Apple grower pollination practices and perceptions of alternative pollinators in New York and Pennsylvania

Mia G. Park[1,2], Neelendra K. Joshi[3,4,5], Edwin G. Rajotte[3], David J. Biddinger[4], John E. Losey[1] and Bryan N. Danforth[1]

[1]Department of Entomology, Cornell University, Ithaca, NY, USA; [2]Department of Biology, University of North Dakota, Grand Forks, ND, USA; [3]Department of Entomology, Pennsylvania State University, State College, PA, USA; [4]Department of Entomology, Fruit Research & Extension Center, Pennsylvania State University, Biglerville, PA, USA and [5]Department of Entomology, University of Arkansas, Fayetteville, AR, USA

Abstract

Pollinator declines coupled with increasing demand for insect pollinated crops have the potential to cause future pollinator shortages for our most nutritious and valuable crops. Ensuring adequate crop pollination may necessitate a shift in pollination management, from one that primarily relies on the managed European honeybee (*Apis mellifera* L.) to one that integrates alternative pollinators. While a growing body of scientific evidence supports significant contributions made by naturally occurring, native bees for crop pollination, translating research to practice requires buy-in from growers. The intention of agricultural extension is to address grower needs and concerns; however, few studies have assessed grower knowledge, perceptions and attitudes about native pollinators. Here we present findings from questionnaire-based surveys of over 600 apple growers in New York State and Pennsylvania, coupled with ecological data from bee surveys. This hybrid sociological and biological survey allows us to compare grower knowledge and perceptions to an actual pollinator census. While up to 93% of respondents highly valued importance of native bees, 20% growers *did not know* how much native bees actually contribute to their orchard pollination. Despite the uncertainty, a majority of growers were open to relying on native bees (up to 60% in NY and 67% in PA) and to making low-cost changes to their farm's management that would benefit native pollinators (up to 68 in NY and 85% in PA). Growers consistently underestimated bee diversity, but their estimates corresponded to major bee groups identifiable by lay persons, indicating accurate local knowledge about native bees. Grower reliance on honeybees increased with farm size; because native bee abundance did not measurably decrease with farm size, renting honeybees may be motivated by risk avoidance rather than grower perception of lower native bee activity. Demonstrated effectiveness of native pollinators and clear guidelines for their management were the most important factors influencing grower decision to actively manage orchards for native bees. Our results highlight a pressing need for an active and research-based extension program to support diversification of pollination strategies in the region.

CAMBRIDGE UNIVERSITY PRESS

Introduction

At least 35% of global food production benefits from insect pollinators (Klein et al., 2007). Bees are by far the most important pollinators in agricultural settings, and in terms of ecosystem service, contribute between $5.7 and $19 billion per year to the United States economy (Levin, 1983; Robinson et al., 1989; Southwick and Southwick, 1992; Morse and Calderone, 2000) and $217 billion per year globally (Gallai et al., 2009). Bees support human health by pollinating our most nutritious food crops (Eilers et al., 2011), for which global demands are projected to rise as developing countries become more wealthy (Aizen and Harder, 2009). With both domestic and wild bees experiencing global declines (Biesmeijer et al., 2006; Potts et al., 2010; Cameron et al., 2011; van der Zee et al., 2012; Burkle et al., 2013), explicitly incorporating pollinator well-being into farm management decisions is necessary to ensure sustainable pollination services.

Although more than 20,000 bee species have been described worldwide (Ascher and Pickering, 2013), pollination management in modern agriculture traditionally involves a single species; in the United States, this species is the European honeybee, *Apis mellifera* L. Commercially available, managed honeybees comprise large colonies that are readily moved into crop fields during bloom. Honeybees are especially important pollinators in large scale, highly disturbed agroecosystems that cannot support wild pollinators. Due to steady declines in honeybee populations over the past 50 yr (National Research Council, 2007) and

significant colony losses due to 'colony collapse disorder' (CCD) (Oldroyd, 2007; vanEngelsdorp et al., 2009), it is becoming increasingly risky to rely on a single pollinator species for food production (Winfree, 2008). Indeed, if honeybees continue to decline, growers may need to diversify their pollinator portfolio to include alternative pollinators in order to sustain adequate crop pollination in the future.

Developing managed alternative pollinators could diversify pollination strategies, but evidence is also building for important crop pollination services by naturally occurring wild bees. Globally, wild bees are more efficient pollinators than honeybees (Garibaldi et al., 2013), and the diversity associated with the communities of wild bees stabilizes pollination services spatiotemporally (Kremen et al., 2004; Klein, 2009; Garibaldi et al., 2011), in a manner that provides resilience to rapid climate change (Bartomeus et al., 2011; Brittain et al., 2013). Optimizing wild bee pollination services, however, may require a shift in pollination management strategies for growers. In contrast to ordering honeybees for a few weeks, long-term efforts may be required to provide wild pollinators with semi-natural or natural areas for food and nesting resources, as well as safety from pesticides beyond the short bloom period (Watson et al., 2011; Kammerer et al., 2016a, b; Park et al., 2015; Joshi et al., 2016). Technical support and education programs will, therefore, be needed to help growers rely on a suite of pollinators and not just the honeybee (Isaacs et al., 2017). Growers may need to modify their pest management practices to accommodate pollinator health (Biddinger and Rajotte, 2015). Pesticide applications to control pests can affect pollinators throughout the growing season, even if apple is not blooming (Mallinger et al., 2015; Park et al., 2015). Even if pesticide sprays are avoided during bloom, modern systemic insecticides applied before flowering may contaminate nectar and pollen (Mogren and Lundgren, 2016). An expansion of integrated pest management (IPM) to integrated pest and pollinator management is a viable solution to managing pests and protecting pollinator health (Biddinger and Rajotte, 2015).

Understanding current grower knowledge and perceptions of alternative pollinators could inform successful outreach and encourage heavier reliance on alternative pollinators, yet only a few such studies exist worldwide (Partap et al., 2001; Kasina et al., 2009; Munyuli, 2011; Hanes et al., 2015; Gaines-Day and Gratton, 2017). Even fewer studies investigate factors affecting grower pollination strategies (Potts et al., 2011; Hanes et al., 2015). Here, we surveyed pollination practices, perceptions of alternative pollinators and willingness to implement bee-friendly management practices among apple growers in New York (NY) and Pennsylvania (PA). We coupled the grower survey data with field observations of bees to (1) compare perceived and documented importance of native bees in orchards, (2) assess grower knowledge gaps and (3) guide future extension efforts for apple pollination.

Methods

Study system

Apple (*Malus domestica* Borkh: Rosaceae) is an economically important crop in temperate regions of the world, including eastern North America. NY and PA rank among the four largest apple-producing states in the United States, yielding on average 1.2 and 0.5 billion pounds of fruit, respectively, and collectively worth $350 million per year (USDA NASS 2016a, b). NY's apple industry is larger with 654 growers managing roughly 40,000 acres (USDA

NASS 2016a) compared with PA's 566 farms over 20,000 acres (USDA NASS 2016b).

Apple is varietally self-incompatible, meaning flowers must receive pollen from another variety to set fruit; cross-pollination is largely carried out by insects (McGregor, 1976; Free, 1993). Renting honeybees to pollinate this mass blooming crop is commonplace in North America; however, several alternative pollinators currently exist, including commercially available, managed bumble bees (*Bombus impatiens*) and mason bees (*Osmia* spp.), as well as wild bees that naturally inhabit agricultural landscapes. Field surveys of orchard pollinators over the past century indicate that wild bees are common visitors to apple flowers, particularly species in the genera *Andrena*, *Bombus*, *Halictus*, *Lasioglossum* and *Osmia* (Hutson, 1926; Brittain, 1935; Phillips, 1933; Gardner and Ascher, 2006; Watson et al., 2011; Ritz et al., 2012; Mallinger and Gratton, 2015; Martins et al., 2015; Russo et al., 2015; Gibbs et al., 2017). Recent empirical studies find wild bees to be as effective, if not more effective, pollinators than honeybees and contribute important pollination services in apple orchards when abundant (Ritz et al., 2012; Mallinger and Gratton, 2015; Martins et al., 2015; Blitzer et al., 2016; Park et al., 2016; Russo et al., 2017). With only a couple of exceptions, wild bee species are native to study regions, whereas honeybees are introduced from Europe.

In addition to apples, northeastern fruit growers often grow other fruit species, such as peaches, nectarines, cherries, pears and various berries. Each of these have their own pollination requirements. A general improvement of wild pollinators in a given area would also benefit these crops (Biddinger et al., 2013a).

Grower surveys

Apple growers in NY and PA were surveyed on four major themes: (1) farm and grower characteristics, (2) current pollination strategies, as well as (3) perceptions and (4) attitudes regarding native and managed alternative pollinators (see Supplementary Material for survey instruments). A total of three survey instruments were administered to apple growers: two in NY and one in PA. In NY, we contracted the United States Department of Agriculture National Agricultural Statistics Service (USDA NASS) NY field office to administer grower surveys in 2009 and 2012. Both years, USDA NASS initially mailed surveys to commercial growers (518 in 2009 and 519 in 2012), then called non-respondents by phone until they reached a minimum 50% response rate (50.6% in 2009 and 57.4% in 2012). The 2009 survey instrument comprised 16 questions, addressing the four major themes, and served as a basis for subsequent surveys (Park et al., 2010). The 2012 survey instrument asked 25 questions, which incorporated questions developed by the PA team on farm characteristics, the use of managed alternative pollinators and perceived contributions of native bees to orchard pollination. We also included questions that assessed the importance of various factors on grower decisions to implement practices that would benefit native bees. For several questions asked in 2009, we added more response categories in 2012 from which growers could choose. Spatially, survey respondents represented growers throughout NY State when compared with the proportion of growers living within specific counties (USDA NASS 2007 and 2012 census data; Table 1). Identifying data were not disclosed by USDA NASS to authors in order to ensure respondents' privacy.

In fall 2010, a survey questionnaire was distributed to PA apple growers with, but a few exceptions, the same questions in the NY

Table 1. County residence of growers who participated in New York and Pennsylvania surveys compared with government censused distributions of apple growers among counties

| | New York | | | | | Pennsylvania | |
| | 2009 | | 2012 | | | 2010 | |
County	Survey	Census[a]	Survey	Census[b]	County	Survey	Census[b]
Wayne	20.2	16.4	22.6	14.4	Adams	26	7.8
Ulster	10.3	5.7	9.2	5.0	Lancaster	24.7	5.9
Orleans	8.8	6.1	10.1	4.9	York	8.2	4.2
Niagara	6.5	6	6.2	5.0	Bedford	4.1	2.1
Columbia	5	4.1	5.6	2.5	Berks	4.1	4.7
Monroe	3.8	3.1	3.3	2.1	Blair	2.7	0.8
Dutchess	2.7	2.4	2.6	2.7	Lehigh	2.7	1.4
Onondaga	2.7	2.2	3.6	2.0	Northampton	2.7	1.4
Orange	2.3	1.3	3.3	1.7	Snyder	2.7	1.3

Data are percentages and only the top nine counties shown.
[a]2007 USDA NASS census.
[b]2012 USDA NASS census.

surveys. Questionnaires were distributed to fruit growers during extension meetings and other extension events, such as field and plant protection days; the questionnaire was also available online. A total of 73 growers responded to this survey, the majority of whom were from Adams County, the main apple production region in the state. The spatial bias of PA survey respondents, from Adams and Lancaster counties, is likely due to the proximity of these growers to meeting locations where surveys were dispensed (Table 1).

Bee surveys

In order to compare grower perceptions and knowledge of native bees to ecological reality, we included data from orchard surveys of bees conducted in NY and PA. We surveyed a total 19 farms between 2009 and 2013 in central NY (Russo et al., 2015) and nine farms between 2007 and 2013 in PA (Joshi et al., 2015, 2016). In NY, all bees observed visiting apple flowers were net-collected along standardized 15 min transects during peak bee activity with temperatures above 60°F (Park et al., 2015). Bee visitation to apple flowers in PA orchards was recorded by observation and net collection at different distances, up to 200 m, from orchard edge (Joshi et al., 2016). Cumulative observed species richness was calculated for each farm across all years of collecting (NY data from Russo et al., 2015). NY bee abundance and species richness in statistical models were based on surveys conducted in 2011 and 2012. NY orchard sizes and percent land cover (i.e., natural, agriculture, developed), within a 1 km radius of farms, were determined using ArcMap10 GIS (ESRI, 2010; see further details in data analysis). To assess drivers of bee community abundance and diversity in PA orchards, we referenced previously published surveys, for which configuration of the adjacent habitat and landscape were characterized by Fragstats 4.0 up to 1 km from orchard edge (Joshi et al., 2016).

Data analysis

Grower survey results were summarized using descriptive statistics. To facilitate comparisons among the three survey questionnaires, some NY 2012 and PA 2010 survey multinomial response variables were collapsed into fewer categories or translated to a common format. For example, several PA survey questions that provided a five-scale Likert response (*always, frequently, sometimes, never, don't know*) were regrouped into a three-scale response (*no, yes, maybe*) or redefined (e.g., *very, moderately, slightly, not at all, don't know*). The χ^2 tests were used to compare frequencies of categorical responses between years and states. Univariate analyses were used to compare means of continuous response variables among different levels of categorical factors. Non-parametric Kruskal–Wallis rank-sum tests were employed when assumptions of equal variance for analysis of variance were not met. We employed generalized linear models (GLM) to explore pre-defined relationships between farm/grower characteristics and perceptions of native pollinators. Specifically, we predicted that perceived diversity, value of native bees as pollinators and openness to relying exclusively on native pollinators would increase as acres in apple production decreased and would be highest for those farms surrounded by natural areas. These predictions are based on the strong link between healthy native pollinator communities in fields close to natural areas (Ricketts et al., 2008; Kennedy et al., 2013), and the assumption that growers may be aware of increased native bee activity in such orchards. To test the effects of farm size, state (NY or PA) and adjacent habitat (collapsed into *natural, agricultural* or *other-mixed*) on estimated number of species, we used a negative binomial GLM (Zuur et al., 2013). To test the same effects on whether native bees were considered valuable for orchard pollination (*yes, no, maybe*) and whether growers had considered relying exclusively on naturally occurring native bees (*yes, no, maybe*), we conducted multinomial logistic regressions. Only main effects of size, state and habitat were included and multinomial logistic models were not reduced.

We used descriptive statistics to summarize bee abundance and species richness recorded in orchard surveys. For NY, in parallel with grower survey analyses, we investigated effects of orchard size and surrounding natural habitat (at 1 km radius) on native bee abundance and cumulative observed species

richness to see if patterns in the bee data reflected grower percep-tions of bee activity and importance in orchards. Size and amount of natural habitat in the landscape were calculated using GIS (ArcMap 10, ESRI). For size, we followed property boundaries of orchards, which does not account for the fact that orchards may be adjacent to other orchards, potentially rendering actual orchard area much larger from a bee's perspective. Assessing amount of semi-natural areas within a given distance of orchard center can account for other orchards nearby; we used 1 km as our buffer radius because it has been found to be a strong predict-ive scale for bee response variables (Kremen et al., 2002; Watson et al., 2011). We did not want to go beyond 1 km as we wanted land cover to reflect what a grower would consider the farm's sur-rounding habitat. GLM and generalized linear mixed models were used to analyze diversity and abundance, respectively. In the abundance model, we included farm as a random effect since repeat collecting events occurred within a year, and because of the strong relationship between bee activity and temperature, we included log-transformed temperature as a covariate. Diversity data were pooled at the farm level, and therefore, did not include temperature or random farm effects in models with diversity as the response variable.

We conducted regressions in R software (R Core Team, 2013), using 'MASS' and 'nlme' packages (Venables and Ripley, 2002; Pinheiro et al., 2017); all other analyses were performed in SPSS (IBM Corp, 2013). For general linear models, assumptions of nor-mality and homoscedasticity were met. For negative binomial regressions, we verified that models were not overdispersed (Zuur et al., 2013).

Results and discussion

Grower and farm characteristics

NY and PA demographics were largely similar with some notable differences in farm size, diversity and surrounding habitat (Table 2

Table 2. Grower demographics, New York (2009 and 2012) and Pennsylvania apple 2010

	New York				Pennsylvania	
	2009		2012		2010	
Grower and farm characteristics	N	Mean	N	Mean	N	Mean
Acreage in apple production	262	79.5 (7.8)	298	80.2 (7.5)	73	96.6 (24.4)
Number apple varieties	262	15.5 (0.7)	298	17.6 (1.0)	73	21.5 (3.7)
		Percent		Percent		Percent
Percent income derived from apple			296			
0–25				35.5		
25–50				12.8		
50–75				23		
75–100				28.7		
Primary habitat surrounding orchard	262		296		73	
Orchard		8.5		5.7		11
Suburban		8.9		8.0		9.6
Forest		18.9		24.3		39.7
Meadow		4.6		3.3		0
Agricultural		37.5		37.3		39.7
Mixed		21.6		21.3		0
Pest management style	249		296		73	
Conventional		24.9		18.5		16.4
IPM		64.3		70		79.5
Organic		8.4		5.4		1.4
Other		2.4		6.1		0
Grow other stone fruits			298		72	
Yes				54.5		93.2
No				45.5		5.5
Grow vegetable crops			298		72	
Yes				42		60.3
No				58.1		38.4

s.e.m. provided with means in parentheses. Blanks indicate the questions or specific responses were not included in surveys.

summarizes results for questions on grower and farm characteristics). On average, growers in our study region had close to 100 acres in apple production, harboring over 15 varieties. Across states, fewer than 10% of growers had more than 200 acres in apple production. Twice as many PA growers owned orchards smaller than 10 acres than NY growers. Percent grower income derived from apple was distributed evenly among three collapsed categories: 0–25, 25–75, 75–100%, and increased significantly with orchard size ($\chi_3^2 = 164.6$, $P < 0.0001$; Fig. 1; question only asked in NY 2012 questionnaire). Crop diversity was higher, but diversity of surrounding habitat types lower for PA growers. Significantly more PA participants grew stone fruit ($\chi_1^2 = 39.4$, $P < 0.001$) and vegetables ($\chi_1^2 = 8.6$, $P = 0.003$) in addition to apple. NY growers reported a full gradient of habitat types surrounding their orchards with *agriculture*, *mixed* and *forest* being the most common. In contrast, most PA orchards seemed to be surrounded by either *forest* or *agriculture* and little in between. Thus, we recorded a continuum of operation size and amount of natural habitat adjacent to orchards across study regions, with more specialized, commercial apple growers in NY than PA.

In terms of pest management strategies, a majority of growers in both states reported using primarily IPM practices. Both PA and NY have well-established IPM programs, developed over the last 40 yr for apple production systems by state, land grant institutions (Kovach and Tette, 1988; Rajotte et al., 1992). By incorporating reduced-risk pesticides (Agnello et al., 2009), sex-pheromone-based mating disruption products (Joshi et al., 2011), as well as pest monitoring and forecasting tools (Damos and Savopoulou-Soultani, 2010), IPM offers reduced-risk pest management programs that are environmentally safer than conventional pest management programs in commercial fruit production (Agnello et al., 2009; Biddinger et al., 2014). Up to a quarter of growers continue to rely on conventional pest management; fewer than 10% of growers manage their orchards organically. Organic apple production is relatively rare in the study region due to high disease and pest pressure (Agnello et al., 2003). Thus, a majority of growers across the region currently follow pest

Fig. 1. Correlation between financial reliance of growers on apple production and amount of land planted in apple.

management programs that encourage diligent use of pesticides, by monitoring pest pressure and spraying only when pest damage causes economic harm (Agnello et al., 2009; Jones et al., 2010); such practices have the potential to be readily modified to accommodate pollinators in commercial apple production (Biddinger and Rajotte, 2015).

Pollination strategies

Concern over reliable pollination was high among all growers. Study-wide, between 36 and 52% growers reported having experienced limited apple pollination due to inadequate visitation by pollinators (see Table 3 for results summary of questions addressing pollination strategies). Several growers commented that bad weather was an important driver of low bee activity. A particularly wet spring in 2011 and cold spring in 2012 may have contributed to higher reports of pollination limitation in 2012 as compared with 2009 in NY. Providing a Likert scale of response options (i.e., *always*, *frequently*, *sometimes*, *never, don't know*) in the two most recent surveys revealed that for the majority of growers, pollinator limitation occurs only sometimes. Only 2–5% of blossoms, compared with 80% for cherry, need to be set for a viable commercial apple crop; however, growers seek higher pollination rates to maximize fruit quality, which, ultimately, dictates market value (Westwood, 1993). Because the king bloom (the center flower of a five-flower cluster) produces the largest fruit, growers will overpollinate to ensure high set of king bloom and thin blossoms (chemically or mechanically) to avoid biennial bearing.

Recent declines in honeybee populations due to CCD were considered a threat to successful apple production by the majority of growers surveyed, but a sizeable percentage were uncertain about the impacts of CCD (Table 3). Grower concerns over the negative impacts of CCD on pollination services echo those found among blueberry growers in Maine (Hanes et al., 2015).

To our surprise, only about 50% of growers reported renting honeybees for apple pollination in both NY and PA ($\chi_1^2 = 2.1$, $P = 0.2$; Table 3). The probability of renting bees increased directly with farm size ($\chi_1^2 = 11.8$, $P = 0.001$, Fig. 2) and was similar between states (state × acre: $\chi_1^2 = 2.7$, $P = 0.1$). Because number of pollinators required for adequate pollination increases directly with farm size, smaller orchards likely do not need supplemental honeybees if located near other operations that rent hives or semi-natural habitat that supports native pollinators (Park et al., 2015). Growers renting honeybees stocked their orchards at similar densities (NY: 2.5 ± 0.4 hives/ac, $n = 181$; PA: 1.9 ± 0.2 hives/ac, $n = 44$; $t_{223} = 0.752$, $P = 0.5$) and paid comparable prices per hive (NY: $63.90 ± 2.8; PA: $59.30 ± 4.40; $t_{151} = 0.631$, $P = 0.5$). In NY, regardless of farm size, a majority of growers considered honeybee rentals a *minor* to *moderate* expense. Similar results were found for PA growers with <100 acres in apple production; however, most large-scale PA growers, with 100–500 acres in apple ($n = 6$), described honeybee rentals to be a *major expense* (within PA, $\chi_{15}^2 = 26.6$, $P = 0.03$). For most producers, hive prices may not have yet inflated to the point where growers would be economically motivated to invest in other pollinator strategies, especially if there is perceived risk in doing so. In PA, a network of growers, including large-scale operations, have demonstrated that adequate pollination can be achieved by relying on native bees alone (Biddinger, pers. obs.). Such demonstrated success is testimony that hive rentals are unnecessary in some orchards within the study region and likely inspire others to try alternative pollination even if economic benefits are not *major*.
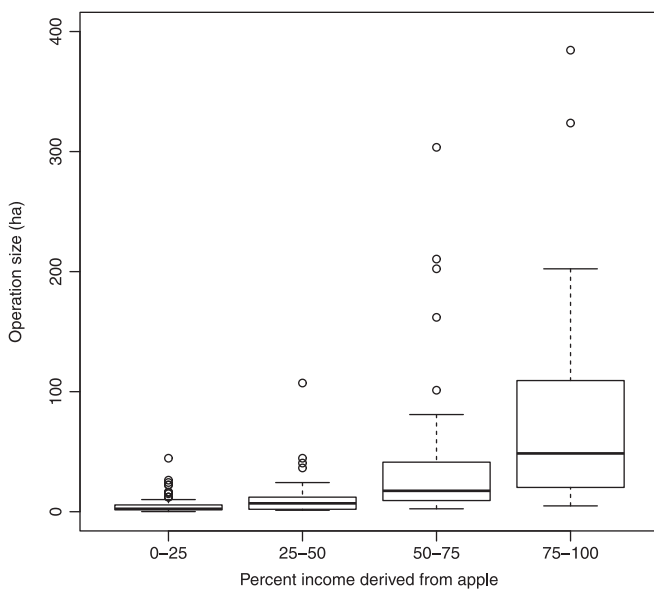
Mia G. Park *et al.*

Table 3. Pollination strategies and concerns among New York and Pennsylvania apple growers

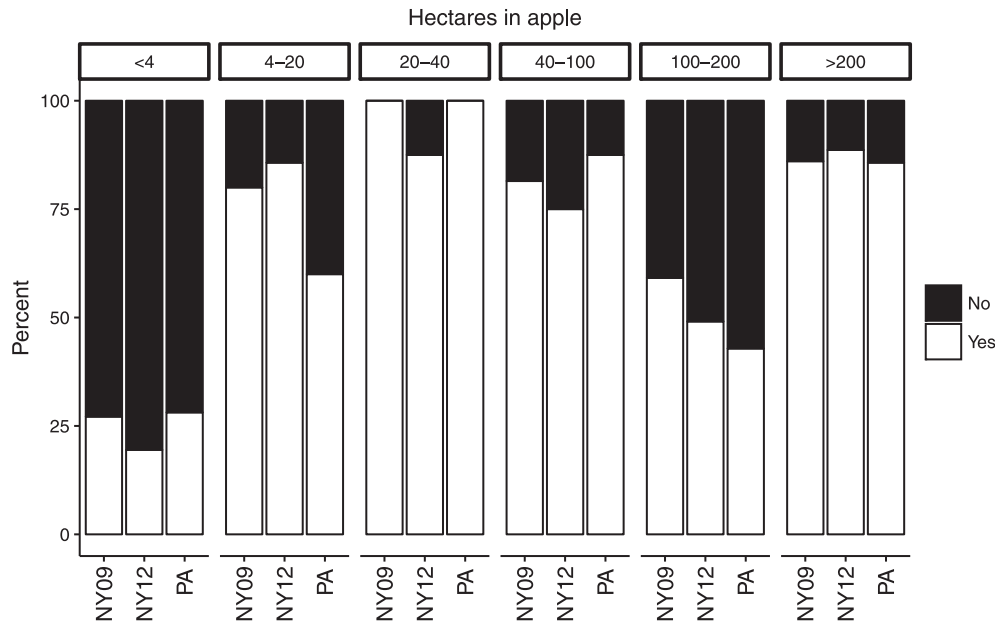| Pollination strategy	New York				Pennsylvania	
	2009		2012		2010	
	N	%	N	%	N	%
Rent honey bees	257		297		73	
Yes		60.7		53.5		49.3
No		39.3		46.5		50.7
Expense of honey bee rentals	223		160		67	
Major		25.11		14.4		8.2
Moderate				33.1		24.6
Minor		74.89		49.4		60.3
No opinion				3.1		4.1
Familiar with mason bees	253		297			
Yes		29.4		42.5		
No		64.3		57.5		
Maybe		6.3				
Use commercial mason bees	253		297		72	
Yes		2		2.7		9.6
No		97.2		97.3		89
Maybe		0.8				1.4
Use commercial bumblebees			297		72	
Always				4.0		4.1
Frequently				2.3		4.1
Sometimes				9.3		13.7
Never				83.3		76.7
Don't know				1.0		1.4
Consider impacts of pesticides	249		295		72	
Yes		93.2		97.3		97.3
No		4.8		2.0		1.4
Sometimes		2		0.7		5.0
CCD threatens apple production	247		297		71	
Yes		59.1		56.7		73.2
No		19.4		10.3		15.5
Maybe/don't know		21.5		33.0		11.3
Pollination limited by pollinator availability	249		297		71	
Yes		36.1		52.3		47.9
No		41		29.2		43.7
Maybe		22.9		18.5		8.5
Considered relying exclusively on native bees	249		297		71	
Yes		51.4		60.3		67.2
No		42.3		36		27.4
Maybe		6.3		3.7		2.7

Fig. 2. Proportion of apple growers in New York (NY) and Pennsylvania (PA) that reported renting honeybees for pollination increased with farm size. NY grower surveys were conducted in 2009 (NY09) and 2012 (NY12).

Grower adoption of bumble bees, as an alternative managed pollinator, was not trivial; however, use and awareness of mason bees was low. In NY and PA, 16.7 and 24.3% growers, respectively, reported using bumble bees, at least, sometimes. Few growers reported having used commercial mason bees for apple pollination, with a study-wide maximum of 8% growers in PA. Commercial bumble bees are more expensive than honeybees, but forage more reliably in cooler, early spring temperatures (Goulson, 2003). Mason bees specialize on fruit trees and are highly effective pollinators (Bosch and Blas, 1994). The native blue orchard bee, *Osmia lignaria*, is rarely collected in NY (Park et al., 2015) or PA orchards (Joshi et al., 2015, Joshi et al., 2016); however, the introduced Japanese horn-faced bee, *O. cornifrons*, is well-established throughout the east coast. There is interest in further developing *O. cornifrons* as an alternative managed pollinator in our study region (Biddinger et al., 2013a, b; T. Pitts-Singer pers. comm.).

Regardless of year and state, almost all (>93%) surveyed growers reported that they already considered pollinator safety when applying pesticides in orchards. Across the study region, apple is an intensively sprayed fruit crop due to intense pest and disease pressure (Agnello et al., 2009). Orchard pesticides have been shown to impact both managed and wild pollinators (Biddinger et al., 2013b; Mallinger et al., 2015; Park et al., 2015). Aside from intrinsic motivations to protect pollinators, growers have many practical reasons to be cognizant of pollinators when considering their pest management options: (1) adequate fruit set for crop production depends on adequate pollination; (2) growers often pay to have bees in the orchard, so harm to bees would be financially counterproductive; and (3) label guidelines restrict the use of insecticides during bloom when bees are most active in orchards. Judicious use of insecticides during bloom is important to reduce pesticide risk for pollinators; however, care should also be taken outside the bloom period. Pollinators are active within orchards before and after apple bloom, foraging ground cover floral resources and/or nesting. Care must also be taken when using pesticides traditionally considered safe for bees, such as fungicides and herbicides. Both fungicides and insecticides applied when apple was not in bloom decreased wild pollinator, but not honeybee, visitation and diversity in NY orchards (Park et al., 2015). The lack of a measurable response of honeybees to pesticides likely results from placing hives in orchards only during bloom and to the tendency of honeybees to forage on non-apple resources at larger spatial scales than wild bees (McArt et al., 2017). Precautions taken by growers during bloom are, therefore, inadequate to maximize pollination services by wild bees. Efforts to promote alternative bee pollination services should, therefore, raise awareness of the vulnerability of alternative pollinators to pesticide applications throughout the growing season.

Knowledge and perceptions of native pollinators

Grower estimates of bee diversity were relatively low, and half of our NY 2012 questionnaire respondents chose *don't know* when given this option. Choosing from a range of values (NY:*1, 10, 30, 40, 100*; PA:*1, 10, 50, 100, 200, 300*), growers estimated that apple flowers are visited by a median of ten bee species, compared with 100 and 52 bee species recorded in field surveys in NY and PA, respectively. Grower estimates, however, approached cumulative bee species richness netted within a single orchard (NY: 15–51 and PA: 10–25). Additionally, low species estimates may reflect a lay person's ability to accurately identify bees based on easily recognizable morphological groups. Bee species are commonly distinguished by characteristics only visible under a microscope, making it challenging to differentiate species in the field. For this reason, native bees are commonly lumped into morphological groups (e.g., 'metallic green bee') to facilitate observations of bee visitation by lay persons. Following 'Pennsylvania Citizen Scientist Pollinator Guide' (Donovall and vanEngelsdorp, 2008), apple bees in our study region represent 12 distinct morphological groups, which mirror median grower diversity estimates of ten species. In sum, growers demonstrated a wide knowledge gap in terms of sheer diversity of native pollinators, with many simply

unwilling to guess. This gap parallels the general public's lack of pollinator literacy, having only recently considered non-honey bee species as important crop pollinators. Of the respondents who did provide diversity estimates, many possessed an accurate local, lay knowledge of the bee fauna visiting their orchards.

In biological surveys, native bee abundance and species richness were significantly and positively influenced by the amount of semi-natural area close to orchards but not by orchard size (Table 4, Joshi et al., 2016). We, therefore, predicted that grower estimates of bee diversity may be higher among growers whose orchards were surrounded by semi-natural areas (i.e., *forest*, *mixed*, *meadow*), but no such relationship was observed (Table 5). Nor did we observe an effect of the number of acres a grower had in apple on their bee diversity estimates. Whether we measured a lack of awareness of the bee fauna visiting orchard or, again, an inability to distinguish bee species is unclear.

We recorded a high appreciation for native pollinators among grower participants, but again some uncertainty about how much native bees actually contribute to orchard pollination. Native bees were viewed by 85–93% surveyed growers as valuable pollinators in orchards; this high appreciation did not change with farm characteristics or state (Table 5). Blueberry (Hanes et al., 2015) and cranberry (Gaines-Day and Gratton, 2017) growers shared similarly high appreciation for native pollinators. When asked to rate the value of native bee contributions to apple pollination (PA 2010 and NY 2012 questionnaires), over 50% of growers chose the highest possible ranking (i.e., 53.4% PA: *always*; 63.6% NY: *very important*); only 6.4 and 8.2% of NY and PA growers, respectively, reported not knowing the value of native bees for their apple orchards. Across the study region, growers estimated that native bees contribute half of orchard pollination services (NY: 45 ± 1.6%, PA: 51 ± 3.5%; $t_{300} = -1.6$, $P = 0.1$), but individual estimates ranged widely and 20% of respondents expressed that they *did not know* (available answer in the NY 2012 survey only). When asked whether alternative managed pollinators, such as mason or bumble bees, were important for apple pollination (PA-only question), 68% were evenly split among alternative managed pollinators being *always*, *frequently* or *sometimes important*; 6% reported they were *never important*; and 29% reported that they *did not know*. Grower uncertainty in the importance of non-*Apis* pollinators is understandable: contributions of native bees have only recently been quantified (Ritz et al., 2012; Mallinger and Gratton, 2015; Blitzer et al., 2016; Park et al., 2016), and efforts to use other managed pollinators are still new.

Over half of the study participants had previously considered relying exclusively on native pollinators (Table 3). As one might expect, more growers who did not rent honeybees (72.4%) had

considered relying on native bees than those who did rent honeybees (44.2%, $\chi^2 = 63.9$, d.f. = 2, $P < 0.0001$); and yet, almost half the growers who rented honeybees had thought about using alternative pollinators and may be especially receptive to integrated crop pollination (Isaacs et al., 2017). Whether a grower had considered relying exclusively on native pollinators was most influenced by farm size (Fig. 3, Table 5). As acreage in apple production increased, grower consideration to rely exclusively on native bees decreased (Table 5). In contrast, orchard size did not have a significant effect on bee visitation or diversity in biological surveys (Table 4). Because percent total income derived from apple production increased significantly with acres in apple production ($\chi^2 = 151.6$, d.f. = 5, $P < 0.0001$; Fig. 2), we conclude that willingness to risk inadequate pollination decreases as apple becomes a greater source of one's income. Importance of producing high-quality fruit to increase one's crop value and meet consumer expectations likely increases with operation size. Nonetheless, even among the largest apple operations, a third of growers had considered foregoing honeybee rentals.

Grower openness to relying exclusively on native pollinators also depended on state and habitat types adjacent to orchards (Table 5). PA growers (67.2%) were significantly more likely to have considered relying on native bees than NY growers (2010: 51.4%; 2012: 60%). We speculate two compatible reasons for this: (1) PA growers had greater exposure to native bee crop pollination, and (2) growers accurately perceived increased native pollinator activity in orchards surrounded by semi-natural habitat. PA growers may have gained more exposure to the idea of relying on native bees from a network of growers already using such practices successfully and from increased extension activities. First, even before hive rental fees had tripled after CCD hit in 2006, a few large PA growers had successfully experimented with not renting honeybees and relying exclusively on native bees; this success provided other growers with a real demonstration that such a pollination strategy was a viable option for commercial production (Biddinger, pers. obs.). Secondly, pollinator extension in PA was likely more active, before and during the study period, due to the presence of the Center for Pollinator Research at Pennsylvania State University (http://ento.psu.edu/pollinators). Native pollinator extension was conducted by Biddinger, an established, fruit entomologist stationed at the Pennsylvania State University Fruit Research and Extension Center. Native pollinator extension in NY was largely conducted by Park, a student at the time, from 2010 to 2012, in the form of annual grower talks, a pollinator booklet, and a Department of Entomology website (entomology.cornell.edu/wildpollinators). Finally, PA respondents may have represented a more biased pool of participants given they were surveyed at extension events.

Table 4. Effects of orchard size and percent semi-natural areas within a 1 km buffer of orchard on bee abundance (GLMM) and observed bee species richness (GLM) in New York State

Effect	Abundance			Diversity		
	Coeff (s.e.m.)	d.f.	*P*-value	Coeff (s.e.m.)	d.f.	*P*-value
Natural area	0.016 (0.0066)	16	0.034	0.45 (0.16)	15	0.012
Size (ac)	0.016 (0.0066)	16	0.27	−10.02 (6.47)	15	0.14
Temperature	1.16 (0.22)	165	<0.0001	–	–	–
Year	−0.66 (0.072)	165	<0.0001	–	–	–

For bee abundance [ln(y + 1) transformed], covariates temperature [ln(x) transformed] and year, as well as a random farm factor were included. All predictors but year were mean centered. Coefficients are not back-transformed. '–' indicates the predictor was not included in the full model.

Table 5. Effects of state, operation size and habitat adjacent to orchards on (1) grower estimates of native pollinator diversity in apple orchards, (2) whether growers considered native bees valuable to apple pollination and (3) whether growers had considered relying exclusively on native bees

Effect	Coeff (s.e.m.)	z	P-value
Estimated bee species richness (d.f. = 540)			
State (ref = NY)	**0.57 (0.00032)**	4.48	**<0.0001**
Operation size (ac)	−0.00020 (0.00032)	−0.63	0.5
Habitat (ref = natural)			
Agricultural	−0.12 (0.11)	−1.11	0.3
Other/mixed	−0.17 (0.12)	−1.36	0.2
Native bees are valuable pollinators (N = 628, ref = no)			
State (ref = NY)			
Yes	0.53 (1.05)	0.50	0.6
Maybe	0.48 (1.13)	0.42	0.6
Operation size (ac)			
Yes	0.00061 (0.002)	0.28	0.78
Maybe	0.0014 (0.002)	0.61	0.54
Habitat (ref = natural)			
Agricultural			
Yes	0.11 (0.66)	0.17	0.87
Maybe	−0.025 (0.72)	−0.034	0.97
Other/mixed			
Yes	−0.30 (0.66)	−0.45	0.65
Maybe	−1.24 (0.79)	−1.57	0.54
Considered relying exclusively on native pollinators (N = 620, ref = no)			
State (ref = NY)			
Yes	**0.63 (0.31)**	**2.04**	**0.04**
Maybe	−0.14 (0.79)	−0.18	0.86
Operation size (ac)			
Yes	**−0.0040 (0.00077)**	**−5.18**	**<0.0001**
Maybe	**−0.0012 (0.0014)**	**−0.84**	**0.04**
Habitat (ref = natural)			
Agricultural			
Yes	**−0.65 (0.22)**	**−2.94**	**0.0033**
Maybe	**−1.16 (0.48)**	**−2.40**	**0.017**
Other/mixed			
Yes	−0.17 (0.25)	−0.68	0.49
Maybe	−0.51 (0.51)	−1.01	0.31

Habitat categories were collapsed into *agriculture*, *natural* and *other*. 'Other' included mixed and suburban habitats. For estimates of bee diversity, a negative binomial GLM was employed and reduced via backwards stepwise regression. Predictors that were not significant (at $\alpha = 0.05$) but contributed significantly to model fit were retained. Multinomial logistic regressions were conducted on response variables with three levels: *yes*, *no* and *maybe* and were not reduced. Coefficients in multinomial logistic regression are log odds ratios. Significant effects are bolded.

Increased PA grower openness to relying on native pollinators could also be linked to PA grower ownership of smaller orchards located near semi-natural areas (Table 2), a documented source of wild pollinators visiting orchards (Watson et al., 2011; Park et al., 2015). Amount and proximity of adjacent natural areas, primarily forest, was a strong predictor of native pollinator abundance and diversity in our field surveys in NY (Table 4) and PA (Kammerer et al., 2016b; Joshi et al., 2016). Congruently, consideration to rely exclusively on native pollinators was significantly lower for

growers whose orchards were surrounded by agriculture than for those whose orchards were near natural or mixed/suburban areas (Table 5). Regardless of state differences, these results suggest an awareness among growers about the levels of native pollinator activity occurring within orchards, and a surprising openness to relying exclusively on native pollinators.

To gauge willingness of growers to enhance native pollination, we asked if they would consider low-cost land management practices that would increase native bees in their orchard. Consistent
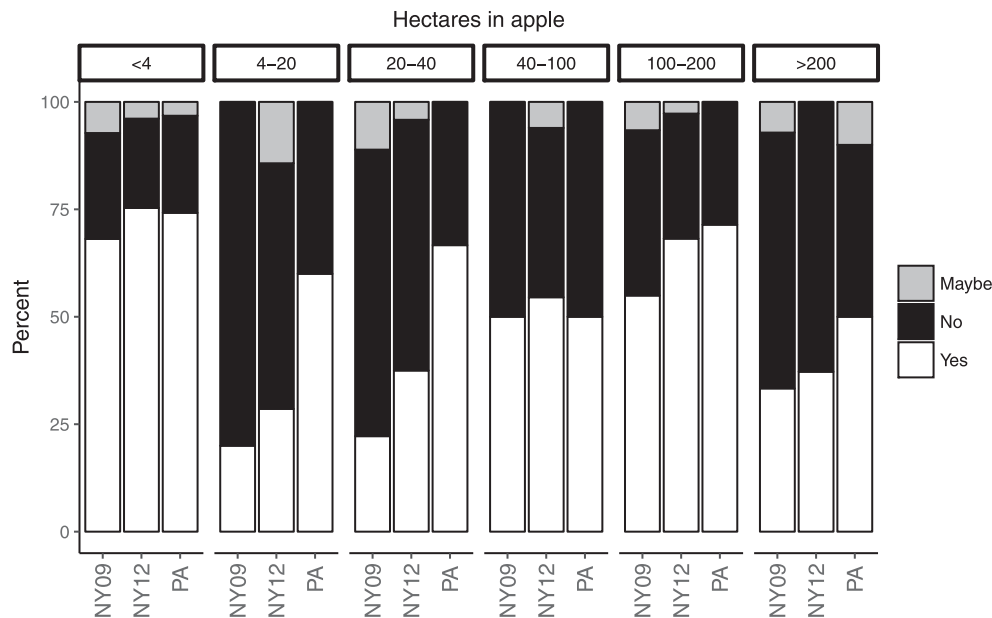
Hectares in apple

Fig. 3. Grower consideration to rely exclusively on native pollinators decreased with farm size. NY grower surveys were conducted in 2009 (NY09) and 2012 (NY12).

across surveys, a majority of growers indicated that they would consider such action, with 85% PA compared with 50–68% NY growers responding *yes*. Growers were also asked about their knowledge of and participation in federal cost-share programs, designed to aid grower efforts to create or maintain pollinator habitat. The Food, Conservation and Energy Act of 2008 provided federal funding to conserve and protect pollinators in agricultural ecosystems (Whittingham, 2011). As a result, growers receive government financial incentives and technical support to adopt pollinator-friendly production practices (Decourtye et al., 2010). In our study region, native bees are pollen foragers, and a continuous source of mixed floral resources near orchards could be important in conserving and maintaining healthy population of these bees (Kammerer et al., 2016a, b). A high proportion of growers (NY: 91%, PA: 75%) reported not knowing about government cost-share programs; of those who did, only 8% of NY and 16% PA growers were enrolled. Thus, apple growers seemed generally open to relying more on native pollinators; however, many were not aware of the resources available to them to enhance native bee habitat in their orchards.

To identify obstacles preventing growers from actively enhancing native pollinator populations in orchards, we asked growers to rank the importance of several factors (from *not at all important* to *very important*) that would influence their decision to implement land management changes for native bees (Fig. 4). Of the top three factors, *proven effectiveness of native pollinators* was most important, *clear guidelines to implement management practices* was second and *environmental stewardship* was third. Recent empirical studies now provide strong evidence for the effectiveness and importance of native pollinators for apple production (Ritz et al., 2012; Mallinger and Gratton, 2015; Martins et al., 2015; Park et al., 2016; Blitzer et al., 2016; Russo et al., 2017). Pollination provided by native bees depends directly on their abundance (i.e., the more bee visits the better the pollination); abundance of native bees varies across orchards due to differences in pesticide use and amount of natural area in the surrounding landscape (Mallinger et al., 2015; Park et al., 2015).

In order for growers to assess the native pollination services available in orchards, accessible protocols to monitor native bee populations need to be developed (Hanes et al., 2015). Citizen science projects, such as the Northeast Pollinator Partnership (http://www.northeastpollinatorpartnership.org/), are a plausible approach to forward such efforts, by (1) gathering large amounts of data on bee abundances, and (2) making data-informed recommendations back to growers about what pollinator strategies they should adopt. Making the scientific evidence on contributions of native pollinators accessible to growers should be a primary goal of future extension efforts.

Growers need adequate technical support and guidance to implement bee-friendly practices (Biddinger and Rajotte, 2015; Isaacs et al., 2017). Because native pollination services vary among orchards, depending on pesticide use and surrounding habitat, one cannot prescribe a single strategy that fits all. Site-specific assessment of grower pollination management options would be ideal. For example, growers with orchards near large tracts of forest could potentially rely exclusively on native bee pollination and focus on minimizing impacts of pesticides. In contrast, a grower whose orchards are surrounded by intense agriculture would focus on creating more pollinator habitat. Habitat enhancements for pollinators require technical support, to identify appropriate seed mixes and manage weeds. Growers enrolled in CRP receive technical advice from their local NRCS office, and non-profit organizations are providing increasing guidance nationally (e.g., The Xerces Society). Local extension programs with established ties to the apple industry also have potential to provide technical assistance and are poised to help balance grower needs to control pests and maximize pollination services (Biddinger and Rajotte, 2015).

Willingness of growers to manage orchards in a manner that would support native pollinators was motivated more by a sense of environmental stewardship than by cost. First, honeybee rentals were not perceived as a major expense by most growers, so if they were considering making changes, it makes sense that motivations not be financial and rather driven by concern for pollinators and
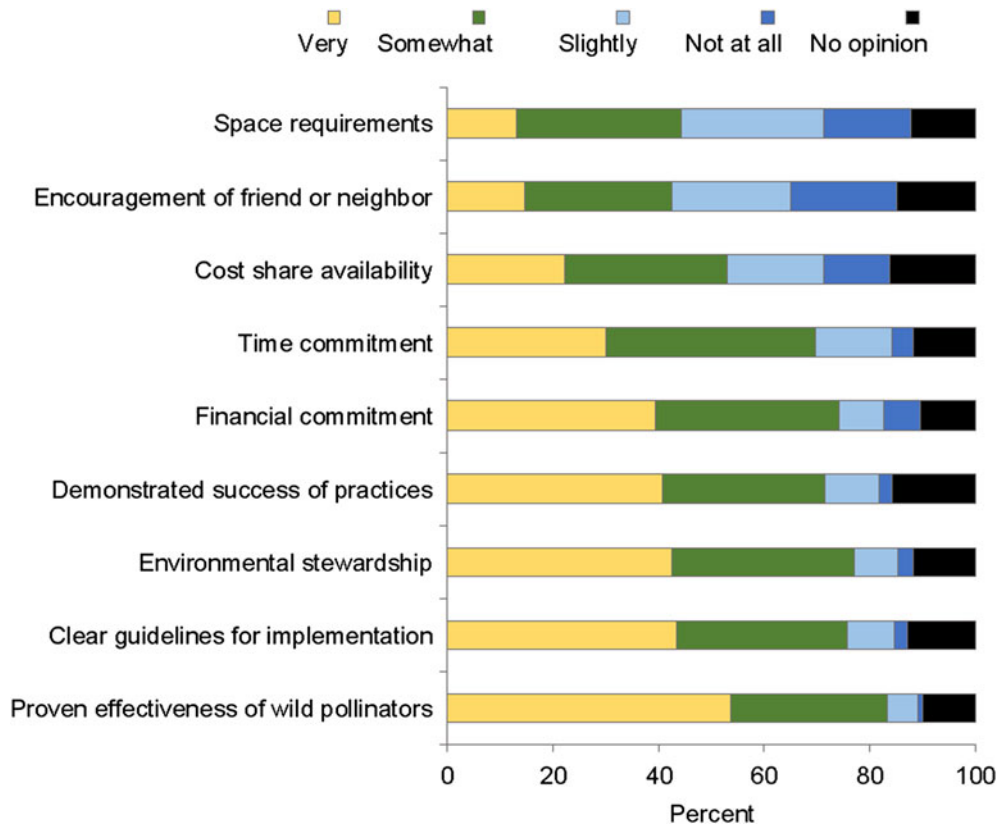
Fig. 4. Importance of factors that would influence grower decisions to adopt new land management practices to protect or enhance native pollinators.

their services. Secondly, the fact that cost was not one of the top three motivations may help explain grower lack of interest/awareness in government cost-share programs. Thirdly and most importantly, if a large pool of growers are motivated by environmental stewardship, they are also likely receptive to outreach and support for managing lands in more bee-friendly ways. Pollinator habitat creation at the landscape scale has been forwarded as a means by which society can increase food sustainability, by enhancing native pollination services for crops, and can conserve diversity in agricultural landscapes (Potts et al., 2011). For such a coordinated vision to become a reality, additional outreach and extension support on crop pollination are needed (Hanes et al., 2015).

Conclusions

Integrating biological and grower survey data allowed us to explore grower awareness of pollinators as well as factors influencing grower perceptions. We found overwhelming support among eastern apple growers for the importance of native bees, an openness to rely more on naturally occurring bees, and willingness to make low-cost changes to enhance native bee populations. Already 50% of growers in the study region rely on ambient pollination by not renting honeybees; even more have, at least, considered relying on native pollinators exclusively. At the same time, we documented sizeable uncertainty among growers about the effectiveness of native and alternative managed bees for apple pollination, as well as a tendency to rent honeybees to maximize production value. Uncertainty about non-honeybee pollinator effectiveness was the largest obstacle reported by growers to

actively managing orchards for native pollinators. Empirical evidence for the importance of wild pollinators in apple orchards has grown within our study regions (Ritz et al., 2012; Blitzer et al., 2016; Park et al., 2016) and beyond (Mallinger et al., 2015; Martins et al., 2015). This seems an opportune time to take the scientific evidence and encourage growers to incorporate alternative pollinators into their pollination strategy. By no means do we advocate that growers abandon the use of honeybees altogether, but a more integrated pollination management approach seems viable in our study regions and may ensure growers continue to receive optimum pollination in the face of volatile honeybee supplies (Isaacs et al., 2017). Proactive steps to support alternative orchard pollinators will not only benefit honeybees and biological control agents, such as parasitic flies and wasps that require nectar and pollen as adults, but also other pollinator-dependent crops often planted nearby. With a strong history of IPM in the region, extension programs provide an existing infrastructure in which to develop technical and informational support to ensure sustainable food production systems that rely on insect pollination, like apple (Biddinger and Rajotte, 2015).

References

Agnello AM, Reissig WH, Kovach J and Nyrop JP (2003) Integrated apple pest management in New York State using predatory mites and selective pesticides. *Agriculture, Ecosystems & Environment* **94**(2), 183–195.

Agnello AM, Atanassov A, Bergh JC, Biddinger DJ, Gut LJ, Haas MJ, Harper JK, Hogmire HW, Hull LA, Kime LF, Krawczyk G, Mcghee PS, Nyrop JP, Reissig WH, Shearer PW, Straub RW, Villanueva RT and Walgenbach JF (2009) Reduced-risk pest management programs for eastern U.S. apple and peach orchards: a 4-year regional project. *American Entomologist* **55**(3), 184–197.

Aizen MA and Harder LD (2009) The global stock of domesticated honey bees is growing slower than agricultural demand for pollination. *Current Biology* **19**, 915–918.

Ascher JS and Pickering J (2013) Discover life bee species guide and world checklist (Hymenoptera: Apoidea: Anthophila). http://www.discoverlife. org/mp/20q?guide=Apoidea_species.

Bartomeus I, Ascher JS, Wagner D, Danforth BN, Colla S, Kornbluth S and Winfree R (2011) Climate-associated phenological advances in bee pollinators and bee-pollinated plants. *Proceedings of the National Academy of Sciences* **108**(51), 20645–20649.

Biddinger DJ and Rajotte EG (2015) Integrated pest and pollinator management—adding a new dimension to an accepted paradigm. *Current Opinion in Insect Science* **10**, 204–209.

Biddinger DJ, Joshi NK, Rajotte EG, Halbrendt NO, Pulig C, Naithani KJ and Vaughn M (2013a) An immunomarking method to determine the foraging patterns of *Osmia cornifrons* and resulting fruit set in a cherry orchard. *Apidologie* **44**, 738–749.

Biddinger DJ, Robertson JL, Mullin C, Frazier J, Ashcraft SA, Rajotte EG, Joshi NK and Vaughn M (2013b) Comparative toxicities and synergism of apple orchard pesticides to *Apis mellifera* (L.) and *Osmia cornifrons* (Radoszkowski). *PLoS ONE* **8**(9), e72587.

Biddinger DJ, Leslie TW and Joshi NK (2014) Reduced-risk pest management programs for eastern U.S. peach orchards: effects on arthropod predators, parasitoids, and select pests. *Journal of Economic Entomology* **107**(3), 1084–1091.

Biesmeijer JC, Roberts SPM, Reemer M, Ohlemüller R, Edwards M, Peeters T, Schaffers AP, Potts SG, Kleukers R, Thomas CD, Settele J and Kunin WE (2006) Parallel declines in pollinators and insect-pollinated plants in Britain and the Netherlands. *Science* **313**(5785), 351–354.

Blitzer EJ, Gibbs J, Park MG and Danforth BN (2016) Pollination services for apple are dependent on diverse wild bee communities. *Agriculture, Ecosystems & Environment* **221**, 1–7.

Bosch J and Blas M (1994) Foraging behaviour and pollinating efficiency of *Osmia cornuta* and *Apis mellifera* on almond (Hymenoptera, Megachilidae and Apidae). *Applied Entomology and Zoology* **29**(1), 1–9.

Brittain C, Kremen C and Klein A-M (2013) Biodiversity buffers pollination from changes in environmental conditions. *Global Change Biology* **19**(2), 540–547.

Brittain WH (1935) Studies in bee activity during apple bloom. *Journal of Economic Entomology* **28**, 553–559.

Burkle LA, Marlin JC and Knight TM (2013) Plant-pollinator interactions over 120 years: loss of species, co-occurrence, and function. *Science* **339** (6127), 1611–1615.

Cameron SA, Lozier JD, Strange JP, Koch JB, Cordes N, Solter LF and Griswold TL (2011) Patterns of widespread decline in North American bumble bees. *Proceedings of the National Academy of Sciences* **108**(2), 662–667.

Damos PT and Savopoulou-Soultani M (2010) Development and statistical evaluation of models in forecasting moth phenology of major lepidopterous

peach pest complex for Integrated Pest Management programs. *Crop Protection* **29**(10), 1190–1199.

Decourtye A, Mader E and Desneux N (2010) Landscape enhancement of floral resources for honey bees in agro-ecosystems. *Apidologie* **41**(3), 264–277.

Donovall L and vanEngelsdorp D (2008) *Pennsylvania Native Bee Survey: Citizen Scientist Pollinator Monitoring Guide.* Portland, OR: The Xerces Society for Invertebrate Conservation, 36 p.

Eilers EJ, Kremen C, Greenleaf SS, Garber AK and Klein A-M (2011) Contribution of pollinator-mediated crops to nutrients in the human food supply. *PLoS ONE* **6**(6), e21363.

ESRI (2011) *ArcGIS Desktop: Release 10.* Redlands, CA: Environmental Systems Research Institute.

Free JB (1993) *Insect Pollination of Crops.* 2nd edn. London, UK: Academic Press.

Gaines-Day HR and Gratton C (2017) Understanding barriers to participation in cost-share programs for pollinator conservation by Wisconsin (USA) Cranberry Growers. *Insects* **8**(3), 79.

Gallai N, Salles J-M, Settele J and Vaissière BE (2009) Economic valuation of the vulnerability of world agriculture confronted with pollinator decline. *Ecological Economics* **68**(3), 810–821.

Gardner KE and Ascher JS (2006) Notes on the native bee pollinators in New York apple orchards. *Journal of the New York Entomological Society* **114**(1), 86–91.

Garibaldi LA, Steffan-Dewenter I, Kremen C, Morales JM, Bommarco R, Cunningham SA, Carvalheiro LG, Chacoff NP, Dudenhöffer JH, Greenleaf SS, Holzschuh A, Isaacs R, Krewenka K, Mandelik Y, Mayfield MM, Morandin LA, Potts SG, Ricketts TH, Szentgyörgyi H, Viana BF, Westphal C, Winfree R and Klein AM (2011) Stability of pollination services decreases with isolation from natural areas despite honey bee visits. *Ecology Letters* **14**(10), 1062–1072.

Garibaldi LA, Steffan-Dewenter I, Winfree R, Aizen MA, Bommarco R, Cunningham SA, Kremen C, Carvalheiro LG, Harder LD, Afik O, Bartomeus I, Benjamin F, Boreux V, Cariveau D, Chacoff NP, Dudenhöffer JH, Freitas BM, Ghazoul J, Greenleaf S, Hipólito J, Holzschuh A, Howlett B, Isaacs R, Javorek SK, Kennedy CM, Krewenka KM, Krishnan S, Mandelik Y, Mayfield MM, Motzke I, Munyuli T, Nault BA, Otieno M, Petersen J, Pisanty G, Potts SG, Rader R, Ricketts TH, Rundlöf M, Seymour CL, Schüepp C, Szentgyörgyi H, Taki H, Tscharntke T, Vergara CH, Viana BF, Wanger TC, Westphal C, Williams N and Klein AM (2013) Wild pollinators enhance fruit set of crops regardless of honey bee abundance. *Science* **339**(6127), 1608–1611.

Gibbs J, Joshi NK, Wilson JK, Rothwell NL, Powers K, Haas M, Gut L, Biddinger DJ and Isaacs R (2017) Does passive sampling accurately reflect the bee (Apoidea: Anthophila) communities pollinating apple and sour cherry orchards?. *Environmental Entomology* **46**(3), 579–588.

Goulson D (2003) *Bumblebees: Behaviour and Ecology.* Oxford, UK: Oxford University Press.

Hanes SP, Collum KK, Hoshide AK and Asare E (2015) Grower perceptions of native pollinators and pollination strategies in the lowbush blueberry industry. *Renewable Agriculture and Food Systems* **30**(2), 124–131.

Hutson R (1926) Relation of the honeybee to fruit pollination in New Jersey. *Bull. NJ Agric. Exp. Stn.* **434**, p. 34.

IBM Corp (2013) IBM SPSS Statistics for Windows, Version 22.0. Armonk, NY: IBM Corp.

Isaacs R, Williams N, Ellis J, Pitts-Singer TL, Bommarco R and Vaughan M (2017) Integrated crop pollination: combining strategies to ensure stable and sustainable yields of pollination-dependent crops. *Basic and Applied Ecology* **22**, 44–60.

Jones VP, Brunner JF, Grove GG, Petit B, Tangren GV and Jones WE (2010) A web-based decision support system to enhance IPM programs in Washington tree fruit. *Pest Management Science* **66**(6), 587–595.

Joshi NK, Hull LA, Rajotte EG, Krawczyk G and Bohnenblust E (2011) Evaluating sex-pheromone- and kairomone-based lures for attracting codling moth adults in mating disruption versus conventionally managed apple orchards in Pennsylvania. *Pest Management Science* **67**(10), 1332–1337.

Joshi NK, Leslie T, Rajotte EG, Kammerer MA, Otieno M and Biddinger DJ (2015) Comparative trapping efficiency to characterize bee abundance,

diversity, and community composition in apple orchards. *Annals of the Entomological Society of America* **108**(5), 785–799.

Joshi NK, Otieno M, Rajotte EG, Fleischer SJ and Biddinger DJ (2016) Proximity to woodland and landscape structure drives pollinator visitation in apple orchard ecosystem. *Frontiers in Ecology and Evolution* **4**, 38. doi: 10.3389/fevo.2016.00038.

Kammerer MA, Biddinger DJ, Rajotte EG and Mortensen DA (2016a) Local plant diversity across multiple habitats supports a diverse wild bee community in Pennsylvania apple orchards. *Environmental Entomology* **45**(1), 32–38.

Kammerer MA, Biddinger DJ, Joshi NK, Rajotte EG and Mortensen DA (2016b) Modeling local spatial patterns of wild bee diversity in Pennsylvania apple orchards. *Landscape Ecology* **31**, 2459–2469.

Kasina M, Kraemer M, Wittmann D and Martius C (2009) Farmers' knowledge of bees and their natural history in Kakamega district, Kenya. *Journal of Apicultural Research* **48**(2), 126–133.

Kennedy CM, Lonsdorf E, Neel MC, Williams NM, Ricketts TH, Winfree R, Bommarco R, Brittain C, Burley AL, Cariveau D, Carvalheiro LG, Chacoff NP, Cunningham SA, Danforth BN, Dudenhöffer J-H, Elle E, Gaines HR, Garibaldi LA, Gratton C, Holzschuh A, Isaacs R, Javorek SK, Jha S, Klein AM, Krewenka K, Mandelik Y, Mayfield MM, Morandin L, Neame LA, Otieno M, Park M, Potts SG, Rundlöf M, Saez A, Steffan-Dewenter I, Taki H, Viana BF, Westphal C, Wilson JK, Greenleaf SS and Kremen C (2013) A global quantitative synthesis of local and landscape effects on wild bee pollinators in agroecosystems. *Ecology Letters* **16**(5), 584–599.

Klein A-M (2009) Nearby rainforest promotes coffee pollination by increasing spatio-temporal stability in bee species richness. *Forest Ecology and Management* **258**(9), 1838–1845.

Klein A-M, Vaissière BE, Cane JH, Steffan-Dewenter I, Cunningham SA, Kremen C and Tscharntke T (2007) Importance of pollinators in changing landscapes for world crops. *Proceedings of the Royal Society B: Biological Sciences* **274**(1608), 303–313.

Kovach J and Tette JP (1988) A survey of the use of IPM by New York apple producers. *Agriculture, Ecosystems & Environment* **20**(2), 101–108.

Kremen C, Williams NM and Thorp RW (2002) Crop pollination from native bees at risk from agricultural intensification. *Proceedings of the National Academy of Sciences* **99**(26), 16812–16816.

Kremen K, Williams NM, Bugg R, Fay J and Thorp RW (2004) The area requirements of an ecosystem service: crop pollination by native bee communities in California. *Ecology Letters* **7**(11), 1109–1119.

Levin MD (1983) Value of bee pollination to U.S. agriculture. *Bulletin of the ESA* **29**(4), 50–51.

Mallinger RE and Gratton C (2015) Species richness of wild bees, but not the use of managed honeybees, increases fruit set of a pollinator-dependent crop. *Journal of Applied Ecology* **52**(2), 323–330.

Mallinger RE, Werts P and Gratton C (2015) Pesticide use within a pollinator-dependent crop has negative effects on the abundance and species richness of sweat bees, *Lasioglossum* spp., and on bumble bee colony growth. *Journal of Insect Conservation* **19**(5), 999–1010.

Martins KT, Gonzalez A and Lechowicz MJ (2015) Pollination services are mediated by bee functional diversity and landscape context. *Agriculture, Ecosystems & Environment* **200**, 12–20.

McArt SH, Fersch AA, Milano NJ, Truitt LL and Böröczky K (2017) High pesticide risk to honey bees despite low focal crop pollen collection during pollination of a mass blooming crop. *Scientific Reports* **7**, 46554.

McGregor SE (1976) *Insect Pollination of Cultivated Crop Plants*. Washington, D.C.: U.S. Department of Agriculture, Agricultural Research Service.

Mogren CL and Lundgren JG (2016) Neonicotinoid-contaminated pollinator strips adjacent to cropland reduce honey bee nutritional status. *Scientific Reports* **6**, 29608.

Morse RA and Calderone N (2000) The value of honey bees as pollinators of U.S. crops in 2000. *Bee Culture* **128**(3), 15.

Munyuli T (2011) Farmers' perceptions of pollinators' importance in coffee production in Uganda. *Agricultural Sciences* **2**(3), 318–333.

National Research Council (2007) *Status of Pollinators in North America*. Washington DC: The National Academies Press.

Oldroyd BP (2007) What's killing American honey bees? *PLoS Biology* **5**((6), e168.

Park MG, Danforth BN and Orr MC (2010) The role of native bees in apple pollination. *New York Fruit Quarterly* **18**(1), 21–25.

Park MG, Blitzer EJ, Gibbs J, Losey JE and Danforth BN (2015) Negative effects of pesticides on wild bee communities can be buffered by landscape context. *Proceedings of the Royal Society B: Biological Sciences* **282**, 20150299.

Park MG, Raguso RA, Losey JE and Danforth BN (2016) Per-visit pollinator performance and regional importance of wild *Bombus* and *Andrena* (Melandrena) compared to the managed honey bee in New York apple orchards. *Apidologie* **47**(2), 145–160.

Partap UMA, Partap TEJ and Yonghua HE (2001) Pollination failure in apple crop and farmers' management strategies in Hengduan mountains, China. *Acta Horticulturae* **561**, 225–230.

Phillips EF (1933) Insects collected on apple blossoms in western New York. *Journal of Agricultural Research* **46**, 851–862.

Pinheiro J, Bates D and Sarkar D and R Core Team (2017) nlme: Linear and nonlinear mixed effects models. R package version 3.1-131.1, https://CRAN.R-project.org/package=nlme

Potts SG, Biesmeijer JC, Kremen C, Neumann P, Schweiger O and Kunin WE (2010) Global pollinator declines: trends, impacts and drivers. *Trends in Ecology & Evolution* **25**(6), 345–353.

Potts SG, Biesmeijer JC, Bommarco R, Felicioli A, Fischer M, Jokinen P, Kleijn D, Klein A-M, Kunin WE, Neumann P, Penev LD, Petanidou T, Rasmont P, Roberts SPM, Smith HG, Sørensen PB, Steffan-Dewenter I, Vaissière BE, Vilà M, Vujić A, Woyciechowski M, Zobel M, Settele J and Schweiger O (2011) Developing European conservation and mitigation tools for pollination services: approaches of the STEP (Status and Trends of European Pollinators) project. *Journal of Apicultural Research* **50**(2), 152–164.

R Core Team (2013) R: A language and environment for statistical computing. R Foundation for Statistical Computing. Vienna, Austria. URL http://www.R-project.org/

Rajotte EG, Bowser T, Travis JW, Crassweller RM, Musser W, Laughland D and Sachs C (1992) Implementation and adoption of an agricultural expert system: the Penn State Orchard Consultant. *Acta Horticulturae* **313**, 227–232.

Ricketts TH, Regetz J, Steffan-Dewenter I, Cunningham SA, Kremen C, Bogdanski A, Gemmill-Herren B, Greenleaf SS, Klein AM, Mayfield MM, Morandin LA, Ochieng' A and Viana BF (2008) Landscape effects on crop pollination services: are there general patterns? *Ecology Letters* **11**(5), 499–515.

Ritz A, Biddinger D, Rajotte E, Sahli H and Joshi N (2012) Quantifying the efficacy of native bees for orchard pollination in Pennsylvania to offset the increased cost and decreased reliability of honey bees. *Penn Fruit News* **92**, 6–66.

Robinson WS, Nowogrodzki R and Morse RA (1989) The value of honey bees as pollinators of United States crops. 2. *American Bee Journal* **129**(7), 477–487.

Russo L, Park M, Gibbs J and Danforth B (2015) The challenge of accurately documenting bee species richness in agroecosystems: bee diversity in eastern apple orchards. *Ecology and Evolution* **5**(17), 3531–3540.

Russo L, Park MG, Blitzer EJ and Danforth BN (2017) Flower handling behavior and abundance determine the relative contribution of pollinators to seed set in apple orchards. *Agriculture, Ecosystems & Environment* **246**, 102–108.

Southwick EE and Southwick L (1992) Estimating the economic value of honey bees (Hymenoptera: Apidae) as agricultural pollinators in the United States. *Journal of Economic Entomology* **85**(3), 621–633.

USDA NASS (US Department of Agriculture, National Agricultural Statistics Service) (2016a) *2015–2016 Agricultural Statistics Annual Bulletin, New York*. Available at www.nass.usda.gov/Statistics_by_State/New_York/Publications/Annual_Statistical_Bulletin/2016/2015-2016%20NY%20Annual%20Bulletin.pdf

USDA NASS (US Department of Agriculture, National Agricultural Statistics Service) (2016b) *2015–2016 Agricultural Statistics Annual Bulletin, Pennsylvania*. https://www.nass.usda.gov/Statistics_by_State/Pennsylvania/Publications/Annual_Statistical_Bulletin/2015_2016/2015-2016%20PA%20Annual%20Bulletin.pdf

van der Zee R, Pisa L, Andonov S, Brodschneider R, Charrière J-D, Chlebo R, Coffey MF, Crailsheim K, Dahle B, Gajda A, Gray A,

Drazic MM, Higes M, Kauko L, Kence A, Kence M, Kezic N, Kiprijanovska H, Kralj J, Kristiansen P, Martin Hernandez R, Mutinelli F, Nguyen BK, Otten C, Özkırım A, Pernal SF, Peterson M, Ramsay G, Santrac V, Soroker V, Topolska G, Uzunov A, Vejsnæs F, Wei S and Wilkins S (2012) Managed honey bee colony losses in Canada, China, Europe, Israel and Turkey, for the winters of 2008–9 and 2009–10. *Journal of Apicultural Research* **51**(1), 100–114.

vanEngelsdorp D, Evans JD, Saegerman C, Mullin C, Haubruge E, Nguyen BK, Frazier M, Frazier J, Cox-Foster D, Chen Y, Underwood R, Tarpy DR and Pettis JS (2009) Colony collapse disorder: a descriptive study. *PLoS ONE* **4**(8), e6481.

Venables WN and Ripley BD (2002) *Modern Applied Statistics with S.* 4th edn. New York: Springer.

Watson JC, Wolf AT and Ascher JS (2011) Forested landscapes promote richness and abundance of native bees (Hymenoptera: Apoidea: Anthophila) in Wisconsin apple orchards. *Environmental Entomology* **40** (3), 621–632.

Whittingham MJ (2011) The future of agri-environment schemes: biodiversity gains and ecosystem service delivery? *Journal of Applied Ecology* **48**(3), 509–513.

Westwood MN (1993) *Temperate-Zone Pomology: Physiology and Culture.* 3rd ed. Portland: Timber Press.

Winfree R (2008) Pollinator-dependent crops: an increasingly risky business. *Current Biology* **18**(20), 968–969.

Zuur AF, Hilbe JM and Leno EN (2013) *A Beginner's Guide to GLM and GLMM with R: A Frequentist and Bayesian Perspective for Ecologists.* Newburgh, UK: Highland Statistics Ltd.