V. Bumblebees and other pollinators

Aspects determining the risk of pesticides to wild bees: risk profiles for focal crops on three continents

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Abstract

In order to conduct a proper risk assessment of pesticides to bees, information is needed in three areas: (i) the toxicity of the pesticide; (ii) the probability of bee exposure to that pesticide; and (iii) the population dynamics of the bee species in question.

Information was collected on such factors affecting pesticide risk to (primarily wild) bees in several crops in Brazil, Kenya and The Netherlands. These data were used to construct 'risk profiles' of pesticide use for bees in the studied cropping systems. Data gaps were identified and potential risks of pesticides to bees were compared between the crops.

Initially, risk profiling aims to better identify gaps in our present knowledge. In the longer term, the established risk profiles may provide structured inputs into risk assessment models for wild and managed bees, and lead to recommendations for specific risk mitigation measures.

Keywords: pesticide, exposure, risk, wild bees, risk profile

1. Introduction

1.1 Importance of pollination

Pollinators contribute greatly to food security. Effective pollination results in increased crop production, better commodity quality and greater seed production. In particular, many fruits, vegetables, edible oil crops, stimulant crops and nuts are highly dependent on animal pollination.

In the three countries included in this study, Brazil, Kenya and The Netherlands, the economic value of pollination services is undeniably important. The value of Brazilian export of eight important agricultural commodities dependent on pollinators is estimated at € 7 billion annually.[1] The annual economic value of insect pollination in East Africa has been estimated at € 900 million.[2] In the Kenyan district of Kakamega alone, 40% of crop production (€ 2.4 million) could be attributed to bee pollination.[3] The value of animal pollination for Dutch agriculture is estimated at € 1 billion annually.[4]

1.2 Role of wild pollinators

Honey bees and bumblebees, often managed, are among the most important pollinators of crops in both temperate and tropical areas.[5] However, wild bees, both social and solitary species, are also essential for pollination of many crops, especially in the tropics and in cropping systems which include a high diversity of crops within the same area. In some cases, wild bees complement pollination done by honey bees, but for many tropical crops wild bees are the principal or only pollinator.[6,7,8,9]

For example, in the Kenyan district of Kakamega, 99% of the crop production value attributable to pollination was provided by wild bees.[3] The main effective pollinators of passion fruit (*Passiflora edulis* Sims) in Brazil are carpenter bees of the genus *Xylocopa* Latreille.[10] The importance of wild pollinators was recently also underlined in oilseed rape and other crops in Europe[11,12] and New Zealand.[13]

1.3 Threats to pollinators

There is increasing evidence that insect pollinators, both wild and managed, are in decline in many regions of the globe, with the clearest cases documented in Europe and North America.[14] Various causes for this decline have been identified, including loss, fragmentation and degradation of habitats, reduction in resource diversity, pests and pathogens of pollinators, competition by introduced pollinators, climate change, reduced genetic diversity, and pesticide use – all potentially causing direct and indirect adverse effects on pollinator populations. There appears to be agreement that not one of these pressures is primarily responsible for the observed pollinator decline, but that interactions among multiple factors are likely in effect.[14,15,16,17] Both managed and wild pollinators face many common threats, and both are subject to significant declines.[5]

Losses in wild bee diversity and numbers are particularly strong under intensive agricultural management.[18] A recent large study in winter cereals showed that insecticide use had a significant negative effect on bee species richness and abundance.[19] So far, no large honey bee losses have been reported from Africa, Australia or South America[20,21], but increasing agricultural expansion and intensification pose a significant risk to both managed and wild pollinators on these continents.[21,22,23] This is illustrated by the fact that pesticide imports have increased by 38% in Kenya between 2003 and 2008 [24], and pesticide sales in Brazil have tripled between 2000 and 2010.[22]

1.4 Pesticide risk assessment

To address the impact that pesticides may have on pollinators several tools have been developed. These tools vary from relatively simple hazard assessments (evaluating only pesticide toxicity) to more sophisticated risk assessments (where a combination of pesticide toxicity and potential exposure to the pesticide is assessed). Since risk assessment integrates pesticide toxicity and bee exposure, it is generally considered to be more relevant for the estimation of potential impact than a hazard assessment. However, not in all cases will appropriate estimates of exposure be available, and a hazard assessment will then provide an initial indication of the likelihood of adverse effects of the pesticide to bees.

Pesticide hazard and risk assessment for bees in the EU, USA or Australia have so far focused on managed western honey bees *(Apis mellifera* L.*)* alone.[25,26,27] However, honey bees may have different intrinsic susceptibility to pesticides than other bees. They may also be exposed in a different manner due to variations in behaviour and life history, and bee populations may respond in varied ways to pesticides because of differing population dynamics. Consequently, the pesticide risk assessment procedures currently applied for managed honey bees are not necessarily directly applicable to other bees. Only recently have pesticide risk assessment methods for bees other than honey bees received more attention[28], but no clear consensus on risk assessment procedures has yet been established.

1.5 Purpose of the study – pesticide risk profiling

In order to conduct a proper risk assessment of pesticides to bees, information is needed in three areas: (i) the toxicity of the pesticide; (ii) the probability of bee exposure to that pesticide; and (iii) the population dynamics of the bee species in question.

Pesticide toxicity data have mainly been generated for the western honey bee, but much less so for other *Apis* species or non-*Apis* bees (either native or managed). Increasingly, however, toxicity tests are being done with bees other than *A. mellifera*, although not all of these have found their way to the international published literature.

The probability and degree of exposure to pesticides depend on cropping and pesticide application practices, pesticide properties, attractiveness of the crop to bees, and certain aspects of bee biology (in particular phenology and behaviour). Data on these aspects of exposure, for a given crop in a given country or region, may be available from agricultural extension services, pesticide registration authorities, bee experts, agronomists and environmental scientists.

Finally, the population dynamics of the bee species will determine how an observed effect of the pesticide (either lethal or sublethal) will affect long-term survival of the population. This includes such factors as the population size of the bee at the time it is exposed to the pesticide, its population growth rate, and the migration capacity of the bee, among others.

In this assessment, we have attempted to collect information relevant to pesticide risk for (primarily wild) bees that are important on a limited number of focal crops. Because this is not a conventional risk assessment, we use the term 'risk profile'. Initially, risk profiling aims to better identify gaps in our present knowledge. In the longer term, the established risk profiles may provide inputs for risk assessment models that consider wild and non-*Apis* managed bees, which may lead to recommendations for specific risk mitigation measures.

2. Methods

2.1 Focal crops

A limited number of economically important focal crops were chosen for developing a risk profile (Table 1). Focal crops were selected because of their dependence on pollination by wild and/or managed bees, and/or because wild bees were known to be active in these crops.

Tab. 1 Focal crops for which pesticide risk factors were assessed.

Country	Brazil	Kenya	Netherlands
Focal crops	Melon Tomato	Coffee Cucurbits (watermelon & squash) French beans Tomato	Apple Tomato (greenhouse)

Cucurbits, such as melon *(Cucumis melo* L.*)*, watermelon *(Citrillus lanatus (Thunb.))* and squash *(Cucurbita moscata (*Duchesne ex. Lam.)*)* are highly dependent on bee pollination and reduced production by more than 90% can be expected when lacking animal pollination.[6] Both honey bees and other bees are important pollinators.

Highland coffee *(Coffea arabica* L.) is self-pollinating, but both honey bees and other bees have been shown to increase yields by over 50%.[6,9,29] Lowland coffee *(Coffea canephora* L.*)* is self-incompatible, and animal pollination is of great importance for berry production.[6,30]

Tomato *(Solanum lycopersicum* L.*)* is self-compatible, but requires wind- or insect-mediated vibration of the flower anthers for pollination (e.g. by buzz pollination).[6] Bumblebees, some stingless bees and some solitary bees are good buzz pollinators.

French beans *(Phaseolus vulgaris* L.*)* are self-compatible, but increases of up to 10% in yield may be possible with optimal pollination. Furthermore, pollination of French beans may improve the quality and uniformity of seed set.[31]

The production of apple *(Malus domestica* Borkh.*)* greatly depends on insect pollination, and honey bees, bumblebees and solitary bees all have been found to increase fruit yields.[6]

2.1 Risk factors

A preliminary list was established of the main factors considered to potentially influence pesticide risk to bees (Table 2). Factors may have different possible effects on pesticide risk to bees. In some cases, a clear correlation between a given factor and an increase or reduction of risk can be assumed. In other cases this relationship is less clear and requires more detailed information on bee biology or the cropping situation. On the basis of this list, a simple questionnaire was designed to collect information on risk factors for focal crops in the three participating countries.

Tab. 2 Pesticide risk factors and their possible effects on bees.

Risk factor	Possible effect on the risks of the pesticide to bees
Exposure – crop factors	
Surface area under crop:	
- overall size	Larger surface area under the specific crop ➔ higher exposure risk
- patchiness	lower fraction of the crop in the overall area ➔ lower exposure risk
Period(s) in the growing season when pesticides are applied to the crop	*Determinant for factors below*
Period(s) in the year when the crop flowers	If overlap between flowering of crop and pesticide applications ➔ higher exposure risk
Period(s) in the year when bees are foraging or collecting nesting materials	If overlap between bee activity in crop and pesticide applications ➔ higher exposure risk
Period(s) when weeds are flowering in the crop which may be attractive to wild bees	If overlap between flowering of weeds and pesticide applications ➔ higher exposure risk
Crop has extrafloral nectaries	If extrafloral nectaries present in crop ➔ higher exposure risk
Crop is regularly infested with honeydew producing insects	If honeydew producing insects present in crop ➔ higher exposure risk
Drinking water is available in the crop	If drinking water in the crop ➔ higher exposure risk
Exposure – bee biology factors	
Location of nest in relation to crop field	In-field and field-border nests ➔ higher exposure risk Off-field nests ➔ lower exposure risk (depending on distance)
Bee foraging range	If in-field and field border nests: shorter foraging range ➔ higher exposure risk If off-field nests ➔ risk depends on distance between nest and sprayed field
Time spent foraging, or collecting nesting materials, per day ('time-out-of-nest/hive')	More hours out-of-nest/hive ➔ higher exposure risk
Period of the day when foraging or collecting nesting materials.	Early/middle in the day ➔ possibly lower exposure risk (if pesticide is applied afterwards and has very low persistence) All-day/late in the day ➔ higher exposure risk
Number of days spent foraging on the crop (for an individual bee)	More days spent foraging ➔ higher exposure risk

Risk factor	Possible effect on the risks of the pesticide to bees
Number of days spent foraging on the crop (for the colony)	More days spent foraging ➔ higher exposure risk
Number of different nectar and pollen plant species used during crop flowering	Fewer species ➔ higher exposure risk
Quantity of pollen collected per day	Higher quantity ➔ higher exposure risk
Quantity of nectar collected per day	Higher quantity ➔ higher exposure risk
Quantity of nectar consumed per day	Higher quantity ➔ higher exposure risk
Body weight	Higher body weight ➔ possibly lower exposure or impact risk *Determinant for other factors*
% of pollen self-consumed	More self-consumed ➔ higher exposure risk to adult
% of pollen fed to brood	More fed to brood ➔ higher exposure risk to brood
% of nectar self-consumed	More self-consumed ➔ higher exposure risk to adult
% of nectar fed to brood	More fed to brood ➔ higher exposure risk to brood
Collective pollen and/or honey storage in the nest (social bees)	If collective pollen and honey storage ➔ lower exposure risk due to mixing, maturation and microbial action; ➔ possibly higher exposure risk if pesticides are concentrated in honey
Exposure & impact – pesticide use/application practices	
Formulation type	Some formulations types (e.g. micro-encapsulation, sugary baits, DP, WP) ➔ higher exposure risk
Pesticide is systemic	Specific exposure/impact assessment
Pesticide is an insect growth regulator (IGR)	If IGR ➔ specific impact on brood
Mode of application	Some modes of application (e.g. dusting, aerial application) ➔ higher exposure risk Some modes of application (e.g. seed/soil treatment with non-systemic pesticide; brushing) ➔ lower exposure risk
Application rate	For the same pesticide product: higher application rate ➔ higher exposure/impact risk
Application frequency	Higher application frequency ➔ higher exposure risk
Systemic pesticides are applied as soil treatment or seed treatment to a previous rotational crop	If systemic pesticides applied to a previous rotational crop ➔ possibly higher exposure risk
Impact & recovery – pesticide properties	
Contact LD_{50} (adult)	Lower LD_{50} ➔ higher impact (for similar exposure levels)
Oral LD_{50} (adult)	Lower LD_{50} ➔ higher impact (for similar exposure levels)
Oral LD_{50} (brood)	Lower LD_{50} ➔ higher impact (for similar exposure levels)
Foliar residual toxicity	Higher residual toxicity➔ higher impact (for similar exposure levels) & ➔lower likelihood of recovery after pesticide impact
Impact & recovery – life history and population dynamics factors[1]	
(Worker) metabolic rate	Higher metabolic rate ➔ lower impact (increased detoxification)
Degree of sociality	High degree of sociality with one or more reproductive queens and separate foragers ➔ lower risk of impact to the population/colony because pesticide effects primarily on foragers (except for IGRs)
Fraction of population/colony active out of the nest/hive (social bees)	Higher fraction of population of colony active out of the nest/hive ➔ higher risk of impact for the whole population/ colonyr5

Risk factor	Possible effect on the risks of the pesticide to bees
Time to reproductive age of queen/reproductive female (egg-adult)	Shorter development time ➔ lower exposure risk (if development partly overlaps with flowering)
Number of offspring per queen/reproductive female	Greater number of offspring ➔ greater likelihood of population recovery after pesticide impact
Number of generations per year	Greater number of generations per year ➔ greater likelihood of population recovery after pesticide impact
Population growth rate [note: is product of previous 3 factors]	Higher population growth rate ➔ greater likelihood of population recovery after pesticide impact
Number of swarms per colony per year	More swarms per year ➔ greater likelihood of population maintenance, if swarming occurs before pesticide impact & ➔ greater likelihood of population recovery after pesticide impact
Migration distance of swarms	Greater swarm migration distance ➔ greater likelihood of population recovery after pesticide impact (if cropping is patchy)

2.3 Data collection

In Brazil, cropping and bee data were collected through discussions with crop and pollination experts and by consulting published and unpublished literature. Pesticide use information was obtained from crop experts and the pesticide registration authority (Ministério da Agricultura, Coordenação-Geral de Agrotóxicos e Afins) through the Sistema de Agrotóxicos Fitossanitários – Agrofit.

In Kenya, cropping and bee data were collected through discussions with crop and pollination experts and by consulting published and unpublished literature. Pesticide use information was obtained from crop experts and the Kenya Pest Control Products Board (PCPB). In addition, an extensive survey was carried out on pollinator knowledge and crop protection practices covering approximately 150 farmers in Machakos, Kirinyaga and Kiambu counties.

In the Netherlands, cropping and bee data were collected through discussions with crop and pollination experts and by consulting published and unpublished literature. Pesticide use information was obtained from Statistics Netherlands (CBS).

Acute LD_{50} values for the western honey bee (*A. mellifera*) were obtained from a recently developed database, compiled from multiple regulatory and non-regulatory data sources.[32] The lowest (generally 48h) LD_{50} value of both oral ingestion and contact tests, as calculated using the rules defined for the database, was used in this report. When LD_{50} values were not available in the database, the Footprint Pesticide Property Database[33] and the Footprint Biopesticides Database[34] were consulted. Results from brood tests, or sublethal toxicity tests, have not been taken into account. Acute LD_{50} values for bumblebees were taken from a recent review.[35] Pesticide toxicity data for bees other than *A. mellifera* and *Bombus* (Latreille) are still limited. No public database appears to exist for such bees and toxicity data for other bees were therefore not included in this assessment.

3. Results

Detailed results of the study are provided elsewhere.[36]

3.1 Presence of bees

The main groups of bees visiting the focal crops in the three countries are listed in Table 3. In all focal crops, except melon in Brazil and tomatoes in the Netherlands, wild bees may contribute significantly to pollination. This is in addition to, or instead of, the honey bee. Furthermore, in all focal crops, the groups and/or species of bees that are regular visitors appear to be relatively well known. In many cases, important pollinators have been identified, although for some crops the role of wild bees as pollinators requires more study.

Tab. 3 Main groups of bees visiting the focal crops, and their role as pollinator of those crops

Country	Crop	Bee group/species visiting the crop Important pollinator	Visitor; not an important pollinator
Brazil	Melon	*Apis mellifera* L. (honey bee)	*Xylocopa* Latreille (carpenter bees) *Frieseomelitta doederleini* (Friese) (stingless bee)
	Tomato	*Bombus transversalis* (Olivier) (bumblebee) *Bombus atratus* Franklin (bumblebee) *Bombus morio* (Swederus) (bumblebee) *Xylocopa grisescens* Lepeletier (carpenter bee) *Augochlora* Smith (sweat bees) *Exomalopsis auropilosa* Spinola (long-horned bee) *Melipona* Illiger (large stingless bees)	*Apis mellifera* L. (honey bee)
Kenya	Cucurbits	*Apis mellifera* L. (honey bee) Halictidae (sweat bees) (e.g. *Lasioglossum* Curtis)	*Xylocopa* Latreille (carpenter bees)
	Coffee	*Apis mellifera* L. (honey bee) *Patellapis* (Friese) (sweat bees) *Xylocopa* Latreille (carpenter bees) *Megachile* Latreille (leafcutter bees)	
	French beans	*Xylocopa* Latreille (carpenter bees) *Megachile* Latreille (leafcutter bees)	*Apis mellifera* L. (honey bee)
	Tomato	*Xylocopa* Latreille (carpenter bee) *Lipotriches* Gerstaecker (sweat bees)	*Apis mellifera* L. (honey bee)
Netherlands	Apple	*Apis mellifera* L. (honey bee) *Osmia rufa* L. *(=O. bicornis)* (red mason bee) *Bombus* Latreille (bumblebees) (mainly *B. terrestris/lucorum* L.*; B. pascuorum* Scopoli*; B. lapidarius* L.*)* *Andrena* Fabricius (sand bees)	
	Tomato	*Bombus terrestris* L. (bumblebee)	

3.2 Risk factors

3.2.1 Exposure – crop factors

Various crop-related factors may increase bee exposure to pesticides, such as overlap between the presence of bees in the crop area and flowering of the crop or weeds, overlap between bee activity on the flowering crop and pesticide application, or the presence of extrafloral nectaries, insects producing honeydew, or drinking water in the crop area. These factors are summarized for the focal crops in Table 4.

The main factors influencing risk are probably the overlap of pesticide applications with crop flowering or with bee activity in the crop area. In all but one crop, pesticides are applied during flowering and bee activity. Only in coffee production in Kenya, pesticide applications during flowering are explicitly being avoided. In most crops, weeds are being mulched or otherwise controlled, and only in apple in the Netherlands there is risk of exposure of bees foraging on Dandelion flowers just before the apple flowering period.

Of the focal crops, only French beans have extrafloral nectaries. Some cucurbits also have them, but the relevant cucurbit crops in Kenya do not. Most crops are regularly infested by honeydew producing insects such as aphids, whiteflies and scale insects. In all three countries these pests are controlled with insecticides, and to what extent bees will be attracted to such pests to forage honeydew requires further study. In general, bees will use nectar as the main drinking water source. However, in the Netherlands, bumblebees may drink (potentially contaminated) condensed water from the greenhouse walls after the sugar water provided in the colony boxes is depleted.

Tab. 4 Factors related to cropping practices that may influence the risk of bee exposure to pesticides.

	Brazil		**Kenya**				**Netherlands**	
Exposure – crop factors	**Melon**	**Tomato**	**Cucurbits**	**Coffee**	**French beans**	**Tomato**	**Apple**	**Tomato**
Pesticide application overlaps with the flowering period of the crop	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes
Pesticide application overlaps with the flowering period of weeds in the crop	No	No?	No	No	No	No	Yes	No
Pesticide application in the crop overlaps with the period when bees are actively foraging or collecting nesting materials in the crop	Yes	Yes	Yes	No?	Yes	Yes	Yes	Yes
Crop has extrafloral nectaries	No	No	No	No	Yes	No	No	No
Crop is regularly infested with honeydew producing insects	No?	Yes?	Yes	Yes	Yes	Yes	Yes	Yes
Crop may be visited by bees for collection of water	Yes	Yes	-	-	Yes	Yes	Yes	Yes
Overall likelihood of exposure	**high**	**high**	**high**	**low**	**high**	**high**	**high**	**high**

- = data not available; ? = possibly

Overall, the likelihood of bee exposure to pesticides used in the focus crops, based on crop-related aspects, can be considered high. The only exception is coffee in Kenya, where pesticides tend not to be applied in the period when bees are foraging.

3.2.2 Exposure – bee biology factors

Bee biology, such as period, duration and range of foraging, nest location, and nectar and pollen consumption, may affect the risk of bee exposure to a pesticide (Table 2). Many of the listed factors are highly variable for individual species, and even more so among groups of bees. For instance, foraging ranges will depend on the availability of suitable flowering plants, but are also determined by bee size. The timing of foraging may be greatly influenced by weather conditions. The quantity of pollen and nectar collected depends on the size of the colony, the size of the bees, and also on the sugar content of the nectar.

Detailed results for all countries and focal crops are available elsewhere. [36] Here, an example of the results for the focal crops in Kenya is provided (Table 5). Information on the African honey bee was available, but it was more limited for *Xylocopa* (carpenter bee) and sweat bees (Halictidae). No information on relevant bee biology factors could be obtained for local leafcutter bees (*Megachile* Latreille) and the sweat bee *Patellapis* (Friese). Based on the limited bee biology data available, there is no reason to expect higher pesticide exposure for *Xylocopa* than for European honey bee in Kenya, but some key factors could not be quantified. The likelihood of exposure to pesticides of African honey bees is probably similar to European honey bees.

Tab. 5 Factors related to bee biology that may influence the risk of bee exposure to pesticides in the focal crops in Kenya.

Exposure – bee biology factors	**Coffee Cucurbits French beans Tomato** *Apis mellifera scutellata*	**Coffee Cucurbits French beans Tomato** *Xylocopa*	**Coffee** *Patellapis*	**French beans Coffee** *Megachile*	**Tomato Cucurbits** **Halictidae**
Location of nest in relation to crop field (approximate distance from crop field)	Inside and in field borders (50–100 m)	Outside and in field borders; fringes of woodlands	-	-	Outside and in field borders; fringes of woodlands
Average bee foraging range (maximum distance from nest)	~1500 m (10 km)	700–1000 m (6 km)	-	-	50–100 m
Time spent foraging or collecting nesting materials	~10–15 trips/d; 4–11 hrs d^{-1} (individual nectar forager); ~1.5 hrs d^{-1} (individual pollen forager)	1–2 hrs d^{-1} (individual bee); Median flight duration 30 min	-	-	4–10 hrs d^{-1}? (individual bee)
Period of the day when foraging or collecting nesting materials	(Early) morning/all day (on cool days)	Early and late in day	-	Mid-day	Entire day
Time spent foraging on the crop (for an individual bee)	5–15 d	Coffee: 30 d French beans: 100 d Tomato: 90 d	-	-	60 d
Time spent foraging on the crop (for the colony)	Coffee: 30 d Cucurbits: - French beans: 100 d Tomato: 90 d	n.a.	n.a.	n.a.	n.a.
Quantity of pollen collected	200–300 mg d^{-1}	-	-	-	<30 mg d^{-1}
Quantity of nectar collected	250 µL d^{-1}	-	-	-	-
Quantity of pollen consumed	~6.5 mg d^{-1} (nurse bee)	-	-	-	-
Quantity of nectar consumed	80–320 mg d^{-1} (forager)	-	-	-	-
Body weight	60–120 mg (worker)	> honey bee	-	-	3–95 mg
% pollen self-consumed by adult	Limited (early adult stage)	-	-	-	-
% pollen fed to brood	Most; stored and transformed	Up to 100%	-	-	Up to 100%
% nectar self-consumed by adult	Some; most stored and transformed, and consumed as honey	-	-	-	-
% nectar fed to brood	Most; stored and transformed and consumed as honey	-	-	-	-
Collective pollen and/or honey storage in the nest	Yes	Limited?	-	No	Limited?
Overall likelihood of exposure compared to the European honey bee	**Similar**	**Similar?**	**Unclear**	**Unclear**	**Greater?**

- = data not available; ? = possibly; n.a. = not applicable; d = day; hr = hour; min = minute; mg = milligram; mL = millilitre; µL = microliter; Sources of the data in this table are provided elsewhere.[36]

Based on bee biology factors, it can be inferred that sweat bees (Halictidae) on tomato in Kenya may be more exposed to pesticides than the honey bees on the same crop. This is because the nests of sweat bees are located close to the field which, in combination with the more limited foraging range, is likely to increase exposure risk. Furthermore, sweat bees are generally smaller than honey bees and individual foraging time appears longer. Finally, almost 100% of collected pollen is fed directly from the field to the brood, which may lead to higher pesticide exposure of offspring than is the case in honey bee or other pollen-storing bees, like stingless bees (Meliponini). When in storage, microorganisms and added nectar in pollen may accelerate breakdown of pesticides.

Overall, the study shows that there are still major data gaps regarding elements of bee biology that influence exposure risk of bees to pesticides in all three countries. For most bee groups, information was available on daily and seasonal flight activity and on foraging patterns. On the other hand, information was lacking on foraging duration, quantities of pollen/nectar collected and amounts consumed by the foraging adults.

3.2.3 Exposure – pesticide use and application practices

The numbers of pesticide products and active ingredients (a.i.'s) registered and/or used on the focal crops in the three countries are summarized in Table 6.

Tab. 6 Number of pesticides registered and/or used in the focal crops.

	Brazil		**Kenya**				**Netherlands**	
	Melon	**Tomato**	**Cucurbits**	**Coffee**	**French beans**	**Tomato**	**Apple**	**Tomato**
Number of active ingredients registered for use on the crop	64	130	11	9	17	23	72	61
Number of active ingredients used per crop	--	--	29	12	20	29	57	66
Number of active ingredients used in period when bees are active in the crop	--	--	25	0?	20	22	54	60
Number of insecticide/acaricide active ingredients used in period when bees are active in the crop	--	--	13	0?	11	15	13	21
Systemic pesticides are applied as soil or seed treatment to a *previous* rotational crop	yes	yes	?	n.a.	?	?	n.a.	n.a.
Number of systemic pesticides used or registered per crop	35	49	14	5	10	12	28	24
Number of insect growth regulators used or registered per crop	4	15	0	0	0	0	3	6

? = data not available; n.a. = not applicable

A large number of pesticides were registered on tomato in Brazil, but it could not be ascertained which were used in periods when bees were active on the crop. Systemic pesticides were confirmed to be applied by soil or seed treatments to previous crops, which might pose a risk for exposure of bees to contaminated pollen or nectar in the subsequent melon or tomato crops.

In Kenya, a considerable number of pesticides were used on cucurbits, French beans and tomato, and a large fraction of these were used throughout the crop cycle, so potentially exposing bees. In coffee, however, most pesticides were used only after flowering, i.e. when bees were either not or less active in the coffee crop.

In the Netherlands, a large number of pesticides is used while bees are active in both apple orchards and on tomato. Greenhouse tomato production always starts with fresh substrate, and previous crops are therefore not relevant. The use of systemic pesticides in previous rotational crops is not relevant in perennial crops such as apple.

3.2.4 Impact and recovery – pesticide properties

Acute toxicity data for *A. mellifera* are reported for most pesticides, as these tend to be required for pesticide registration. However, in many cases, only acute contact and oral test results obtained on adult worker bees are available.

On average, acute LD_{50} values for honey bees were available for 94% of the a.i.'s used in the various focal crops (Table 7). For only 70% of a.i.'s used on tomato in the Netherlands an acute LD_{50} could be found. This was partly due to the relatively large number of bio-pesticides and general disinfectants being used in that crop. Only few acute LD_{50} values for bumblebees were available.

Tab. 7 Number of acute LD_{50} values available for honey bee and bumblebee in the focal crops, and their associated hazard.

Country Crop	Number of pesticides registered or used	Number of pesticides with an acute LD_{50} for honey bee	Number of pesticides with an acute LD_{50} for bumblebee	% pesticides (no.) which are		
				Highly toxic[1] (LD_{50} < 2 µg bee^{-1})	Moderately toxic (2 ≤ LD_{50} ≤ 11 µg bee^{-1})	Practically non-toxic (LD_{50} > 11 µg bee^{-1})
Brazil						
Melon	64	61	4	28% (17)	13% (8)	59% (36)
Tomato	130	119	13	36% (43)	5% (6)	59% (70)
Kenya						
Coffee	12	12	2	42% (5)	8% (1)	50% (6)
Cucurbits	29	29	9	52% (15)	7% (2)	41% (12)
French beans	20	20	5	40% (8)	5% (1)	55% (11)
Tomato	29	28	7	50% (14)	7% (2)	43% (12)
Netherlands						
Apple	57	52	5	10% (5)	11% (6)	79% (41)
Tomato	66	52	5	21% (11)	8% (4)	71% (37)

[1] Based on the hazard classification for honey bees according to the US-EPA.[27]

Since application rates were not available for all crops, only a comparison of hazards was made of the pesticides used in the different focal crops. The LD_{50} values (the lowest of the oral or contact LD_{50} was used) were classified according to the US-EPA hazard ranking for honey bees[27] (Table 7). The hazard classification for honey bee was then applied as a surrogate for all bees in this study.

The majority of pesticides used in both focal crops in the Netherlands were classified as practically non-toxic to bees. In Kenya the largest fraction of pesticides used was classified as highly toxic to bees, and this concerned all four crops. Both Brazilian crops were intermediate as to the hazard of the pesticides being used. Of the crops assessed in this study, the highest pesticide hazard to bees was found to be in cucurbits and tomatoes in Kenya; the lowest hazard in apple in the Netherlands.

The US-EPA toxicity classification primarily addresses the hazard of pesticides applied as a spray. Systemic pesticides applied as seed or soil treatment are not explicitly covered. However, a relatively large number of systemic pesticides are also being used on the focal crops (Table 6). The worst case toxicity–exposure ratio (TER), as defined by EPPO for pesticides with systemic action, was also calculated.[25] It was found that whenever this systemic TER resulted in a high risk classification, the pesticide had already been categorized as highly toxic by the EPA oral/contact toxicity classification. One can therefore conclude that the EPA hazard classification is also 'protective' for bees when systemic pesticides are concerned, at least for the compounds evaluated in this study.

Tab. 8 Factors related to the bee's life-history and population dynamics which may influence the impact of a pesticide to bees in the focal crops in Brazil.

Impact – bee life history and population dynamics factor	Brazil					
	Melon Tomato	**Tomato**				
	Apis mellifera (Africanized)	*Bombus*	*Xylocopa grisescens*	*Augochlora*	*Exomalopsis auropilosa*	*Melipona*
(Worker) metabolic rate	Hybrids < non-hybrid African or European subspecies	-	-	-	-	-
Degree of sociality	Eusocial	Primitively eusocial	Parasocial	Solitary	Parasocial	Eusocial
Fraction of adult population/colony active out of the nest/hive (social bees)	~35%	< 100%	Up to 100%	100%	100%	< 100%
Time to reproductive age of queen/reproductive female (egg-adult)	~33 d	-	35 – 69 d	-	-	-
Number of offspring per queen/reproductive female	8 – 12 offspring colonies/ parental colony yr^{-1}	-	5 – 8 yr^{-1}	-	-	-
Number of generations per year	3–4	-	1 – 4	-	-	-
Population growth rate [note: is product of previous 3 factors]	16-fold colony increase yr^{-1}	< honey bee	< honey bee	< honey bee	< honey bee	-
Number of swarms per colony per year	Up to 60	n.a.	n.a.	n.a.	n.a.	-
Migration distance of swarms	> European subspecies (=500–600 m; max. 1600 m)	n.a.	n.a.	n.a.	n.a.	-
Overall likelihood of pesticide impact compared to the European honey bee	**Lesser**	**Greater**	**Greater**	**Greater**	**Greater**	**Unclear**

? = data not available; n.a. = not applicable; d = day; m = metre; yr = year; Sources of the data in this table are provided elsewhere.[36]

Insect growth regulators (IGRs) tend to have a relatively low toxicity to adult bees, but may be very toxic to the larvae. A hazard classification based on acute LD_{50} obtained from adult bees is then not appropriate and toxicity data on bee brood are required.[25] Relatively few IGRs are being used on the focal crops (Table 6), and therefore no specific assessment of their risk was conducted.

3.2.5 Impact and recovery – life history and population dynamics

The life-history and population dynamics of the bee species will determine to a large extent how its populations will resist to or recover from such pesticide impact (Table 2).

As an example, information compiled on factors related to life history and population dynamics of the bee groups present on the focal crops in Brazil is shown in Table 8. Information for the other study countries is provided elsewhere.[36]

Limited specific information was available for Africanized honey bee and the carpenter bee *Xylocopa grisescens* Lepeletier, in Brazil. The Africanized honey bee has a considerably higher population growth rate and swarming rate than the European subspecies. As a result, it can be expected that the Africanized honey bee can recover quicker from pesticide-induced adverse effects on the population than the European honey bee.

It can be assumed that population growth rates of all the listed solitary and parasocial bees, will be lower than that of the honey bee. Also, the fraction of the total population which will be out of the nest foraging or collecting nesting materials will be greater for the solitary, parasocial and primitively eusocial bees, than for honey bees and stingless bees. As a result, it is likely that pesticide impact on individual bees will affect more of the populations of the carpenter bees, the solitary sweat bees, the long-horned bees and to a lesser extent the bumblebees, than of the more social bees. In addition, the lower population growth rates would result in less rapid population recovery of these groups.

4. Discussion and conclusions

4.1 Data availability

With respect to the presence of bees in the focal crops, generally it was known which groups of bees were active on the crop, although in a number of cases identification was only known along fairly broad taxonomic groups. The role of the wild bees as pollinators was relatively well known for melon in Brazil, coffee and French beans in Kenya, and tomato in the Netherlands. The lack of data for the other crops underlines the importance to obtain better insights on the exact role of wild bees as pollinators.

With respect to exposure, data were generally available for crop factors and for pesticide use and application factors, although in many cases these data were not complete. Data were limited or lacking especially for factors related to bee biology. As a consequence, it is generally possible to infer the overall likelihood of exposure of wild bees in the focal crops. However, it is often not possible to further qualify or quantify the degree of exposure of individual bee taxa.

With respect to impact and recovery, toxicity data were available for most pesticides used in the focal crops. However, these were mainly limited to acute toxicity to honey bees. Few toxicity studies have been published for bumblebees, and even less so for other bee species. Availability of data on life history characteristics and population dynamics of, in particular, wild bees was poor or completely absent. Much of the research needed on pollination biology would also be of high value to pesticide risk profiling and assessment. Given the limited resources available for such research, it seems important that pesticide ecotoxicologists and pollination biologists seek active collaboration to optimize and mutually complement on-going and planned research efforts.

4.2 Risk profiles

The risk profiling approach used in this study was developed because a comprehensive risk assessment method for wild bees, or even for honey bees in non-temperate cropping systems, is not yet available. The results of this study indicate that important data gaps still exist with respect to, in particular, bee biology and quantification of exposure that may preclude the establishment of a proper risk assessment procedure for wild bees in the near future. However, the elaboration of a risk profile, as outlined in this study, may provide a preliminary qualification of the risks of pesticide use to (wild) bees in specific crops.

There are important differences between a risk assessment and a risk profile. A risk assessment for bees, conducted for the registration of a pesticide, tends to focus on a specific pesticide product, includes a quantitative estimate of exposure and of effect, and refers to explicit acceptability criteria (e.g. the hazard quotient or toxicity-exposure ratio, in the EU/EPPO approach).

A risk profile, on the other hand, focuses on the cropping system. It includes (where possible) a quantitative measure of effects, but generally comprises only a qualitative (or semi-quantitative) estimate of exposure, and can therefore not quantify risks. As a result, explicit acceptability criteria are not used.

We consider risk profiling a particularly useful approach to:

- conduct a qualitative evaluation of pesticide risks to bees in specific cropping systems;
- compare potential risks of pesticide use to bees among cropping systems;
- facilitate discussion among researchers, regulators, farmers and beekeepers on pesticide risks to (wild) bees;
- identify data/information gaps;
- set priorities for further research (e.g. with respect to crops, bee groups, types of pesticides); and
- set priorities for risk mitigation.

In the absence of agreed quantitative risk assessment procedures for wild bees, or honey bees in (sub-) tropical cropping systems, establishing a risk profile provides a structured assessment of potential risks of pesticides to bees in a given crop situation while making explicit any knowledge gaps. This forms a good basis for discussion among researchers, regulators, farmers and beekeepers on how to value potential pesticide risks to bees and pollination in specific cropping systems.

The establishment of a risk profile further helps to set priorities for research, by identifying crops, species or groups of bees, or types of pesticides that merit additional study. For instance, additional research efforts would clearly be justified for pollinator-dependent cropping systems, where there is a great likelihood of exposure of bees to pesticides, and a large fraction of moderately toxic pesticides is being used, i.e. for which the resulting impact on bees may not be clear. Another priority example for research would be a pollinator-dependent crop, in which many highly toxic pesticides are being used, but where the likelihood and extent of exposure of bees is not clear. The focus of research would be different according to the uncertainties that need to be clarified for the cropping system in question.

Even though risk profiling will often lead to less concrete conclusions about risk than formal risk assessment, the establishment of a risk profile could also lead to risk mitigation. In a number of cases, the outcome of a risk profile will be clear enough to warrant risk mitigation measures to be developed and/or to be taken. This would, for instance, be the case if there is a great likelihood of exposure of bees to various highly toxic pesticides in a highly pollinator-dependent crop. The risk of adversely affecting pollinators and crop production in such cases is so great that immediate implementation of risk mitigation measures is justified. The requirement for risk mitigation should, in such high risk cases, not be made conditional to the generation of further data.

Table 9 provides suggestions for priority setting for research and for developing (additional) risk mitigation on the basis of the outcome of a risk profiling exercise. Priorities are mainly based on the likelihood of exposure of bees on the one hand and the toxicity of the pesticides used in the crop on the other. Priorities are also based on the pollination dependency of the crop and the population dynamics of the bee.

Tab. 9 Priority setting for research or for (additional) risk mitigation, based on the outcome of a risk profile for a given cropping system.

Priority for research 'R', or for (additional) risk mitigation 'M' (if in brackets [ ], the priority is secondary to the main priority)		**Crop dependence on pollination**						
		High			**Limited**			**No**
		Likelihood of exposure of bees to pesticides			**Likelihood of exposure of bees to pesticides**			
		High	**Low**	**Unclear**	**High**	**Low**	**Unclear**	
Severity of impact – Large fraction of the pesticides used in the crop are:	Highly toxic	M [R]		R [M] §	M §		R §	
	Moderately toxic	R [M] §		R §				
	Practically non- toxic	R §						

§ In particular if bee population dynamics or life history are likely to increase the severity of pesticide impact or reduce the speed of recovery

It is important to realize that this type of priority setting is relevant to risks of pesticides to bees in crops, in particular those that are to some extent dependent on pollination. It does not guide research or risk mitigation priorities unrelated to crop pollination, e.g. which focus on biodiversity protection. Other criteria are important for such aspects of bee conservation.

This structured profiling exercise of pesticide risks to (wild) bees in different cropping systems on different continents has, according to current knowledge, not been carried out previously. The list of risk factors (Table 2) used in the assessment is definitely not exhaustive, and the possible effects these factors may have on pesticide risks to bees will clearly need further research. It is hoped that this present work can be used as a basis for conducting similar studies elsewhere. Over time, this should result in a more precise set of risk factors, and progressively generate a more comprehensive database of risk profiles for different cropping systems and situations. In the long term, risk profiling is expected to contribute to the development of formal risk assessment procedures for wild bees and for honey bees in non-temperate ecosystems.

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