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On-farm experiences shape farmer knowledge, perceptions of pollinators, and management practices

Julia Osterman [a,b,*], Patricia Landaverde-González [a,b], Michael P.D. Garratt [c], Megan Gee [d], Yael Mandelik [e], Aleksandra Langowska [f], Marcos Miñarro [g], Lorna J. Cole [h], Maxime Eeraerts [i], Danilo Bevk [j], Omri Avrech [e], Zbigniew Koltowski [k], Flor Itzel Trujillo-Elisea [l], Robert J. Paxton [a,m], Virgine Boreux [n], Colleen L. Seymour [o,p], Brad G. Howlett [d]

[a] Martin Luther University Halle-Wittenberg, General Zoology Institute of Biology, Hoher Weg 8, 06120 Halle (Saale), Germany
[b] Helmholtz Centre for Environmental Research-UFZ Leipzig, ESCALATE, Department of Computational Landscape Ecology, Permoserstrasse 15, 04318 Leipzig, Germany
[c] Centre for Agri-Environmental Research, School of Agriculture, Policy and Development, University of Reading, Reading RG6 6AR, UK
[d] The New Zealand Institute for Plant and Food Research Ltd., 8140 Christchurch, New Zealand
[e] Department of Entomology, The Hebrew University of Jerusalem, Rehovot 7610001, Israel
[f] Institute of Zoology, Poznań University of Life Sciences, Poznań, Poland
[g] Servicio Regional de Investigación y Desarrollo Agroalimentario (SERIDA), Ctra AS-267, PK 19, E-33300 Villaviciosa, Asturias, Spain
[h] Integrated Land Management, SRUC, JF Niven Building, Ayr KA6 5HW, UK
[i] Department of Plant and Crops, Faculty of Bioscience Engineering, Ghent University, Coupure Links 653, Ghent, Belgium
[j] Department of Organisms and Ecosystems research, National Institute of Biology, Večna pot 111, 1000 Ljubljana, Slovenia
[k] The National Institute of Horticultural Research, Apiculture Division, 24-100 Pulawy, Poland
[l] El Colegio de la Frontera Sur, Unidad Campeche, A. Rancho Polígono 2-A, Ciudad Industrial, CP 24500 Lerma, Campeche, Mexico
[m] German Centre for Integrative Biodiversity Research (iDiv) Halle-Jena-Leipzig, Puschstrasse 4, 04103 Leipzig, Germany
[n] Nature Conservation and Landscape Ecology, University of Freiburg, Germany
[o] Kirstenbosch Research Centre, South African National Biodiversity Institute, Private Bag X7, Claremont 7735, South Africa
[p] DST-NRF Centre of Excellence, FitzPatrick Institute of African Ornithology, University of Cape Town, 7701, South Africa

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ABSTRACT

Mitigating pollinator declines in agriculturally dominated landscapes to safeguard pollination services requires the involvement of farmers and their willingness to adopt pollinator-friendly management. However, farmer knowledge, perceptions, and actions to support on-farm pollinators and their alignment with science-based knowledge and recommendations are rarely evaluated. To close this knowledge gap, we interviewed 560 farmers from 11 countries around the world, cultivating at least one of four widely grown pollinator-dependent crops (apple, avocado, kiwifruit, oilseed rape). We particularly focused on non-bee crop pollinators which, despite being important pollinators of many crops, received less research attention than bees. We found that farmers perceived bees to be more important pollinators than other flower-visiting insects. However, around 75% of the farmers acknowledged that non-bees contributed to the pollination of their crops, seeing them as additional pollinators rather than substitutes for bees. Despite farmers rating their own observations as being most important in how they perceived the

* Corresponding author at: Martin Luther University Halle-Wittenberg, General Zoology, Institute of Biology, Hoher Weg 8, 06120 Halle (Saale), Germany.
E-mail address: jul.osterman@gmail.com (J. Osterman).

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contribution of different crop pollinator taxa, their perception aligned closely with results from available scientific studies across crops and countries. Farmer perceptions were also linked with their pollinator management practices, e.g. farmers who used managed bees for crop pollination services (more than half the farmers) rated these managed bees as particularly important. Interestingly, their willingness to establish wildflower strips or manage hedgerows to enhance pollinator visitation was linked to their ecological knowledge of non-bees or to government subsidies. Farmers adapted practices to enhance pollination services depending on the crop, which indicates an understanding of differences in the pollination ecology of crops. Almost half of the farmers had changed on-farm pollination management in the past 10 years and farm practices differed greatly between countries. This suggests integrated crop pollination measures are being adapted by farmers to reach best pollinator management practices. Our findings highlight the importance of studying local knowledge as a key to co-design locally-adapted measures to facilitate pollinator-integrated food production as ecological intensification tools.

1. Introduction

With 38% of the land surface currently under agricultural land use (FAO, 2021), farmer decision-making and the practices they subsequently implement are crucial for crop yields as well as impacting biodiversity. Ongoing world population growth and changes in human diet preferences (Godfray et al., 2010) further result in increasing land area used for agriculture (Aizen et al., 2019) as well as landscape simplification through agricultural intensification (Kehoe et al., 2017). Approximately 75% of globally important crops depend on animal pollination (Klein et al., 2007), especially crops that provide essential human nutrients (Eilers et al., 2011). Furthermore, the area of land cultivated with pollinator-dependent crops is increasing disproportionately to other crops (Aizen et al., 2019) and to the availability of honey bees as managed pollinators (Aizen and Harder, 2009). Although yield stability benefits from diverse pollinator communities (including bees and non-bees) (Hoehn et al., 2008; Garibaldi et al., 2013; Mallinger and Gratton, 2015; Rader et al., 2016; Senapathi et al., 2021), agricultural expansion and intensification remain major drivers of biodiversity loss (Kehoe et al., 2017), decreasing the stability of yield in pollinator-dependent crops (Deguines et al., 2014). Therefore, there is an urgent need for farmers to safeguard pollinators and their diversity to ensure sufficient pollination and secure global food production.

Ecological intensification has been proposed as a more nature-based solution to safeguard food production, while at the same time not harming or even potentially enhancing biodiversity (Bommarco et al., 2013; Kleijn et al., 2019). For example, flower strips have been shown to enhance pollinator communities over time, leading to enhanced crop pollination services and yields in adjacent crops that surpass implementation costs (Blaauw and Isaacs, 2014). Several governmental programs encourage farmers to incorporate biodiversity-friendly measures through subsidies, especially in North America and Europe (Garibaldi et al., 2019; Pe'er et al., 2020). Nevertheless, farmers can be reluctant to implement ecology-based measures, even when evidence supports the benefits they can deliver (Kleijn et al., 2019). Moreover, perceptions of agricultural biodiversity and ecosystem services differ substantially between farmers and scientists, suggesting a communication gap (Maas et al., 2021), which might affect the uptake of ecological measures (Knapp et al., 2021).

Effectively employing ecological intensification is knowledge-intensive, context-dependent, and continually being refined as new evidence emerges (Gemmill-Herren et al., 2021). Some aspects of nature`s contribution to agricultural production have only recently been addressed by scientists, for example the contribution of non-bees (i.e., flies, butterflies, beetles, moths, birds) to crop pollination (Rader et al., 2016). Yet it is clear that the contribution of different insect groups to pollination varies with the crop system studied (Rader et al., 2016, 2020) and the geographic region (Brown and Cunningham, 2019; Dymond et al., 2021). In addition, there is often a lack of evidence (Albrecht et al., 2020) or no scientific consensus of optimal practices to boost pollination services (Rollin and Garibaldi, 2019) or recommendations might be context dependent. For example, honey bee colony density recommendations are highly variable even within the same crop (Delaplane and Mayer, 2000; Rollin and Garibaldi, 2019) and fixed hive stocking rates do not guarantee consistent pollinator visitation rates (Howlett et al., 2015; Osterman et al., 2021). In addition, benefits of measures to enhance biodiversity might take several years to be effective (Blaauw and Isaacs, 2014). This uncertainty makes the communication of scientific findings between researchers and farmers and recommendations for best practice problematic.

Farmer perception of pollinators in general, and especially of non-bees, are rarely studied (Garbach and Morgan, 2017; Breeze et al., 2019; Rawluk and Saunders, 2019; Hevia et al., 2021). Local and indigenous knowledge can provide some solutions to the current challenge of pollinator decline, but there is no integration and analysis of this knowledge for its practical use (IPBES, 2016). Understanding indigenous and local knowledge is crucial because it can provide complementary perspectives and extend our understanding of the spatial and temporal dynamics of biodiversity, provide vital information on the use of locally adapted crop varieties and support practices that are tailored to local visions and needs (Sutherland et al., 2013). The few studies addressing farmer knowledge reveal that local understanding about pollinators and pollination can vary enormously between regions, countries, and crops (Kasina et al., 2009; Frimpong-Anin et al., 2013; Hanes et al., 2015; Smith et al., 2017; Breeze et al., 2019; Elisante et al., 2019; Hevia et al., 2021). While some of these differences arise from variation in information sources or education, it may also derive from personal experiences, which likely vary between crops, regions and farming approaches, but this has been little studied. In addition, little is known about how farmer perceptions and knowledge influence their decision-making, and to what extent governmental subsidies can enhance the uptake of environmentally friendly measures (Kleijn et al., 2019).

Our main goal was to assess farmer perceptions of pollinators, their sources of information, and how perceptions are linked with management practices, as farmers can be key to safeguard pollinators and the services they provide. By interviewing farmers across crops and countries, contextdependent preferences can be identified and can assist in the identification of effective practical management strategies that farmers are willing and capable to implement. We, therefore, interviewed 560 farmers cultivating one of four pollinator-dependent crops (apple, avocado, kiwifruit, and oilseed rape) across 11 countries on four continents, using quantitative surveys, to:

(1) understand how farmers perceive the relative importance of different pollinator groups and determine how these change across geographical regions and crops;
(2) investigate the sources of farmer knowledge, with a focus on non-bees, and determine the knowledge gaps farmers perceive should be filled by scientists; and
(3) assess the extent that farmer decision-making, e.g., on-farm pollination management, can be linked to their perception of pollinators, economic incentives, or scientific recommendations.

Increasing our understanding of how farmers perceive pollinators, the ecosystem services they provide and pollination restoration measures is critical to develop management practices that are agronomically viable and practical to implement.

2. Methods

2.1. Data collection and design of the survey

We surveyed farmers growing at least one of four cultivated crops in countries across both northern and southern hemispheres: apple (*Malus domestica*), oilseed rape (*Brassica napus* L. or OSR), avocado (*Persea americana*), or kiwifruit (*Actinidia deliciosa*). These represent economically valuable crops for which the role of non-bee insects is either well established or not well known (Rader et al., 2016). Detailed information on their pollination requirements can be found in the Supplementary Material. Data were collected from 11 countries across four continents (United Kingdom (UK), Australia, Mexico, New Zealand (NZ), Guatemala, Israel, Germany, Belgium, Poland, Spain, and Slovenia; Table S1 and Fig. 1). The original English version of the survey can be found in the

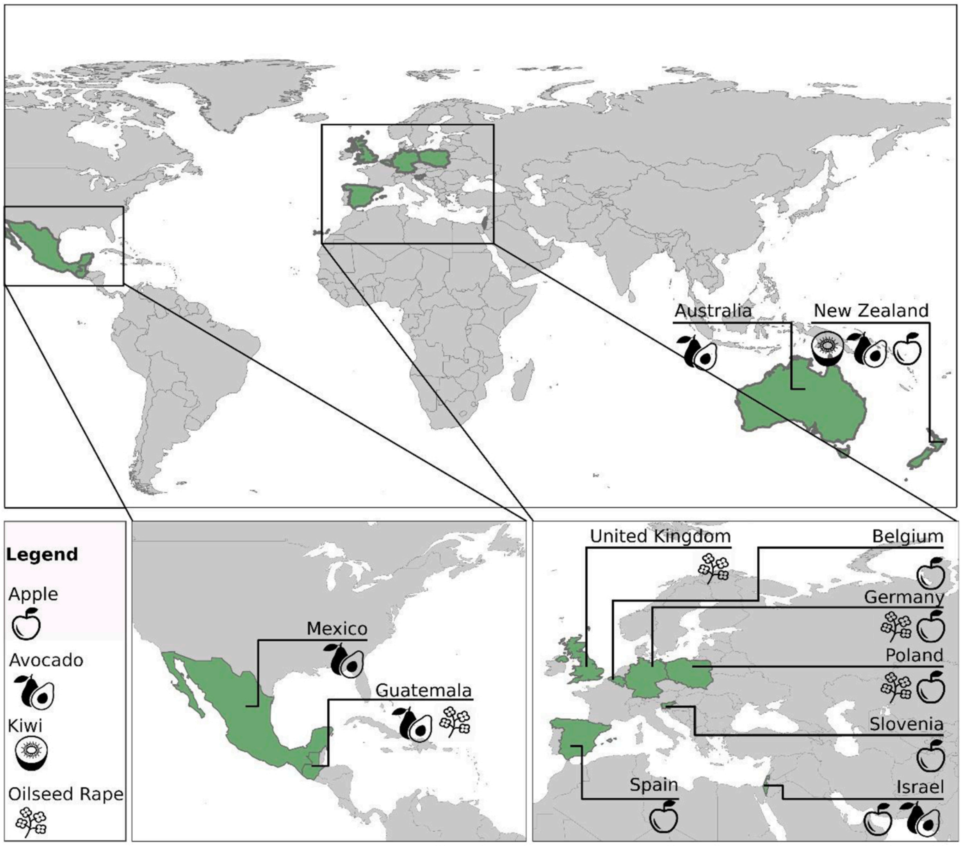

Fig. 1. World map, highlighting the 11 countries (in green) in which farmers were interviewed alongside information on crops grown. (For interpretation of the references to colour in this figure, the reader is referred to the web version of this article.)

Supplementary Material or online (https://www.surveymonkey.com/r/3QLPZBS). A detailed description of the survey design and the collection process can be found in the Supplementary Methods. In total, we collected 560 fully complete and usable surveys (mean 33 questionnaires ± 12 SD per country and crop; see Table S1). The survey included 13 questions regarding: (i) general farm characteristics and management (e.g., size, crops cultivated, organic or non-organic farming; questions 1–4 in the questionnaire); (ii) farmer perceptions of the importance of pollinators in relation to their cultivated crops, with a particular focus on non-bee insects and their pollination services (questions 5, 6, 7, 12); (iii) source of farmer knowledge in regard to non-bees (questions 8, 13); and, (iv) general pollinator management practices in the past, their current practices, and those anticipated in the future (questions 9, 10, 11). The survey data were collected following the German Rat for Sozial- und Wirtschaftsdaten (2017). Every participant was informed that the interviews are voluntarily, will be anonymised and that the interviews can be withdrawn at any time. The survey included a written consent for the collection and processing of the personal survey data (see Supplementary Material).

2.2. Farmer perceptions on the importance of bee and non-bee pollinators to their crops production

To determine whether farmers vary in their perception of the importance of different pollinator groups (aim 1, question 5 of the questionnaire), we asked them to evaluate the importance of pollinators on a Likert-type scale (Likert, 1932): *not at all important pollinator* (0), *minor pollinator* (1), *somewhat important pollinator* (2) or *very important pollinator* (3). Farmers rated pollinators separately for 7 different functional groups (i.e., honey bees, bumble bees, other (wild) bees, flies, beetles, moths/butterflies, and others). We then analysed differences in the scores for pollinators using a cumulative linked mixed model (CLMM) in R (R Core Team, 2019), which can be used to analyse ordinal data (function `clmm`, package ordinal`; (Christensen, 2018)). Preliminary analyses revealed a significant two-way interaction between pollinator type and crop cultivated, meaning that the perceived importance of pollinators varied depending on the crop. Therefore, separate analyses were performed for each crop type. Farmer identity was included as a random factor to account for non-independence of the scoring. Separate CLMMs for each crop included pollinator type, country, and their interaction (pollinator type*country), as well as production form (i.e. organic vs. non-organic) as fixed factors.

To further investigate farmers' understanding of the role of non-bees as pollinators, we asked why they perceived non-bees to be effective crop pollinators (aim 1, question 6). Answers were: i. *they are more reliable pollinators than bees*, ii. *they visit my crop when bees are not active*, iii. *they provide additional pollination above what bees can do* and iv. *other reasons* (open question). We analysed whether farmer responses (reason picked yes or no) differed between question categories, crop type, country, and production form, by using a generalized linear mixed model (GLMM) with farmer identity as random factor and assuming a binomial error distribution.

Farmers were further asked the extent to which non-bees contributed to their crop yield (in percentage, question 7). We analysed differences in the responses with crop type, country, and management type as fixed factors, using a GLM with a Tweedie distribution to account for the zero-inflation of the data using the R package "statmode" (Giner and Smyth, 2016). Additionally, farmers were asked whether they thought non-bee pollinators could play a more important role in the pollination of their crop in the future (question 12). To investigate differences between countries, crops cultivated and production form, we used a GLM with binomial error distribution.

2.3. Origin of farmer knowledge and knowledge gaps that should be filled by scientists

To understand how farmers became aware of non-bees as pollinators (aim 2), we asked farmers to state their information sources (question 8). Answers were: i. *I have seen them*, ii. *other farmers*, iii. *farm advisor or agronomist*, iv. *farmer workshop*, v. *through farmer resource (magazine, pamphlet)*, vi. *other media (*e.g.*, radio, tv, internet)*, vii. *scientists (publication, discussion)* and an open option to allow additional answers (multiple answers possible). For statistical analyses, we excluded data from Germany and Slovenia as the option "*scientists"* was not included in those questionnaires. We then tested differences in information source picked (yes/no) between information source, crop type, country, and production form in the remaining dataset by using a GLMM with farmer identity as a random effect and a binomial error distribution.

Farmer perceptions of pollinator importance could be related to on-farm experiences, i.e., by observing the abundance of different flower-visitors per crop and country. Therefore, we performed a literature search for studies which had recorded flower visitor abundance (for details see Supplementary Methods and Table S2). We used a cumulative linked model (CLM) to investigate if the median score of a pollinator per country and crop (i.e., based on Likert evaluations of the importance of each taxon: see above) could be explained by the observed relative abundance derived from scientific studies. Pollinator type and relative abundances were fixed factors.

Knowledge gaps perceived by farmers: Farmers were asked which information and in which format further knowledge of non-bees as pollinators should be disseminated (question 13). For the statistical analysis, we excluded data from Israel as a translation error of the question occurred. We first investigated whether farmers desired more information, and then categorised their responses.

2.4. Linking farmer management practices with their perception of pollinators and external incentives

To understand whether farmer knowledge influences their decision-making (aim 3), we asked farmers to outline their practices to promote pollinators or enhance pollination services (see questions 9 and 10 in the questionnaire). These included direct management of pollinators (e.g., honey bee hives, purchase of fly pupae) and intensity (e.g., hives per hectare) for four pollinator groups (honey bees, bumble bees, other bees, and non-bees). In a separate analysis, for all four managed pollinator types (i.e., providing honey bee hives, bumble bee hives, other bees, and non-bees), we then investigated whether pollinator management (implemented yes/no) is affected by farmer perceptions using GLMs with binomial error distribution, scoring honey bees, bumble bees, other bees, and the median of non-bees, with crop type, country, and production form included as fixed factors. The median of non-bees was used to reflect the overall perception by farmers. We also investigated differences in the number of honey bee hives per ha provided by farmers to their crop, with crop type, country, and production form as fixed factors, using a GLM with a Tweedie distribution.

2.4.1. Habitat enhancement

Farmers were asked whether they promote pollinators or pollination services by i) planting floral strips, ii) managing hedgerows, or iii) other management forms, with the possibility to give free answers, which were categorised post-hoc. We also examined whether external incentives, i.e., subsidies, influenced decision-making regarding hedgerow management or the establishment of wildflower strips. We collected information per country on the existence of governmental economic support for such ecological management interventions. We analysed the three practices (i.e., establishment of floral strips, hedgerow management, and other practices) separately to understand whether farmer perceptions or governmental incentives drive the implementation of pollinator-friendly measures and whether there are differences between crops and production form. In all three cases, we used a GLM with a binomial error structure with implementation (yes/no) as the dependent variable. Farmer perceptions of pollinators were represented by scores given to the importance for honey bees, bumble bees, other bees and the median score of non-bees. The presence of subsidies was included as a fixed factor for floral strips and hedgerows.

2.4.2. Change in pollination management

Farmers were asked whether their pollination management approach had changed within the last ten years and, if so, in which way (question 11). The given answers were divided into 5 categories post-hoc. The change in pollination management (yes/no) by farmers was investigated by using a GLM with a binomial error distribution in which crop type, country, and farm management type were fixed factors.

All data were analysed in R-3.6.1 for Windows (R Core Team, 2019).

3. Results

3.1. Farmer perceptions of pollinator importance, with a focus on non-bees

Farmers valued pollinator importance differently depending on functional groups. Honey bees were rated as very important (median score 3), bumble bees and other bees as somewhat important (median score 2), and non-bees (flies, butterflies, beetles) as minor pollinators (median score 1). We found that 52% of all farmers rated "other pollinators" (e.g., wasps, ants, and birds) with a median of 0 (not at all important; Fig. 2), while the rest of the farmers did not rate this pollinator group. For apple, avocado, and OSR farmers, we detected an interaction effect between country and pollinator type (Fig. 2, Table 1), meaning that farmers perceive pollinators differently depending on their location. For example, Australian avocado farmers ranked flies as very important pollinators whereas farmers from Mexico ranked flies as not at all important pollinators (Fig. 2). For bumblebees the reverse was true (Fig. 2), as they were ranked as not at all important by Australian farmers but as somewhat important by Mexican farmers. Overall, organic farmers ranked pollinators higher than non-organic farmers (Table 1).

Farmers mainly considered that non-bees contributed additional pollination to their crop (mean ± SE; 74% ± 2) or that they pollinated their crops when bees were not active, i.e., different visit time (45% ± 2), while a minority (10% ± 1) rated non-bees as more reliable pollinators than bees and 9% (± 1) indicated non-bees provide additional benefits, such as differing in traits (e.g., size). The proportion of farmers selecting reasons why non-bees are beneficial differed between the categories described before ($\chi2 = 322.33$, DF = 3, $P < 0.001$), crop cultivated ($\chi2 = 13.67$, DF = 3, $P = 0.004$), countries ($\chi2 = 47.59$, DF = 10, $P < 0.001$), and between production form ($\chi2 = 10.35$, DF = 1, $P = 0.002$, see Fig. 3). For example, in New Zealand only around 30% of the kiwifruit

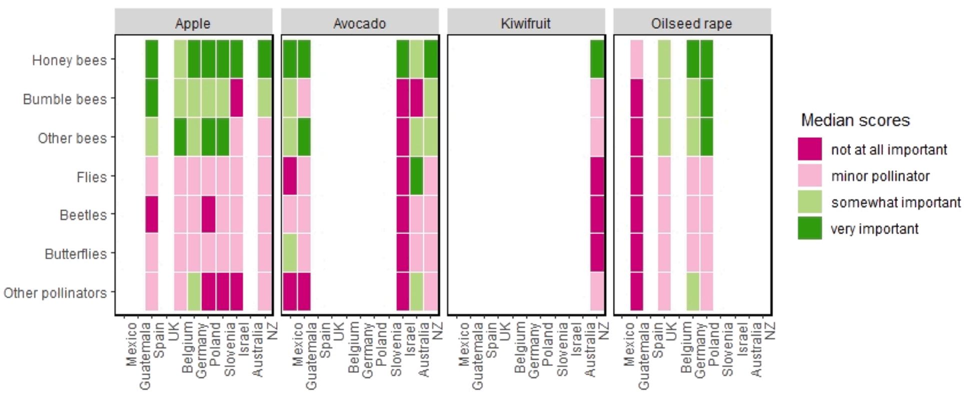

Fig. 2. Importance of pollinator groups across countries. Heat maps illustrating the perceived median importance of pollinators split by the four crops farmers cultivate and by country. Missing data represent options with insufficient scores. Scores of pollinator importance by farmers follow a Likert-type scale: *not at all important pollinator* (0), *minor pollinator* (1), *somewhat important pollinator* (2) or *very important pollinator* (3).

Table 1
Results of generalized linear mixed-effects models of crop type, pollinator type, their interaction and management on pollinator importance scores.

Comparison	*DF*	LRT	*P*
Full model			
Pollinator	6	1484.23	**< 0.001**
Crop	3	8.25	**0.041**
Organic	1	5.91	**0.015**
Country	10	78.08	**< 0.001**
Pollinator x Crop	18	212.93	**< 0.001**
Apple			
Pollinator	6	809.73	**< 0.001**
Country	6	10.43	0.108
Organic	1	4.37	**0.037**
Pollinator x Country	36	228.21	**< 0.001**
Avocado			
Pollinator	6	413.62	**< 0.001**
Country	4	30.00	**< 0.001**
Organic	1	0.240	0.625
Pollinator x Country	24	304.46	**< 0.001**
Kiwifruit[a]			
Pollinator	6	186.17	**< 0.001**
OSR			
Pollinator	6	304.46	**< 0.001**
Country	3	53.10	**< 0.001**
Organic	1	4.83	**0.028**
Pollinator x Country	18	44.43	**< 0.001**

[a] Kiwifruit farmers were all non-organic and all located in New Zealand

farmers stated that non-bees can provide additional pollination as opposed to around 50% of the apple farmers (Fig. 3). Overall, farmers estimated that non-bees perform 19% of the ecosystem service of pollination. This estimation differed markedly between countries (GLM, $F_{40,\ 2140} = 3.34$, $P < 0.001$), crops ($F_{12,\ 1602} = 2.79$, $P < 0.001$), and also between production form ($F_{4,\ 532} = 2.84$, $P = 0.024$). More farmers (57%) believed that non-bees could play a more important role for crop pollination in the future, than those who did not (27%). The rest (16%) did not express an opinion or indicated they did not know. These proportions differed between countries ($\chi2 = 52.94$, DF = 10, $P < 0.001$) but not between crops ($\chi2 = 4.96$, DF = 3, $P = 0.175$) nor production form ($\chi2 = 0.83$, DF = 1, $P = 0.364$).

3.2. Origin of farmer knowledge and knowledge gaps that should be addressed by scientists

Most farmer awareness of non-bees as pollinators was through observing them in the field (57%), 21% through farmer resources (magazines, pamphlets), 19% through workshops, 17% from scientists, 15% from other farmers, 14% from advisors, 9% from other media (e.g., radio, tv, internet) and 6% specified other sources. The proportion of farmers differed between type of information source ($\chi2 = 644.94$, DF = 7, $P < 0.001$), crops ($\chi2 = 49.68$, DF = 3, $P < 0.001$), countries ($\chi2 = 74.82$, DF = 8, $P < 0.001$), as well as

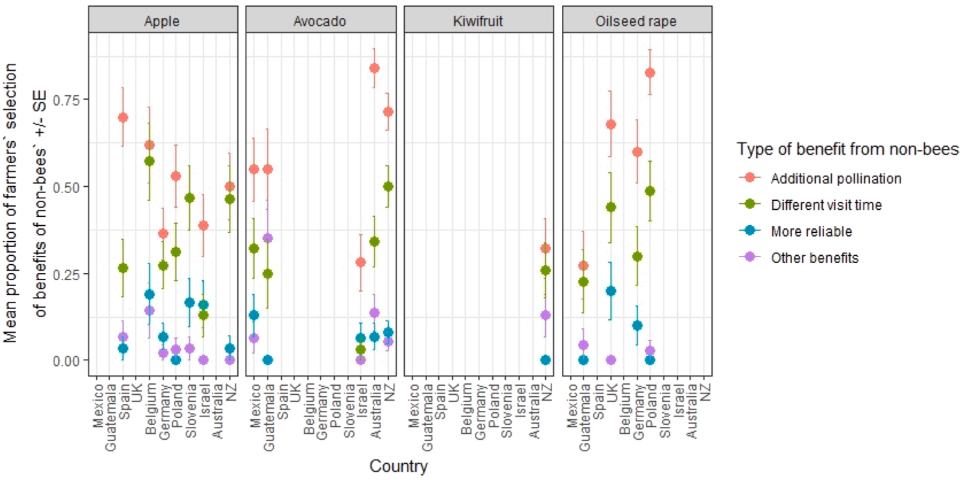

Fig. 3. Mean proportion of farmers selecting the reason for benefits of non-bees for the pollination of their crop for the four crop types and country. Error bars indicate ± 1 SE.

between production form ($\chi2 = 6.22$, DF = 1, $P = 0.013$; Fig. 4). Interestingly, farmer scores of pollinator importance were positively related to relative abundance (percentage) of those pollinators; as observed per crop and country by researchers (CLM, LRT = 4.917, $P = 0.027$; Fig. 5).

Knowledge gaps perceived by farmers: 62% of farmers stated that they would like to receive more information about non-bees as pollinators. In particular, farmers were interested to know about the importance of non-bees as crop pollinators, their biology, and how to promote them (Fig. S1). Workshops and farmer conferences were mentioned most often as a preferred way to disseminate scientific evidence (Fig. S1).

3.3. Linking decision-making with farmer perceptions of pollinators, scientific evidence, and external incentives

We found that 59% of all farmers added managed honey bee hives, 9% bumble bees, and 4% other bees to supplement pollination services. Only 1% of all farmers provided non-bees for pollination services. Those supporting pollination services used one of the four managed pollinator functional groups, but only 3% of the farmers used other pollinators without using honey bees. Overall, 62% of the farmers managed crop pollinators by one or more species and 38% did not.

On-farm management of pollination services was linked to farmer perception of pollinator importance as well as the country (see Table S3). Strong positive links were found between perceived honey bee, bumble bee and other bee importance and their management, but no links across taxa (e.g., the use of honey bees was not linked to perceived importance of bumblebees; Table S3). That non-bees were only used by 1% of the farmers (n = 6) was slightly surprising, given that some farmers rated them as very important pollinators (i.e., flies (11%, n = 63); beetles (7%, n = 38); butterflies (8%, n = 44)). Interestingly, while the management of bumble bees and other bees are crop dependent, this was not apparent for honey bees, indicating that honey bees were ubiquitously implemented across crops (Table S3, Fig. S2). Farmers who provided honey bee hives for pollination services stated also the number of hives per hectare. We compared those with recommendations in studies reviewed by Rollin and Garibaldi (2019), consisting mostly of data from Delaplane and Mayer (2000) (Fig. S3). Only kiwifruit farmers provide a similar number of hives per hectare to those recommended, while farmers cultivating apple, avocado and oilseed rape provide lower numbers than recommended (Fig. S3). We found differences in honey bee hive stocking rate between crops ($\chi2 = 56.66$, DF = 3, $P < 0.001$), countries ($\chi2 = 99.66$, DF = 10, $P < 0.001$) and production form ($\chi2 = 3.68$, DF = 1, $P = 0.049$).

Promoting pollinator services to crops through habitat enhancement was also undertaken by some farmers, with 27% establishing floral strips, 23% managing hedgerows, and 23% stating other forms of management. The establishment of floral strips was positively driven by both availability of subsidies and farmer perceptions of non-bees (Table S4). Hedgerow management was positively influenced by subsidies and differed between crops (Table S4, Fig. S4). For example, no kiwifruit farmer implemented hedgerows while 20% of the OSR famers did so without subsidies and around 70% when subsidies were present (Fig. S4).

In total, farmers mentioned 24 further habitat enhancement strategies (Fig. S5). The reduction of pesticide use was mentioned most frequently (5%), followed by mixed cropping (3%) and provisioning of nesting habitat (3%). These practices differed strongly between countries (Table S4). For example, farmers from Mexico and Guatemala indicated the use of mixed crops, mainly traditional plants that grow in the Mayan milpa agroecosystem or the use of arboreal plants as hedgerows that also provide flowers. Interestingly, some farmers, mostly avocado and kiwifruit farmers, actively attract pollinators with scent or sugar syrup. Some also carried out artificial pollination i.e., spraying of pollen for an adequate pollination service (Fig. S5). Moreover, some farmers implemented non-bee-specific measures (e.g., an Australian avocado farmer, stated: "use dead kangaroos for flies").

Almost half of the farmers (45%) stated that they had changed their pollination management (habitat enhancement and managed pollinators) in the last 10 years, while the rest did not answer this question (19%) or had not changed their pollination management

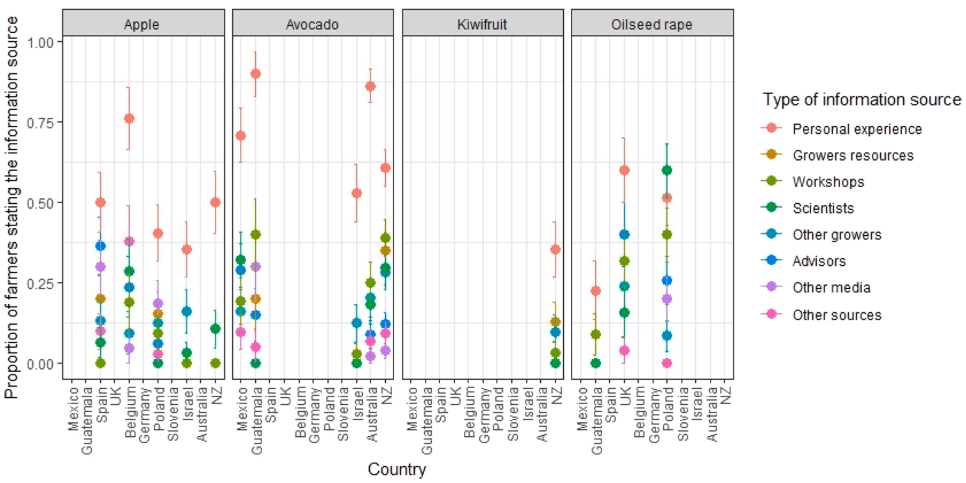

Fig. 4. Mean proportion of farmers stating their information sources for non-bees as pollinators for the four crop types and country. Error bars indicate ± 1 SE.

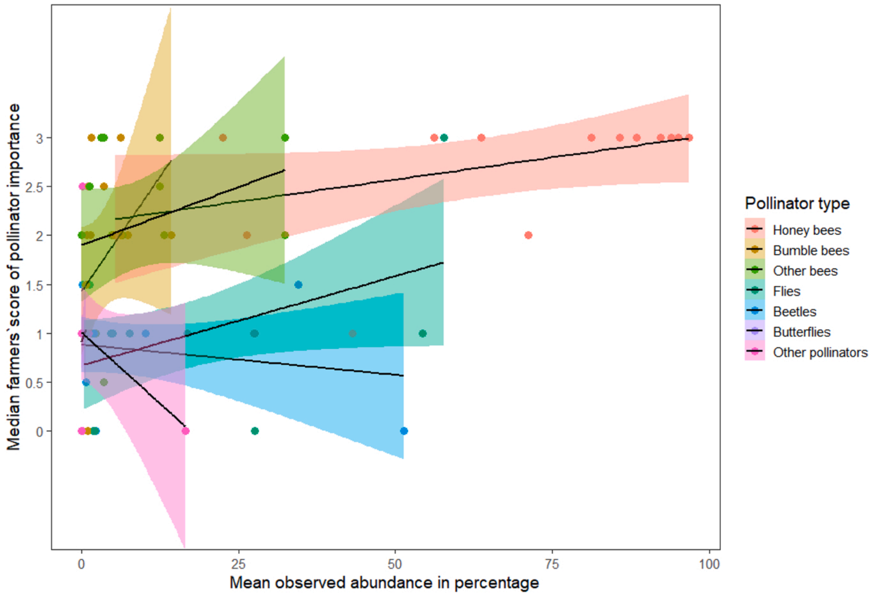

Fig. 5. Linking farmer knowledge with ecological observations. Relationship between the median farmer scores of pollinator importance per crop and country with the mean relative observed abundance in percentage by pollinator type. Plotted lines show the predicted relationships per pollinator type, dots represent means/median per crop and country per pollinator type and shaded areas indicate the 95% confidence intervals of the relationships.

(36%). The proportion of stated changes in pollination management differed between countries ($\chi2 = 76.32$, DF = 10, $P < 0.001$) and crops ($\chi2 = 20.56$, DF = 3, $P < 0.001$) but not between production form ($\chi2 = 0.00$, DF = 1, $P = 0.962$). We identified 29 different types of changes (see Fig. S6) of which the increase in honey bee hive number was mentioned most often (11%), while some farmers stated they no longer used or had reduced the number of honey bees for pollination services (7%).

4. Discussion

To our knowledge this is the first study to examine farmer knowledge of non-bee pollinators across multiple countries and crops. Although the importance of managed and wild bees as pollinators of most insect-pollinated crops grown across the globe has been widely recognised by scientists (Garibaldi et al., 2013, 2017; Rollin and Garibaldi, 2019) and farmers (Hanes et al., 2015; Garbach and Morgan, 2017; Park et al., 2018; Eeraerts et al., 2020; Maas et al., 2021), the role of non-bee insects has been largely overlooked until recently (Rader et al., 2016, 2020; Hevia et al., 2021; Howlett et al., 2021). The limited research on the effectiveness of non-bee crop pollinators (Rader et al., 2020) and their management on farms (Howlett et al., 2021) has provided an opportunity to assess farmer knowledge about these pollinators in the absence of extensive scientific research and management recommendations. We show that farmers are holders of knowledge mainly obtained through their own experiences. This knowledge largely mirrored scientific research findings (where available), and was nuanced, varying between countries, crops grown and production system (i.e., non-organic vs. organic).

4.1. Farmer perceptions of pollinator importance with a focus on non-bees

Farmers generally ranked bees higher than non-bees in their importance as pollinators of their crops, a finding reflected in the scientific literature (Rader et al., 2016, 2020) and recorded from other farmers (Hevia et al., 2021). However, non-bees were recognized by the majority of farmers as probable pollinators providing useful additional and complementary pollination services to that provided by bees rather than potentially replacing them. This is supported by the conclusions of a meta-analysis of global studies conducted by Rader et al. (2016). On average, farmers estimated a contribution of 19% from non-bees to the pollination service provided to their crop. This compares with findings by Rader et al. (2016) that found non-bees contribute 25–50% of the total number of visits to crops and that fruit set increases with non-bee abundance independently of bee visitation rate. Despite limited research compared to bees, many farmers perceived that non-bees play a useful role in crop pollination.

4.2. Origin of farmer knowledge and knowledge gaps that should be filled by scientists

In this study, we demonstrate for the first time that farmer knowledge of the perceived importance of pollinators is connected to the relative abundances of pollinators, as reflected in published studies (Table S2). This suggests that farmers observe, recognise and value pollinating taxa based on their abundance as crop flower visitors. A particularly interesting finding of our study is that the extent of knowledge held by farmers on non-bee pollinators was based on their own observations (>50% of farmers) rather than through scientific research findings. To date, scientists have largely focussed on the importance of bees, the management of pollinators (Garibaldi et al., 2017; Rollin and Garibaldi, 2019) and landscape/habitat enhancement strategies to promote wild and managed bees (Garibaldi et al., 2017). As a result, comprehensive management guidelines towards promoting non-bees are largely lacking (Rader et al., 2020; Howlett et al., 2021). We therefore believe that farmer knowledge is an untapped resource that could be harnessed to co-design farmer-scientist research that delivers knowledge and recommendations better suited to farmers across agricultural landscapes.

4.3. Linking decision-making with farmer perceptions of pollinators, scientific evidence, and external incentives

Around 60% of the interviewed farmers used one or more managed pollinators. Nearly all of these farmers placed honey bees in or near their crops for pollination (59% of farmers) with just 3% using managed non-*Apis* pollinators (i.e., bumble bees, other bees, non-bees) without employing managed honey bees at the same time. The global importance of honey bees as a managed pollinator of insect-pollinated crops is well-recognised (Garibaldi et al., 2013; Rollin and Garibaldi, 2019), including by farmers (Hanes et al., 2015; Garbach and Morgan, 2017; Park et al., 2018; Eeraerts et al., 2020; Hevia et al., 2021). Farmer perceptions of bees were linked to pollinator management. Farmers providing bees on their farms simultaneously rated those managed pollinator taxa higher than farmers not providing them. At the same time, we found marked differences in bee pollinator management between countries, e.g., differences in the use of honey bee hives as well as their stocking rate was mainly explained by location. Regional differences in pollinator abundances and availability driven by landscape structure or geographical region could be the driver behind the use, or not, of honey bees. For example, in New Zealand, avocado and kiwifruit farmers must rely heavily on managed honey bees as few wild pollinators visit these crops (Howlett et al., 2017; Read et al., 2017). In other countries, wild pollinators visiting these crops can occur in much higher abundance (Miñarro and Twizell, 2015; Dymond et al., 2021). Also, regional differences might occur due to differences in beekeeping costs or differences in pollination requirements of different crops and cultivars (Eeraerts et al., 2020). Adapting to local conditions through their own experiences could therefore drive farmer decision-making rather than science/industry recommendations as those where only mentioned for kiwifruit (only sampled in New Zealand) but not for the three other crops. To avoid pollination deficits or deleterious effects of too-high stocking rates on wild bee populations or crop production (Sáez et al., 2014; Lindström et al., 2016), the effect of pollinator density should be further investigated, especially since many farmers stated they had increased stocking rates. Findings should be well communicated between scientists, policy makers and practitioners (Evans et al., 2021), to develop more dynamic site-specific recommendations that optimise pollination services and safeguard wild pollinators.

Farmer decision-making might not only be related to their own knowledge and perceptions. While there are many studies on managing bees, their deployment by farmers varies greatly (Stephen, 1961; Crane, 1983; Velthuis and Van Doorn, 2006). For example, in a survey in Belgium, most cherry farmers perceived solitary bees as important pollinators, but their management or encouragement was very low due to the absence of practical management guidelines (Eeraerts et al., 2020). While the knowledge and perception of farmers was linked in this study with the management of bees, managing non-bees was almost non-existent despite some farmers rating them as very important pollinators. Lack of robust management guidelines on how to promote non-bees or the uncertainty of their contribution to pollination can be barriers to establishing new pollinator management practises (Hanes et al., 2015; Breeze et al., 2019), and only a few studies investigate the benefit and potential of non-bees as managed pollinators (Howlett and Gee, 2019). We conclude that farmer knowledge can be linked to their decision-making, but only when practices are well established, clear, or easy and economically viable to implement.

Although our study indicated farmers that grow insect-pollinated crops mostly have a solid understanding of pollinators and their contribution to crops, habitat enhancements might be perceived as an economic risk (Breeze et al., 2019; Kleijn et al., 2019). Also, pollinator-friendly measures targeted at increasing pollinator diversity have shown variable effects on crop pollination and yield (Albrecht et al., 2020). We found that around a quarter of the farmers established wildflower strips and a quarter managed hedgerows to support pollinators. Governmental subsidies were linked to an increase in the establishment of these measures. For instance, more than 60% of the farmers established floral strips in countries where subsidies were available, compared to less than 20% where they were not, which highlights a financial barrier to implementation (Fig. S4). We can therefore confirm the importance agricultural policies as a tool to enhance the uptake of biodiversity-friendly measures to safeguard pollination services and reverse the biodiversity loss in agricultural landscapes (Mupepele et al., 2021). By supporting evidence-based measures to enhance biodiversity, farmers can be encouraged to implement them, especially when bureaucratic procedures are simplified (Eeraerts et al., 2020).

Additionally, traditional practices in Mexico (living hedgerows) and Guatemala (milpa agroecosystem) seem to fulfil similar functions to those provided by hedgerows and floral strips. The existence of such traditional management practices may explain the lack of government subsidies for pollinator management in the region. Living hedgerows are native plants from each ecological region chosen for their resilience, provision of wood, shade, and nectar (Reyes and Rosado, 2000). The milpa agroecosystem is a complex Mayan practice that consists of growing mixed crops within a system of rotation and regeneration that allows heterogeneity of food sources considered supportive to native bee populations (Landaverde-González et al., 2017). It provides an important example of how indigenous farmer knowledge shapes traditional farming practices. Such knowledge and practices can provide significant insight into the long-term sustainable management of ecosystems leading to improved outcomes for pollinator biodiversity and improved community wellbeing (IPBES, 2016; Hill et al., 2019).

Farmers seemed to recognize differences in the pollination ecology of crops and adapt their measures accordingly. For example, the application of pollinator attracting scents was almost exclusively mentioned by kiwifruit farmers (Fig. S5). Unlike the other study crops, kiwifruit flowers do not produce a nectar reward (see Supplementary Methodology), limiting visits by nectar feeding insects.

Hence, the use of attractants to boost pollinator visitation is likely considered a worthwhile investment to boost fruit yields. Furthermore, farmers of crops highly dependent on insect pollination might be more willing to adopt biodiversity-friendly measures than those cultivating crops with lower dependency, a fact that should be further investigated. For the latter farmers, an increase in subsidies may be one way to incentivise grower uptake if governmental or industry policies require action.

Grower pollinator management strategies may also be influenced by whether they grow perennial crops (e.g., apple, avocado, kiwifruit that remain in one place for many years) or annual crops (e.g., oilseed rape that are rotated yearly across the farm). For example, annual crop growers must sow and rotate crops yearly, unlike perennial crops that typically remain in place for many years. In these circumstances, managing hedgerows or other non-crop woody vegetation for pollinators may lead to more reliable provision of pollination services to perennial crops across years. Few studies have explored the degree to which wild pollinators (particularly non-bees) associated with woody vegetation such as hedgerows move and deliver pollination services to rotated annual crops (Schmidlin et al., 2021), although pollination services have been noted to decline exponentially with distance from flower strips and hedgerows (Albrecht et al., 2020). Hence incentives to implement measures might be different as perennial crops, like fruit trees, are planned and planted often for decades while oilseed rape must be sown and rotated across the farm every year. We found, however, that oilseed rape farmers are more likely to manage hedgerows, especially when subsidies are available. One reason for this could be the additional benefits hedgerows provide, especially for annual crops, such as protection from wind and water erosion of soil (Baudry et al., 2000).

In the past 10 years, 45% of interviewed farmers had adapted their pollination management, including beekeeping, encouragement of pollinators, and land management (Fig. S6), suggesting that farmers are trialling a variety of measures to boost on-farm pollinator services through their own experiences. Our study highlights the strong potential for delivering future applied outcomes by using local knowledge held by farmers to guide research activities resulting in more resilient on-farm pollination and the willingness of farmers to adopt practices that support crop pollination (McCracken et al., 2015). This provides opportunities to verify the effectiveness of farmer-led strategies, which may then be more easily integrated into broader farm management practices (Kleijn et al., 2019) and as a consequence protect pollinators in the agricultural landscape.

4.3.1. Knowledge gaps perceived by farmers

Most (62%) farmers were keen to receive more information on pollination management, particularly from scientists, about non-bee pollinators. Some farmers were also interested to know which flowers apart from their crop can be beneficial for non-bee pollinators. Ecological plant-pollinator network analyses provide a visual tool to communicate those findings to farmers (Howlett et al., 2021). Scientific evidence should be disseminated through direct contact such as farmer conferences, farm advisors and workshops rather than (social) media or magazines if it is to influence farmer decisions. Indeed, social learning can be crucial to the adoption of new management techniques (Garbach and Morgan, 2017).

4.4. Shortcomings and knowledge gaps

Despite our efforts to reach a broad range of farmers, we acknowledge the potential for sampling bias towards famers with better ecological knowledge, who may have responded more willingly to our questionnaire. Furthermore, our findings were likely biased towards farmers with pre-established contact with researchers, as we used our existing farmer networks or those of associated primary industry bodies. This could have resulted in a higher percentage of farmers stating scientists as an information source of non-bees as pollinators. Also, we acknowledge that, for some country and crop combinations, the minimum of 20 surveys might not be representative. Unfortunately, in some countries, accurate data on the total number of farmers per crop are not available, so we cannot calculate the representative number of farmers that would be needed for these analyses, nor is calculation of confidence intervals and sampling error possible. Nevertheless, overall, the number of questionnaires per country and crop gave us a substantial insight into differences in farmer knowledge and their decision-making. We aimed to target a broad range of farmers by approaching them through a variety of communication media e.g., farming press, direct contact, farmer conferences, regular mail, and internet platforms. Also, we argue that better informed farmers can support early-stage implementations of new techniques and inform others in farmer networks (Garbach and Morgan, 2017).

5. Conclusions

Here, we demonstrated that farmer perceptions of pollinators are linked to their on-farm experiences and that these perceptions are closely aligned with the scientific literature. This highlights that local knowledge provides an important and accurate source of information which should be more widely recognized when shaping pollinator management decisions. We also conclude that farmer decision-making is influenced by their beliefs, availability of robust and practical management guidelines, and external incentives. We recommend the dissemination of scientific evidence, especially those of complex coherency, through direct contact, such as farmer conferences and workshops. By using local and indigenous knowledge, ecological measures to increase pollination services can be restructured through cooperation between scientists and farmers (see policy briefing outlining key actions in the supplementary material).

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CRediT authorship contribution statement

Brad G. Howlett: Research idea, Methodology, Writing, Supervision, Project Administration, Funding Acquisition. **Michael P.D. Garratt:** Research idea, Project Administration. **Megan Gee:** Research idea, Methodology, Supervision, Project Administration. **Julia Osterman:** Methodology, Validation, Formal analysis, Data curation, Writing, Visualization. **Aleksandra Langowska:** Data collection, Editing. **Patricia Landaverde-González:** Writing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Except where otherwise noted, all data used in this study were collected as part of the farmer surveys described. These data and associated R scripts are available on request to J.O. The data that supports the findings of this study are available on request from the corresponding author, J.O.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.gecco.2021.e01949.

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