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Published Version

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To link to this article DOI: http://dx.doi.org/10.1002/pan3.10055

Publisher: Wiley

Received: 2 April 2019 | Accepted: 4 September 2019
DOI: 10.1002/pan3.10055

RESEARCH ARTICLE

PEOPLE AND NATURE | BRITISH ECOLOGICAL SOCIETY

Linking farmer and beekeeper preferences with ecological knowledge to improve crop pollination

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Funding information
Nederlandse Organisatie voor Wetenschappelijk Onderzoek, Grant/Award Number: 841.11.001; Ministarstvo Prosvete, Nauke i Tehnološkog Razvoja, Grant/Award Number: 43001; Natural Environment Research Council, Grant/Award Number: NE/K015419/1 and NE/N014472/1; Javna Agencija za Raziskovalno Dejavnost RS, Grant/Award Number: V4-1622 and P1-0255; Rural and Environment Science and Analytical Services Division; Bayer Crop Science; European Cooperation in Science and Technology, Grant/Award Number: oc-2013-1-15320; BBSRC, Grant/Award Number: BB/R00580X/1; The Scottish Government Rural Affairs and the Environment Strategic Research Programme

Handling Editor: Charles Watkins

Abstract

1. Pollination by insects is a key input into many crops, with managed honeybees often being hired to support pollination services. Despite substantial research into pollination management, no European studies have yet explored how and why farmers managed pollination services and few have explored why beekeepers use certain crops.
2. Using paired surveys of beekeepers and farmers in 10 European countries, this study examines beekeeper and farmer perceptions and motivations surrounding crop pollination.
3. Almost half of the farmers surveyed believed they had pollination service deficits in one or more of their crops.
4. Less than a third of farmers hired managed pollinators; however, most undertook at least one form of agri-environment management known to benefit pollinators, although few did so to promote pollinators.
5. Beekeepers were ambivalent towards many mass-flowering crops, with some beekeepers using crops for their honey that other beekeepers avoid because of perceived pesticide risks.
6. The findings highlight a number of largely overlooked knowledge gaps that will affect knowledge exchange and co-operation between the two groups.

KEYWORDS
beekeeping, ecosystem services, pollination services, rural sociology

1 | INTRODUCTION

Pollination is a key ecosystem service in global crop agriculture, improving crop productivity in 75% of the world's significant crops (Klein et al., 2007), underpinning an estimated $235–577 bn in annual production globally (IPBES, 2016) and supporting the supply of key micro-nutrients in human diets (Smith, Singh, Mozaffarian, & Mayers, 2015). In many regions, pollination services are primarily supplied by wild insects from the surrounding landscape (Garibaldi et al., 2013) and the demand for pollination services growing more rapidly than the supply of honeybees (Breeze et al., 2014), leading to an increased reliance on declining wild pollinators (IPBES, 2016). However, managed insects are often key pollinators, particularly in large, homogenous landscapes, with the European honeybee (*Apis mellifera*) providing approximately half of the recorded crop visits in European studies (Kleijn et al., 2015).

Many farming practices designed to enhance crop production have resulted in long-term pressures on the wild and managed pollinators required to maximize productivity (IPBES, 2016). For example, agricultural intensification generally leads to loss of non-crop forage habitat in the wider agricultural landscape, negatively influencing wild pollinators (Kennedy et al., 2013; Ricketts, Regetz, & Steffan-Dewenter, 2008) and honeybee colony survival (Smart, Pettis, Euliss, & Spivak, 2016) and increasing pollinator reliance on mass-flowering crops for food resources (Holzchuh et al., 2016). Mass-flowering crops, however, only provide a pulse of food during the crop flowering period, resulting in a forage deficit in simplified landscapes (Persson & Smith, 2013) and increase exposure to pesticides, potentially impacting on bee fitness at various scales (Rundlof, Andersson, & Bommarco, 2015; Tsvetkov et al., 2017 but see IPBES, 2016). These effects support evidence that, globally, growth in crop yields is negatively correlated with increasing crop dependence upon pollination (Garibaldi, Aizen, Klein, Cunningham, & Harder, 2011).

Scientific understanding of the relationships between farming practices, landscape composition and pollination services is increasing rapidly (IPBES, 2016). Comparatively less is known about the perceptions and knowledge base of the main stakeholders (farmers and beekeepers) within this system and how they make management decisions. In particular, little is known about the extent to which farmers perceive pollination service deficits (yield reductions due to inadequate pollination) and how they respond to these deficits (Hanes, Collum, Hoshide, & Asare, 2013). Similarly, although there is some evidence that trade-offs between benefits (honey yields, pollination fees etc.) and costs/risks (management costs, low honey quality etc.) to beekeepers can affect decisions on hive placement (Lee, Sumner, & Champetier, 2018; Rucker, Thruman, & Burgett, 2012), how these and other environmental factors affect hive placement Europe is largely unknown.

Understanding the perceptions of farmers and beekeepers can identify preferences, actions and knowledge gaps regarding the interrelations between honeybees and crop pollination, identify potential collaborations between the two stakeholder groups and assist in the formulation of effective actions. Here, we present results of two parallel Europe-wide questionnaire surveys that collectively explore (a) the use and avoidance of crops by beekeepers and their motivations for these decisions, (b) farmers' perceptions of pollination service deficits and their pollination management and (c) the collective views and incentives of both farmers and beekeepers on what can be done to bolster pollination services.

2 | MATERIALS AND METHODS

2.1 | Surveys of farmers and beekeepers

Two separate quantitative surveys were designed, one for beekeepers and the other for growers of insect-pollinated crops (hereafter, 'farmers'). After determining the core research questions, informal consultation with the UK farmers and beekeepers was used to identify motivations for beekeepers using or avoiding crops or farmers used particular pollinators.

The farmer survey was initially tested by 10 UK farmers or farm advisers, while the beekeeper survey was piloted by 54 members of the UK Bee Farmers Association in May and June 2015. Slight edits to the phrasing of some questions in both surveys were made in response to the pilot phase and final surveys were distributed between September 2015 and March 2016.

Both questionnaires had a similar format: asking respondents to name crops that they used and avoided (beekeepers) or used particular pollinators for (farmers). Once named, respondents were invited to select from number of reasons for their decisions. Additional, limited response, questions were posed to contextualize the responses from each group, for example whether beekeepers considered themselves professional or hobbyists. Finally, a series of open questions were used to gain further insights into what each group believed could be done to improve pollination service provision. Beekeepers were asked (a) what factors would encourage them to manage more hives and what, (b) farmers and (c) policy could do to encourage them to provide more pollination services to crops. Farmers were asked to name interventions they would like to use to bolster pollination services and what was preventing them from doing so. The final surveys (Appendix S1) were created and distributed in the online survey software Qualtrics. All responses were recorded anonymously, identified only by a unique number. The questionnaire was approved by the ethics committee of the University of Reading and informed consent was obtained from all participants.

The survey was translated into the appropriate language and distributed in 21 European or European Near Neighbour countries (Table 1). Surveys were widely distributed through farmer networks, beekeeper and farmer associations and blogs, and in some countries also through targeted media outlets with reminders sent out approximately a month after the initial send. Effort was made to promote the farmer survey to both horticultural and arable farmers as honeybees are typically more widely used in permanent crop systems but the study aimed to capture a wider plurality of views.

Results were translated back into English by native speaking co-authors. For each country, survey response data were only included in analyses where there were at least 20 responses to both the beekeeper and farmer survey. This threshold resulted in a final dataset from 10 countries (Table 2) largely due to low responses from farmers. Responses to the open questions were reviewed and grouped together based on the keywords (see Appendix S7 for full results).

In some cases, crop types were merged into a single category for analytical purposes. For example, cherry, sweet cherry and sour cherry were merged into the category 'cherry' as many respondents had not specified which species they were using. Duplicate responses, where a single respondent repeatedly named the same crop to answer the same question (crop used, crop avoided or crop requiring pollination) were also removed.

TABLE 1 Countries and languages in which the survey was distributed

Country	Language(s)
Belgium	French, Dutch
Bosnia and Herzegovina	Bosnian (Cyrillic and Latin)
Croatia	Croatian
Cyprus	Greek
Czech Republic	Czech
Estonia	Estonian
Germany	German
Greece	Greek
Hungary	Hungarian
Ireland	English
Israel	Hebrew
Italy	Italian
Malta	English, Maltese
Netherlands	Dutch
Poland	Polish
Portugal	Portuguese
Serbia	Serbian
Slovakia	Slovakian
Slovenia	Slovenian
Spain	Spanish
UK	English

2.2 | Synthesis of empirical data on crop pollination in Europe

Data on total planted crop area (in hectares per country) across Europe were collected from the FAO statistical database (FAOSTAT, 2019a) for the year 2015, the most recently available data at the time of analysis. Orchard crop area was not available and was not estimated due to differences in the use of the term 'orchard' in different countries (including or excluding citrus or olives for example). For some crops (chestnut) these data were absent and hence correlations between use and avoidance were not conducted. Due to the insufficient sample size of farmers in some countries, no statistical analysis could be conducted to draw any meaningful trends.

2.3 | Statistical analysis

Statistical analyses were conducted in R version 3.2.0 using the base packages (R Core Team, 2018). Tests of differences between binary beekeeper and farmer background questions (e.g. professional vs. hobby beekeeper) between countries were conducted using pairwise Kruskal–Wallis tests. Correlations between (a) beekeeper years of experience and number of hives, (b) farmers' perceived pollination service deficits and maximum extent of yield loss without pollination and (c) between crop use/avoidance and total planted crop area (across all countries) were explored using Spearman's Rank correlation analysis.

3 | RESULTS

In total, 1,708 beekeepers and 426 farmers from 10 European countries provided usable responses (Table 2). Of the beekeepers, 71% identified

TABLE 2 Response numbers from countries used in the analysis

Country	Beekeepers	Farmers
Cyprus	31	32
Estonia	104	59[a]
Greece	193	21
Italy	196	58
Malta	38	39
Netherlands	191	32
Portugal	150	57
Slovenia	320	29
Serbia	134	41
UK	352	58
Total	1,708	406

[a]In total over 500 farmers in Estonia responded to the questionnaire. To prevent this from dominating the response set, a random subsample of 59 farmers was selected for use in the analysis, equal to one greater than either the UK or Italy (jointly the next highest scoring countries). In addition, to prevent the sample being heavily weighted towards farmers who did not name crops, the random sample of Estonian farmers was stratified by an average of the number of UK and Italian farmers who had listed 0, 1, 2 and 3 crops.

as hobbyists and 29% as professionals (Appendix S2). Respondents managed on average 71.5 (*SD* ±152) hives each and have kept bees for an average of 14.3 (*SD* ±14.2) years. Professional beekeepers (n = 488) had significantly more years of beekeeping experience (χ^2 = 221.22, df = 59, $p < .001$) and kept significantly more hives than hobby beekeepers (χ^2 = 972.22, df = 131, $p < .001$). Years of beekeeping experience was positively correlated with hive number (ρ = 0.436, df = 1,706, $p < .001$). As expected, the number of hives managed varied significantly between countries, with Cypriot, Portuguese and Greek beekeepers managing more colonies per beekeeper than most other countries (Chauzat et al., 2013). Between country differences in beekeeping experience were largely nonsignificant (Appendix S2). At present there is no Europe-wide census of beekeeping activities, with individual countries instead collecting different data, making comparison difficult. Compared with 2010 data compiled by Chauzat et al., (2013), professionals represent a greater than expected proportion of respondents but have a lower than expected number of hives/beekeeper (Appendix S2). This may be due to inconsistencies between beekeepers who identified as professional or those that are classified as such, although this definition varies between countries (Chauzat et al., 2013).

Among the farmers, 17% practiced organic farming, 11% took part in agri-environment schemes (AES) and 8% practised both. Statistics on the number of farmers in agri-environment schemes are not available. The sample over-represents the organic farmers who account for c. 3.4% of farmers in the surveyed countries (EUROSTAT, 2019), likely due to the channels the survey was distributed through. The relatively low response rate of farmers is not atypical for online surveys and the survey's particular niche subject is likely to have increased self-selection bias towards the farmers who actively consider pollination.

3.1 | Use and avoidance of crops by beekeepers

Beekeepers identified 101 crops (including crop groups) that they used and 80 that they avoided. There was significant overlap between the two groups with five of the 11 most commonly used crops being also among the 10 most avoided crops (Figure 1). However, few individual beekeepers listed the same crop as both used and avoided, with the exception of Maize, where 24% of those who used the crop (n = 114) also wished to avoid it. Of the beekeepers using and avoiding maize, 62% indicated that they moved their hives within the year. By contrast, chestnut and buckwheat were widely used but not avoided by any beekeeper. At country-specific level, crop use was significantly correlated with planted crop area (ha/country), in buckwheat (ρ = 0.975, df = 8, p = .005) and sunflower (ρ = 0.929, df = 8, p = .006). By contrast, crop avoidance by country was significantly correlated with planted crop area in apple (ρ = 0.778, df = 8, p = .023), oilseed rape (ρ = 0.883, df = 8, p = .003), grape (ρ = 0.827, df = 8, p = .006), potato (ρ = 0.747, df = 8, p = .033) and sunflower (ρ = 0.939, df = 8, $p < .001$).

When asked for reasons why they use or avoid crops, beekeepers (Table 3) indicated that honey yield (50% of responses), crop accessibility (49% of responses), crop availability (46% of responses) and importance for colony growth and survival (43% of responses) were the main factors driving crop use. Payment for pollination services was only a factor influencing crop use in 18% of responses, primarily in the Netherlands, Serbia and the UK, for oilseed rape, sunflower and apple respectively.

Concern over pesticide exposure was the primary reason to avoid a crop (Table 4, 74% of responses), followed by concerns over the toxicity of the nectar to bees and humans (30% of responses). Other factors, including a lack of payment, were only listed in 11% of responses across all crops.

3.2 | Farmer perception of pollination service deficits and pollination management

Farmers named 106 crops which they grew and believed require insect pollination (Appendix S2). Of these, only three crops were grown by ≤10% of respondents: apple (18% of respondents), oilseed rape (13%) and strawberry (10% of respondents). Of the 12 most widely named crops (minimum: 17 responses), only five were among the 12 most widely used by beekeepers, and only three among the 10 most avoided. In particular, soft fruits and unspecified 'orchards' were more frequently named by farmers as requiring pollination services than named by beekeepers as used or avoided crops.

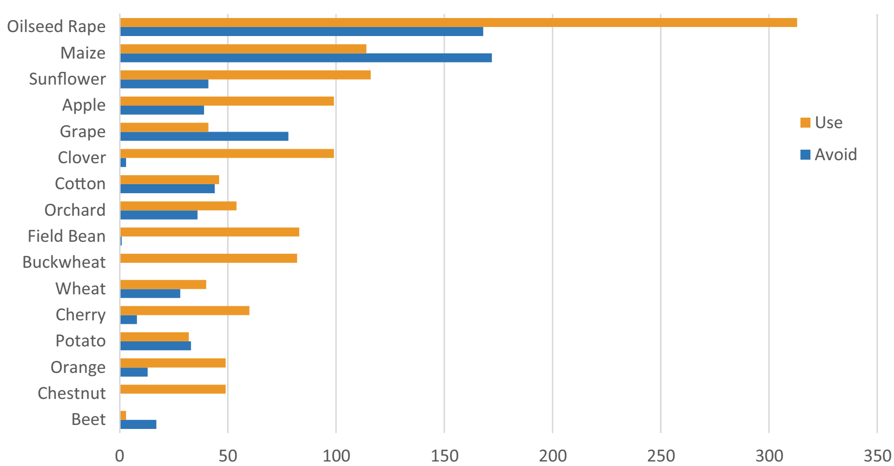

FIGURE 1 Summary of the main crops used (orange) and avoided (blue) by beekeepers. The crops represent the 12 most commonly used (due to tied values) and 10 most commonly avoided across all 1,708 respondent beekeepers

TABLE 3 Summary of reasons why beekeepers use crops

Crop	*N*	Yield (%)	Quality (%)	Access (%)	Available (%)	Sustain (%)	Recommended (%)	Paid (%)	Own (%)	Growth (%)	Reliable (%)
Apple	99	28	13	42	42	28	6	26	24	44	24
Buckwheat	82	56	43	50	50	67	18	7	24	59	34
Cherry	60	42	18	47	45	55	8	28	18	58	25
Chestnut	49	67	63	47	57	51	27	2	24	43	51
Clover	99	62	45	58	47	41	8	5	17	53	51
Field Bean	83	70	40	65	36	37	4	22	5	55	36
Maize	114	7	5	24	12	11	1	2	8	13	5
Oilseed Rape	313	73	19	58	71	41	12	16	3	57	52
Orange	49	71	51	57	55	47	16	2	16	59	47
Orchard	54	33	24	37	41	35	13	26	20	43	15
Sunflower	116	73	32	61	46	37	47	37	8	22	11
All crops		50	30	49	46	37	13	18	13	43	32

Note: *N*: Number of respondents across all countries that listed this crop as one they used. Yield: the crop has a good honey yield. Quality: the crop produces a high-quality honey. Access: the crop is easily accessible. Available: the crop is widely available within the landscape. Sustain: the crop is important to sustain colonies. Recommended: the use of the crop was recommended by another beekeeper. Paid: the beekeeper is paid to provide pollination services to the crop. Own: the beekeeper also owns the crop and wants it to be pollinated. Growth: The crop is important for colony growth. Reliable: the crop produces reliable honey yield. Eleven crops were selected as equal numbers named orange and chestnut. Orchard denotes unidentified orchard crops.

TABLE 4 Summary of reasons why beekeepers avoid crops

Crop	*N*	Yield (%)	Unreliable (%)	Quality (%)	Alternatives (%)	Toxic (%)	Pesticides (%)	No pay (%)	Recommended (%)	Disease (%)
Apple	39	8	8	3	13	31	69	10	13	3
Beet	17	18	0	0	12	0	71	12	6	18
Cotton	44	9	14	18	18	16	73	16	16	9
Grape	78	24	12	8	15	27	91	5	12	8
Maize	172	22	12	12	15	35	80	8	10	5
Oilseed Rape	168	4	6	36	20	21	61	18	5	4
Orchard	36	0	14	11	6	44	83	11	6	0
Potato	33	21	21	18	21	21	85	9	6	12
Sunflower	41	29	29	17	22	63	78	17	15	20
Wheat	28	43	11	14	21	18	71	7	7	7
All crops		17	12	16	18	30	74	11	9	8

Note: *N*: Number of respondents across all countries that listed this crop as one they avoided. Yield: the crop has poor honey yield, unreliable: the crop produces unreliable honey yields. Quality: the honey produced from the crop is of poor quality. Alternatives: there is better alternative forage available at the same time of year. Toxic: the nectar is toxic to bees or humans. Pesticides: the crop has an unacceptable risk of pesticide exposure. No Pay: the beekeeper is not paid for pollinating this crop. Recommended: other beekeepers have advised that this crop should be avoided. Disease: the crop has an unacceptable risk of bringing hives into contact with pests or diseases. Orchard denotes unidentified orchard crops.

Approximately 49% of farmers indicated that they experienced yield deficits due to inadequate pollination (pollination deficits) in at least one crop they grew (Appendix S3). Of these, c. 56% (n = 68) hired one or more managed pollinators. Farmers' perceptions of yield dependence upon insect pollination often differed substantially from literature estimates (Klein et al., 2007), including four crops where yield loss estimates were >20% lower (melon, watermelon, chestnut and pear) and one crop where estimates were >20% higher (tomato) than literature medians (Figure 2).

In terms of pollination management, 31% of farmers indicated that they own honeybees, 29% hire one or more pollinating taxa (in total, 47% either owned or hired at least one managed pollinator) and, despite few farmers partaking in agri-environment schemes (AES), 64% use one or more of three environmental management measures: flower-rich field margins (29%), avoid spraying at field margins (low input margins) (51%) and hedgerows (40%). In Estonia, Portugal, Italy and Serbia, >25% of respondents owned their own honeybees compared with <10% of respondents in the Netherlands, the UK or Greece (Appendix S4). Serbian farmers accounted for almost half (48%) of managed solitary bee use, on several crops. Enhancing pollination was not often mentioned as a reason for using environmental management measures, both across all crops pooled and individual crops (Appendix S5).

Farmers' of management decisions were mostly driven by the effectiveness (managed honeybees and bumblebees), recommendations from other farmers (solitary bees) or improving yield through means other than pollination services (environmental management; Appendix S5). Using an ordinal 0–5 scale of pollinator effectiveness per crop, farmers believed that honeybees were the most effective source of pollination services (median score 5), followed by agri-environment measures (median score 4), managed bumblebees (median score 4) and managed solitary bees (median score 3). At a crop-specific level, honeybees had the highest or joint-highest median effectiveness scores in 10 of the 12 most common crops. Of the other crops, bumblebees had the highest effectiveness score for melon (median 4) and solitary bees for pear (median 4.5). In watermelons, all measures had an equal median score of 5 (Appendix S6).

3.3 | Views on incentives to support honeybees and enhance crop pollination services

Each questionnaire ended with a number of optional open questions. As expected, these have lower response rates than other questions; however, in all cases professional beekeepers provided a similar proportion of answers to amateurs. Common factors that beekeepers suggested would incentivise them to increase the number of hives they keep from current levels include: improved honey yield (n = 140, 8% of respondents), greater forage availability to sustain colonies (n = 111, 6% of respondents) and stronger honey markets (n = 102, 6% of respondents; Appendix S7). For beekeepers, reducing pesticide exposure was the most commonly suggested measure that both farmers (n = 400, 23% of respondents) and policymakers (n = 140, 8% of respondents) could undertake to support increased honeybee pollination services, although few beekeepers suggested banning some or all pesticides (n = 20, 1% of respondents as a farmer action and n = 65, 4% of respondents as a policymaker action). Greater farmer willingness to pay for pollination services (n = 158, 9% of respondents), policymakers introducing subsidies for pollination services (n = 122, 7% of respondents) and increasing awareness of beekeeper pollination services (n = 135, 8% of respondents as a farmer action and n = 118, 7% of respondents as a policymaker action) were also commonly suggested. Professional and hobby beekeepers gave similar answers to most questions. Hobbyists made up a disproportionate majority of respondents wanted greater forage availability in order to manage more hives (82 of 111) or (if provided by farmers) provide more pollination services (102 of 115). This difference is driven by the large number of hobbyists who do not move their hives. Hobbyists also made up a majority of those who wanted policymakers to ban one or more pesticides (47 of 65).

Farmers most frequently listed hiring honeybees (n = 19, 6% of respondents), bumblebees and increasing on-farm flower abundance and diversity (both: n = 11, 4% of respondents) as measures they would like to implement in the future, but citing lack of experience (68% with honeybees, 64% with bumblebees) and expenses (60% with flower abundance and diversity) as the main barriers.

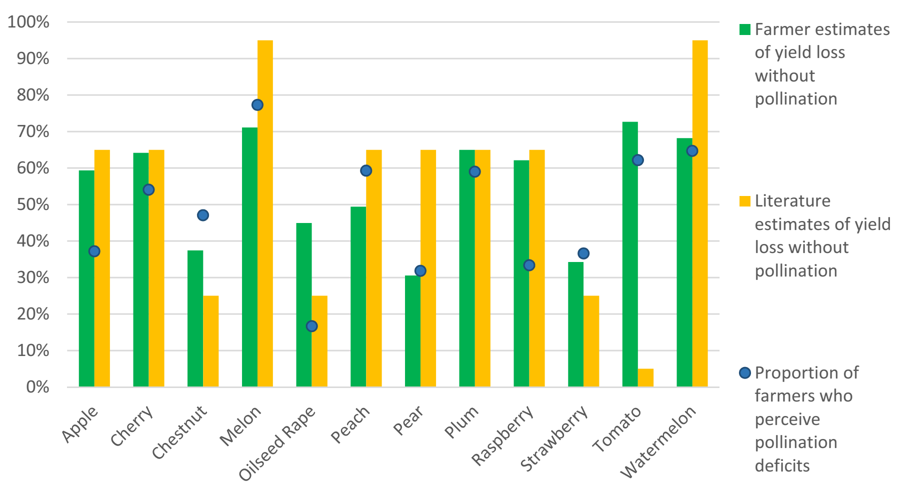

FIGURE 2 Farmers' perceived yield loss in the absence of pollination services compared with literature estimates (from Klein et al., 2007) and percentage of farmers who perceive pollination service deficits, arranged by crop

4 | DISCUSSION

Despite the benefits of pollination to high-value crop systems (IPBES, 2016), the perceptions of farmers and beekeepers on pollination management have been largely overlooked. This study used parallel surveys across 10 European countries to compare beekeeper use of crops with farmer demands for pollination services. The findings highlight opportunities for further co-operation between beekeepers and farmers as approximately half of the farmers surveyed believed they were experiencing pollination deficits (yield losses due to inadequate pollination). Many beekeepers used mass-flowering crops due to their accessibility and high honey yields, but there was widespread crop avoidance due to pesticide exposure. By identifying such barriers and knowledge gaps, wider collaboration between these two key stakeholders can be developed.

4.1 | Beekeeper crop use and avoidance

Beekeepers, as a group, were ambivalent about utilizing flowering crops, with some beekeepers preferring to utilize certain crops while others preferring to avoid these very same crops (Figure 1). This results from beekeepers perceiving different trade-offs between the benefits of using these crops as forage (mainly honey yield, access and availability) and the perceived costs, primarily the risks of exposure to pesticides. Oilseed rape and sunflower were widely used by beekeepers for their honey yields and resources, while at the same time widely avoided by others primarily because of perceived pesticide risk. Research into pesticide impacts on honeybee colonies has produced mixed results, from no impact to moderate effects on short-term colony functioning (Holder, Jones, Tyler, & Cresswell, 2018; IPBES, 2016; Tsvetkov et al., 2017, Woodcock et al., 2017), and therefore fails to provide clear guidance to beekeepers. Furthermore, despite these concerns, field beans and buckwheat were widely used and rarely avoided, suggesting that these crops are perceived as relatively safe, despite often being treated with insecticides and potentially being cross contaminated by metabolites from previous treatments in a rotation (Botias, David, Hill, & Goulson, 2016). Professional and more experienced beekeepers were also less likely to avoid crops because of pesticide risks. Collectively, these findings indicate that, lacking clear advice from empirical research beekeepers judge the risks of pesticides from their own experiences and other sources (e.g. the media).

Use of crops was most often driven by honey yield potential, accessibility or the time of the year the crop flowered. Literature on nectar and honey production is sparse, although generally those crops that were used for nectar by a high proportion of beekeepers tend to have a greater quantity and concentration of nectar than other crops (notably buckwheat, sunflower and oilseed rape – Free, 1993). For many crops listed, the total concentration of nectar has not been studied, notably chestnut which many beekeepers used but only one avoided. However, a small number of hobby beekeepers indicated that they used crops which bear no nectar (e.g. maize) because they are good sources of honey. These findings indicate that beekeepers use personal experience rather than scientific literature to determine the honey yield of a crop. Therefore, further research into how different beekeepers perceive trade-offs between honey yield and pesticide risk will be a key step in fostering co-operation with the farmers growing high-yielding crops.

4.2 | Farmer perceptions of pollination services

Approximately half of the sampled farmers believed they had a pollination deficit (yield shortage due to inadequate pollination) in one or more of their crops. The crops that were most widely identified as experiencing pollination deficit (e.g. melon/watermelon, tomato) are not the ones that beekeepers tended to favour or avoid. This may be partially due to the specialized nature of many farmers, where they predominantly grow one or only few different crops, compared to beekeepers who can place their hives in several different cropping systems to take advantage of optimal nectar resources. While pollination deficits have been reported in particular case studies (e.g. Garratt et al., 2014), it is impossible to estimate how widespread such deficits are without extensive monitoring of pollination services (e.g. Carvel et al., 2016). Pollination deficits often manifest in obvious ways on crops such as strawberries (greater proportion of malformed fruits – Klatt et al., 2014), but in many other crops (e.g. oilseed rape) this could be conflated with deficits in other areas, such as pest regulation (Lundin, Smith, Rundlöf, & Bommarco, 2013). These findings point to an urgent need for widespread monitoring of pollination services to inform farmers and effectively allocate resources to areas that are experiencing, or are at high risk of, pollination deficits.

Despite the widespread perception of pollination deficits, less than a third of farmers (29%) actively hired managed pollinators, possibly due to a lack of clear-cut information on pollination management available to farmers. Most recommendations on the number of hives per hectare to achieve optimal pollination of a particular crop are based on expert judgement rather than primary research (Rollin & Garibaldi, 2019). Although, studies generally demonstrate linear relationships between crop yield and pollinator visitation (Klein, Steffan-Dewenter, & Tscharntke, 2003), this relationship is likely to reach a saturation point where all plant ovules are fertilized (Morris, Vasquez, & Chacoff, 2010) and excessive pollination damage economic output in some crops (Garratt et al., 2014; Saez, Morales, Ramos, & Aizen, 2014). Consequently, the relationship between managed pollinator density and yield is unlikely to be linear in many crops and will require specific studies to determine efficient honeybee use.

Many farmers used one or more of three agri-environment management measures (hedgerows, flower-rich field margins and low input margins). Both hedgerows and flower-rich field margins are particularly beneficial environmental management measures for pollinators, even in already diverse landscapes (Scheper et al., 2013), and may therefore can enhance productivity (Blaauw & Isaacs, 2014; Pywell et al., 2015). This, along with the high average rating for pollinator effectiveness, suggests that farmers recognize the benefits of these management options, despite pollination services not being the main motivator behind habitat creation. Farmers therefore appear to view pollination as a low priority, focusing instead on managing for what they perceive as more pressing issues, such as soil quality (Zhang, Potts, Breeze, & Bailey,). However, research increasingly suggests that yields of pollinated crops are limited by inadequate pollination (Garibaldi et al., 2011) and pollination is at least as important as conventional inputs (Fijen et al., 2018), further highlighting the need to better examine the actual importance of pollination services across Europe.

In five of the 12 most commonly named crops, farmers' estimated yield loss in the absence of pollinators differed by more than 20% to literature estimates. However, the literature base is also small, not standardized and often old for many crops. More recent studies have demonstrated that the impact of pollination on crop yield differs between varieties (Garratt et al., 2016; Hudewenz, Pufal, Bogeholz, & Klein, 2013), local landscape context and interactions with other inputs (e.g. Lundin et al., 2013). Although they are unlikely to be based on empirical methods, farmers' perceptions may possibly more accurately reflect current, local conditions. However caution should be exercised in interpreting these perceptions for niche crops as a small number of farmers also believed that wind pollinated crops (e.g. 13 farmers named wheat as a pollinated crop). Standardized field studies (Carvel et al., 2016; Garratt et al., 2016) exploring pollinator dependence of current and emerging varieties, in relation to other inputs and landscape context, would allow for researchers and agronomists to provide better advice on pollination management.

4.3 | Future collaborations: reducing pesticides

Reducing, but not banning, pesticide use was the most widely suggest farmer and policy action among professional and hobby beekeepers. Presently, European farmers typically use insecticides to preempt pest damage rather than directly control outbreaks (Ahmed, Englund, Åhman, Lieberg, & Johansson, 2011; Zhang, Potts, et al.,). The EU's recent restriction on neonicotinoid insecticides (European Commission, 2018), which are typically applied before seeding arable plants, is likely to cause farmers to revert to older compounds (e.g. pyrethroid sprays- Zhang et al., 2017), which have not been as rigorously assessed for their impact on pollinators (IPBES, 2016). An alternative is integrated pest management (IPM), where farmers encourage natural enemies of pests within their fields and only apply insecticides when pest densities reach a certain threshold, reducing exposure of non-target pests and potentially saving farmer costs (Zhang, Garratt, Bailey, Potts, & Breeze, 2018). Furthermore, despite evidence for the effectiveness of lower chemical use in supporting pollinator populations (Scheper et al., 2013), the surveyed farmers who used low input field margins were more likely to perceive pollination deficits and rarely indicated that they used this management to improve pollination services.

Uptake of change is slow because farmers often do not perceive benefits from natural enemies (Zhang, Potts, et al.,), and are concerned that neighbouring farmers will not fully co-operate (Stallman & James, 2015), increasing the risks of their fields being a safe haven for pests (Wilson & Tisdell, 2001). Enhancing uptake will therefore require dedicated efforts to translate research into practical activities by focusing on outcomes that are relevant to farmers at a local scale (Kleijn et al., 2019). This evidence base can then be developed into programmes that, ideally, are demonstrably effective, trustworthy and with low initial risk (e.g. through no-cost trials; Reed et al., 2014).

4.4 | Future collaborations: developing pollination markets

Although few beekeepers indicated that payments received were a reason for using a crop, beekeepers widely stated that payments for pollination services would be a major incentive. Such markets for pollination services are relatively small in Europe, often run by beekeeping associations and with no centralized price or membership information available. American style large-scale migratory pollination markets, with beekeepers migrating between countries is theoretically possible. However, in Europe there is no single highly concentrated crop market on the scale of the California almond market (FAOSTAT, 2019a) upon which the profitability of the US pollination market depends (Ferrier, Rucker, Thurman, & Burgett, 2018; Lee et al., 2018). Other factors such as different standards for bee health and training between countries (Chauzat et al., 2013), and the large number of languages in Europe (compared to the United States where English is the majority language) would also complicate such international markets. Instead, expanding national markets may be more viable.

Apart from the presence of a high demand crop, the viability of pollination markets is dependent upon a combination of: (a) the availability of suitable forage for colony survival and honey production outside of crop flowering, (b) the market price of honey, (c) the level of pollination service payments (Champetier, Sumner, & Wilen, 2015; Lee et al., 2018). If suitable forage is not available, supplemental feeding has a cost to both beekeeper profits and colony fitness, reducing the value of the colony as a unit of honey and pollination production in the future (Champetier et al., 2015). Such additional forage can be provided through dedicated in-field planting (flower margins), crop diversification or habitat maintenance (Cole, Brocklehurst, Robertson, Harrison, & McCracken, 2017), which are supported by agri-environment schemes in some of the countries surveyed (Batary, Dicks, Kleijn, & Sutherland, 2015). However, while forage increases were widely suggested by beekeepers as a means to increase service provision, most of these were hobbyists, indicating that forage constraints are not a problem for professional beekeepers.

Increases in honey prices/profits and payments for pollination services were widely cited by professional beekeepers as factors that would encourage them to expand their stocks. Honey prices are heavily influenced by international trade with low cost imports often contributing to gradual reductions in domestic honey prices (Lee et al., 2018). As of 2015, four of the countries surveyed (UK, Italy, Netherlands and Cyprus) import more honey than they produce, primarily from China (domestic honey data absent for the Netherlands and Malta; FAOSTAT, 2019a,b). In these countries, simple market controls such as tariffs may affect domestic honey prices, but more significant interventions such as subsidies may be required to increase honey profits in other countries.

Increasing payments for pollination services will require farmers to be willing to pay beekeepers profitable sums (Breeze, Dean, & Potts, 2017; Champetier et al., 2015), believe it is important (Zhang, Potts, et al.,) and believe this is more viable than alternative measures (e.g. growing pollinator independent crops; Ferrier et al., 2018). Such an economy could arise naturally through increased dialogue and barter between farmers and beekeepers. However if government or other third party intervention is required then prices should be based on the demonstrable economic benefits of additional bee hives against the full costs of supplying and managing hives all year round (Champetier et al., 2015; Lee et al., 2018) and address issues of free riding, whereby farmers may receive pollination benefits from hives hired by other farmers (Asare, Hoshide, Drummond, Criner, & Chen, 2017).

Subsidies, another measure widely suggested by professionals, may provide a solution to these problems. Currently, each EU country receives c. €4.3/hive in support for beekeeping related issues, but not support for pollination services and of the countries surveyed, only Greece, Italy and Cyprus spend any of this subsidy on supporting local honey production (Majewski, 2017). Expanding these funds to subsidise, for example providing services to low nectar crops, could expand commercial pollination without rising farming costs. Regardless of how it achieved, any expansion of beekeeping markets should be mindful of potential negative impacts on wild pollinators (Lindstrom, Herbertsson, Rundlof, Bommarco, & Smith, 2017) and the potential health impacts of bee colony movement (IPBES, 2016).

4.5 | Shortcomings and knowledge gaps

Although efforts were made to capture as broad a range of beekeepers and farmers as possible, the sample is biased towards organic farmers and professional beekeepers. The latter is less of an issue as amateurs typically own only a minority of national hives (Chauzat et al., 2013) and are less likely to provide pollination services (Breeze et al., 2017). However the limited farmer response, makes interpreting national scale trends and the appropriate responses very difficult.

Interpretation of these results is further hindered by a lack of statistical information on apiculture (hobby and professional) in each country, with only ad hoc data available (Chauzat et al., 2013; Majewski, 2017). Collecting these data in a regular, open and consistent manner should be a priority to underpin further research into apiculture across Europe and properly target initiatives and resources. Secondly, the findings highlight an urgent need to better understand how the perceptions of farmers and beekeepers around crop pollination are formed through further social science work building on this study. Understanding this will be essential to tailor research on for example pesticide spraying regimes, hive numbers or hive placement into practical outcomes (Kleijn et al., 2019). Finally, the study demonstrates that efforts to facilitate communication between farmers and beekeepers would be valuable to support pollination service security into the long term.

ACKNOWLEDGEMENTS

This paper was drafted during two workshops organized by D.K. (Wageningen) and A.-M.K. (Freiburg) and financed by the European Cooperation in the field of Scientific and Technical Research – COST, SUPER-B (Sustainable Pollination in Europe: joint Research on Bees and other pollinators), reference oc-2013-1-15320. Further funding were provided by BBSRC, NERC, ESRC and the Scottish Government under the Global Food Security Programme (T.D.B.: grant BB/R00580X/1), Bayer Crop Science (V.B., A.-M.K.), UK Natural Environmental Research Council (L.D.: grants NE/K015419/1 and NE/N014472/1), Netherlands Organisation for Scientific Research (D.K., J.S.: project 841.11.001), The Scottish Government Rural Affairs and the Environment Strategic Research Programme 2016-2021 (L.C.), Slovenian Research Agency (research core funding No. P1-0255 and V4-1622). Ministry of Education, Science and Technological Development of Serbia (Project 43001). The authors wish to thank Mike Garratt for invaluable comments on prior versions of this paper and Weiyue Wang for Mandarin translation.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHORS' CONTRIBUTIONS

T.D.B. to G.P. and D.K. designed the study, analysed the data and wrote the first draft of the manuscript; all the authors contributed data and revised the manuscript.

DATA AVAILABILITY STATEMENT

Except where otherwise noted, all data used in this study were collected as part of the farmer and beekeeper surveys described. These data and associated R scripts are available on request from T.D.B. These data are not publicly available due to them containing information that could compromise participant consent agreements. Informed consent was obtained from all subjects.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

How to cite this article: Breeze TD, Boreux V, Cole L, et al. Linking farmer and beekeeper preferences with ecological knowledge to improve crop pollination. *People Nat*. 2019;00:1–11. https://doi.org/10.1002/pan3.10055