, C.S. (1997). Foraging Ecology of Nectar-Collecting Bumblebees and Honeybees. PhD Thesis, University of Cambridge.
- Williams, I.H. (1985). The pollination of swede rape (*Brassica napus* L.). *Bee World* **66**, 16–22.
- Williams, I.H. (1987). The pollination of lupins. *Bee World* **68**, 10–6.
- Williams, I.H. (1988). The pollination of linseed and flax. *Bee World* **69**, 145–52.
- Williams, I.H., Martin, A.P., Ferguson, A.W. and Clark, S.J. (1990). Effect of pollination on flower, pod and seed production in the white lupin (*Lupinus albus*). *J. Agric. Sci.* **115**, 67–73.
- Williams, I.H., Carreck, N. and Little, D.J. (1993). Nectar sources for honeybees and the movement of honeybee colonies for crop pollination and honey production in England. *Bee World* **74**, 160–75.
- Williams, I.H. and Free, J.B. (1974). The pollination of onion (*Allium cepa* L.) to produce hybrid seed. *J. Appl. Ecol.* **11**, 409–18.
- Willmer, P.G. (1983). Thermal constraints on activity patterns in nectar feeding insects. *Ecol. Entomol.* **8**, 455–69.
- Willmer, P.G., Bataw, A.A.M. and Hughes, J.P. (1994). The superiority of bumblebees to honeybees as pollinators; insect visits to raspberry flowers. *Ecol. Entomol.* **19**, 271–84.
- Wilson, G.F. (1929). Pollination of hardy fruits: insect visitors to fruit blossoms. *Ann. Appl. Biol.* **16**, 602–29.
- Yalden, P.E. (1982). Pollen collected by the bumblebee *Bombus monticola* (Smith) in the peak district, England. *J. Natural History* **16**, 823–32.