Grower networks support adoption of innovations in pollination management: the roles of social learning, technical learning, and personal experience

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Abstract
Management decisions underpinning availability of ecosystem services and the organisms that provide them in agroecosystems, such as pollinators and pollination services, have emerged as a foremost consideration for both conservation and crop production goals. There is growing evidence that innovative management practices designed to support pollinators: planting flowering cover crops and other floral resources; retaining areas of permanent habitat (wooded patches, old-fields) to support pollinators; and using combinations of bees (e.g., *Apis mellifera* with other species) can support diverse pollinators and increase crop pollination. However, there is considerable debate regarding factors that support adoption of these innovative practices. We surveyed 367 growers in a major specialty crop-producing region of the United States, southwest Michigan. We evaluated adoption of three innovative practices, which are at various stages of adoption: 17% of growers adopted combinations of bees, representing an innovation in use by early adopters; 27% of growers adopted flowering cover crops, in use by the early majority; 55% of growers retained permanent habitat for pollinators, in use by the late majority. Our analysis included evaluation of grower experience with concerns and benefits associated with each practice, as well as the influence of grower networks. Networks included: social learning, measured as grower-to-grower communication, and technical learning, measured as grower communication with agencies and extension specialists. We found that growers' personal experience with potential benefits and concerns with the three innovative management practices had significant positive and negative relationships, respectively, with adoption of all three innovations. Social learning and technical learning played complex roles in decisions to adopt innovative practices, depending on the content of social discussion; the influence of these groups may have different levels of importance, depending on the stage of adoption that a practice is experiencing in the agricultural community. Social learning was positively associated with adopting use of combinations of bees, highlighting the potentially critical role of peer-to-peer networks in supporting early adoption of innovations. Engaging with grower networks and understanding grower experience with benefits and concerns associated with innovative practices is needed to inform outreach, extension, and policy efforts designed to stimulate use of management innovations in agroecosystems.

Keywords: Agroecology; Conservation; Ecosystem Services; Pollinators; Social network analysis

1. Introduction

The Millennium Ecosystem Assessment documented global patterns of degradation in ecosystem services (MEA, 2005), including the service of pollination which is needed to sustain plant diversity and crop production. The current crisis in declining pollinator populations illustrates the challenge of developing approaches to sustain or increase the capacity of social-ecological systems to manage critical ecosystem services (Barthel *et al.*, 2010). Addressing this challenge is critical to agroecosystems, as flows of ecosystem services are directly affected by growers' land management practices, and how practices articulate with the surrounding landscape (Foley *et al.*, 2005; Zhang *et al.*, 2007). There is a growing call to investigate decision-making in coupled human natural systems in general (Díaz *et al.*, 2011), and a pressing need to increase understanding about how growers manage ecosystem services needed to support crop production in farmlands.

This study aims to bridge this critical knowledge and action gap by evaluating growers' pollination management practices and their related knowledge systems in a major specialty crop-producing region of the United States, southwest Michigan. In particular, it evaluates growers' communication networks relevant to pollination management, which describe who-speaks-with-whom (Scott, 1988), investigating which characteristics can be used to understand adoption and use of management innovations designed to support pollinators and enhance crop pollination. These management innovations include using honey bees in combination with other pollinators, and creating, restoring, or retaining habitat with the aim of attracting and retaining diverse pollinators. Conserving pollinators and pollination services has emerged as a national priority in the United States (Pollinator Research Action Plan, 2015) and a foremost consideration for sustaining crop production because pollination provided by bees and other insects is required for production of many of the most economically important fruit, nut, and vegetable crops (Delaplane and Mayer, 2000).

Sustaining pollinators and pollination services is a critical conservation challenge and a major economic consideration in agricultural systems: pollination by managed honey bees (*Apis mellifera*) supports production of food, fiber, and forage crops estimated at $15 billion (Losey and Vaughan, 2006); unmanaged, wild bee pollination supports an additional $3 billion. Demand for pollination of fruits and vegetables is projected to grow as consumption of these foods increases (Aizen *et al.*, 2009; Garibaldi *et al.*, 2009). This trend is evident in the U.S., as evidenced by a 30% increase in bearing acres of fruits and nuts since 1980 (USDA- ERS, 2009). At the same time, the future ability of honey bees to meet crop pollination demands is uncertain (Berenbaum, 2007) as their populations are facing significant challenges including losses from *Varroa* mites and Colony Collapse Disorder (Ellis *et al.*, 2010; Pettis and Delaplane, 2010). Recent modeling work has emphasized that wild bee abundance is likely to be declining in the same areas of the United States where acreage of pollinator-dependent crops is increasing, suggesting the potential for future mismatches in pollination supply and demand in these regions (Koh et al., 2016).

Thus, management innovations to sustain pollinators and their services are expected to play an imperative role. Yet, few studies have investigated growers' goals, perceptions, and practices related to managing pollinators and pollination services. As a result, there is limited understanding of the considerations that contribute to growers' decisions to adopt (or reject) management innovations such as alternative managed pollinators, or on-farm pollinator habitat. To bridge this critical knowledge gap, we surveyed specialty crop growers of blueberry, apple, and cherry (e.g., high-value, pollinator dependent crops) in southwest Michigan in order to address two main goals.

The first goal was to evaluate growers' pollination management practices, communication networks, and knowledge systems related to pollination management. Knowledge systems comprise the actors, organizations, and resources that link information and know-how with action (Buizer *et al.*, 2010; Kalafatis *et al.*, 2015). At the heart of knowledge systems are individual belief systems that encode people's knowledge and perceptions and form the proximate basis for decision-making (Lubell *et al.*, 2014). To understand how growers manage the ecosystem service of pollination, this study explicitly investigates growers' management goals and experience with benefits and concerns of pollination management strategies. These individual considerations help shape belief systems and inform decisions (Stern *et al.*, 1999; Lubell *et al.*, 2014).

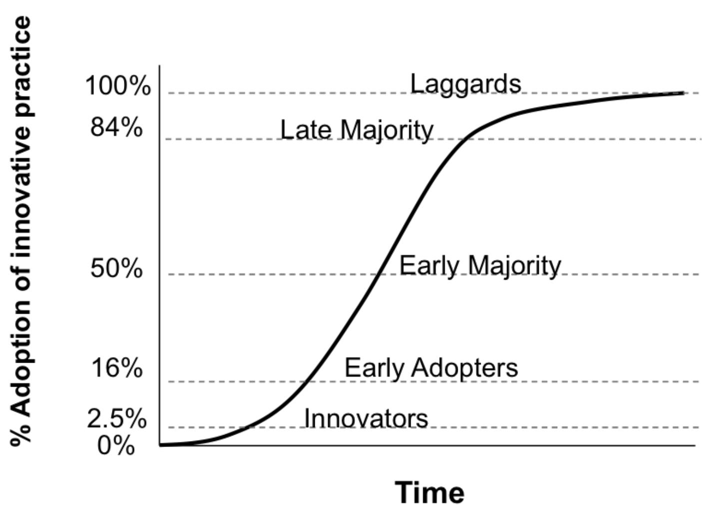
The second goal of the study was to investigate the characteristics of growers, their knowledge systems, and communication networks to understand patterns of adoption and use of several key management innovations: planting flowering cover crops and other floral resources; retaining areas of permanent habitat (i.e., wooded patches, old-fields, marshes) to support pollinators; and using combinations of pollinators. Flowering cover crops and other floral enhancements, such as plantings along field margins that provide nectar and pollen resources, can increase pollinator species richness and crop yield in Michigan blueberry production (Blaauw and Isaacs, 2014). Retaining areas of semi-natural habitat (e.g., wooded areas, meadows within the farm or at the periphery) can result in greater pollinator species richness and higher fruit set (Garibaldi *et al.*, 2011). Additionally, combinations of different pollinator species (e.g., honey bees plus wild bees; or honey bees plus an alternative managed bee (e.g. *Osmia* spp. or *Bombus* spp.)) can be used to diversify pollination strategies; combinations of pollinators have been shown to be more effective than honey bees alone in some crops (Brittain *et al.*, 2013). All of these practices are associated with integrated crop pollination, defined as the combined use of different pollinator species, habitat augmentation, and farm management practices to provide reliable and economical crop pollination (Isaacs *et al.,* 2012).

In support of these goals, the study used a quantitative survey to investigate grower characteristics, knowledge systems, and communication networks to build understanding about the actors and information sources through which growers share information about pollination management. Taken together, these elements form a critical context for actualizing diffusion of innovation theory, which describes how information about innovative practices spreads throughout a community of practitioners (Rogers, 2010). We consider the importance of communication networks in facilitating both technical and social learning. Technical learning encompasses participating in extension and outreach programs, such as those offered through cooperative extension, which is a traditional means of knowledge transfer to farmers and agricultural organizations (Lubell *et al.*, 2014). With respect to pollination of specialty crops, extension specialists are expected to play an important role of communicating research findings to growers. However, contemporary agricultural knowledge systems incorporate diverse experts; producer associations, government agencies, non-profit organizations, and other groups also offer programs that can support technical learning (Lubell *et al.*, 2014).

Diffusion of innovations can also be supported by social learning, which refers to how growers learn from each other as well as actors with different roles and is supported by social capital (Foster and Rosenzweig, 1995) and networks among farmers and other stakeholders (Warner, 2007). Formation of these communication networks can be sparked through participation in outreach and extension programs, which provide opportunities for social interaction (Lubell and Fulton, 2008). At the same time, existing networks can spread awareness about programs and provide means of encouraging participation. In particular, understanding communication patterns can provide insights into the connections that support social learning (Bandura and McClelland, 1977). Thus, we also use communication data surrounding pollination management to evaluate networks, which describe growers and their contacts (people, organizations) as "nodes" that are connected by "links" that describe information flow and can be analyzed using social network analysis (Wasserman and Faust, 1994). Networks of growers and other experts have long been important to agriculture (Warner, 2007), and information sharing through these key channels can facilitate understanding of benefits and constraints of new practices and thus provide critical support in considering management innovations (Rogers, 2010).

Diffusion theory describes five successive stages of adoption of a management innovation (Figure 1). Innovators, the first to adopt new practices, active in the first phase, tend to be risk tolerant, while latter adopters are progressively more risk-averse. In agriculture, diffusion research has found that adoption of management innovations is the product of a complex interwoven set of factors, including peer-to-peer diffusion (e.g., social learning), farm system compatibility with an innovation, grower perceptions of the innovation, and grower demographics (Adesina and Zinnah, 1993; Adesina and Baidu-Forson, 1995; Negatu and Parikh, 1999; Neill and Lee, 2001).

Figure 1: Adoption of innovative practices in agriculture, conceptual diagram of adoption curve. Diffusion theory (Rogers, 2010) describes five stages of adoption, in which different types of growers are active: innovators, early adopters; early majority; late majority; and laggards. Risk tolerance is expected to range from high for innovators to lower for the late majority and laggards.



Taken together, the two goals of this study allowed us to analyze the roles of grower characteristics, knowledge systems, and communication networks in adoption of three innovative management practices—using combinations of bees, planting flowering cover crops, and retaining areas of permanent habitat—that can support diverse pollinators in a major U.S. specialty crop producing region. We found that each of these three practices is at a different stage of adoption: 17% of growers adopted combinations of bees, representing an innovation in use by early adopters; 27% of growers adopted flowering cover crops, representing an innovation in use by the early majority; 55% of growers retained permanent habitat for pollinators, representing an innovation in use by the late majority (Figure 1). Social learning (described by connections with other innovative growers, organizations, and information sources) and technical learning (comprising traditional extension and government programs) play complex roles in decisions to adopt innovative practices, depending on the content of social discussion, and the influence of these groups may have different levels of importance, depending on the stage of adoption that a practice is experiencing in the agricultural community.

2. Materials and Methods

2.1 Regional context, Southwest Michigan

We surveyed specialty fruit growers in five Michigan counties: Allegan, Berrien, Muskegon, Ottawa, and Van Buren County. The study region is in the southwest corner of the Michigan "fruit belt," located along the western side of state's lower peninsula (Schaetzl, 1995). The surveyed counties comprise the state's primary blueberry growing region (MDARD, 2016) and contribute significantly to the state's rank as the nation's leading producer of blueberries and position in the top three producers of apples in the U.S. (NASS, 2012a). The region's microclimate variation, particularly the moderating effect of Lake Michigan on extreme temperatures, favors fruit production: areas near the lakeshore experience extreme cold temperatures much less frequently than inland locations (Longstroth and Hanson, 2012).

2.2 Data collection and analysis

We distributed the survey to specialty crop growers of apples, blueberries, and cherries from October 2014 to March 2015, requesting data from all growers that reported production of 0.1 acres or more of these crops in the 2012 Agricultural Census. Growers received a letter of introduction, accompanied by a copy of the survey (Dillman, 2000). Following the introduction, data was collected through surveys returned by mail and surveys conducted by phone, using the U.S. Agricultural Census collection protocol (NASS, 2012b). In total the survey was distributed to 793 growers, with 367 fully complete and usable surveys received and a response rate of 46% (per response rate calculation guidelines (AAPOR, 2000)). Useable surveys included blueberry (n = 240), apple (n = 107), and cherry (n = 20) growers. Growers were assigned to one of these crop groups based on their identification of the most important crop for their gross farm income during the 2014 growing season.

The survey population adequately represents specialty crop growers in the study region, reflecting average farm sizes and farmer age (Table 1). Complete usable surveys represent 51% of the total berry growing farms in Michigan. The sample of growers that identified apples and blueberries as the crops that contribute most to their farm's gross income was larger than the sample of growers identifying cherries, which likely reflects that most tart cherry production is concentrated outside of the study region in the northern part of the state. However, our survey does sufficiently represent growers of the focal crops in the study region. The survey included 24 questions about crops and pollination management practices, management priorities, use of practices to attract pollinators and associated benefits and concerns, network of contacts, and demographic data (survey instrument available online, http://icpbees.org/wp-content/uploads/2016/03/ICP_Survey_11-1-2014.pdf).

Table 1. Farm size and acres, by county for survey respondents reported as number of farms and acres in specialty crops, including mean followed by standard error (se), of apple, blueberry, and cherry production for focal counties. Agricultural Census data presented in the shaded column (NASS, 2012a).

	Agricultural Census 2012	**Grower Survey 2014-15**							
County	Farm size* acres	Farm size *acres (se)*	Apple *farms*	Apple *acres (se)*	Blueberry *farms*	Blueberry *acres (se)*	Cherry *farms*	Cherry *acres (se)*
Allegan	194	126.5 (26.2)	10	10 (5.0)	35	40.3 (14.4)		
Berrien	147	152.6 (23.6)	49	21.8 (4.1)	27	7.6 (2.6)	9	9.6 (0.3)
Muskegon	144	135.8 (53.3)	2	1.5 (1)	18	65.1 (35.3)		
Ottawa	137	204.7 (56.2)	23	29.9 (11.7)	56	68.5 (29.1)	2	0.8 (0)
Van Buren	157	204.2 (57.2)	23	10.5 (4.5)	104	43.8 (8.5)	9	4.7 (0.2)
Survey Mean & Total	**155.8**	**182.4 (24.9)**	**n = 107**	**21.1 (4.2)**	**n = 240**	**41.0 (7.6)**	**n = 20**	**5 (0.1)**

2.2.1 Practices & priorities

We evaluated growers' current pollinator management practices, including: the pollinator species used for the most important crop (defined as most important to the farm's gross income from crop production); specific practices to support pollinators (e.g., planting flowering cover crops, creating nesting sites, retaining permanent habitat); approaches to pest management (e.g., timing and method of pesticide and fungicide applications). Growers reported practices as those currently used, those tried in the past and discontinued, and practices that have never been used.

We investigated growers' priorities for pollinator management using a four-point Likert scale to evaluate growers' rating of a suite of nine management objectives (rated as always, often, sometimes, or never a priority). We used analysis of variance (ANOVA) to evaluate responses followed by Tukey-mean separation tests; these data are presented as mean followed by standard error (se) throughout. When analyzing count data or frequency of responses, we used Chi-squared analysis. Results are reported at the 95% confidence level, unless otherwise noted.

2.2.2 Grower networks

Network data were collected using a form of the name-generator technique (Marsden, 2005); participants were invited to list up to five people with whom they communicate regarding pollination management, as well as the type of role (e.g., job type and home organization) of each contact. Prior to analysis, names of network contacts were anonymized and transformed for spelling errors using a Levenstein procedure (Morgan and Garbach, 2016). The role data were coded into eight standardized categories, comprising beekeepers, growers, extension specialists, commercial suppliers, commodity groups, government agencies, and non-profit organizations (NGOs). If role data were not available, or did not fit within these categories, they were coded as "other." Connections were realized using a linking algorithm developed for this purpose (Morgan and Garbach, 2016); we visualized the resulting networks using ORA software (Carley *et al.*, 2013). To help provide a more comprehensive overview of information sources on pollination management, we also asked growers to identify the most important source of information regarding crop pollination. We considered shared information sources as part of grower networks for analysis.

We used linear regressions combined with descriptions of network structures to identify influential organizations, and key organization types and roles of contacts, related to adoption and use of three key practices: combinations of bees, flowering cover crop, and retaining permanent habitat areas. We were interested in two broad sources of support for adoption of innovative practices: 1) information sources and connections with other agencies that provide traditional outreach and technical support, and 2) innovative growers, representing technical learning and social learning, respectively. We explored both broad classes of information sources and specific organizations of interest within the context of the study area, and applications of network context to policy considerations. The procedures used for information source features included in our network analysis was informed by Wasserman and Faust (1994) and described in detail in the Supplemental Information.

2.2.3 Regression analysis

Following network visualizations and initial analysis, we used logistic regression to examine the influence of technical learning, measured through connections to government and extension, and social learning, measured through connection to other innovative growers. We included several aspects of farmer demographics and farm capital characteristics, as diffusion theory has emphasized these aspects as potentially important determinants of whether farmers adopt innovative practices (e.g., Prokopy et al., 2008). The demographic variables that we evaluated were growers' age, experience (measured as number of years as a specialty crop grower), and education level; the farm capital characteristics were farm size (acres), and income (measured as the farm's gross annual income from crop production). As experience and education were significantly correlated with age, (Table 2), we selected age as the variable to represent this aspect of grower demographics. Similarly, we selected farm size to represent farm capital, noting that it is significantly correlated with income (Table 2), and thus including both variables in regression models is unlikely to add additional information. We also accounted for growers' production style, organic vs. conventional in our regression models.

Table 2. Correlations between grower demographic and farm capital characteristics.

	Age	Experience	Education	Farm size	Income
Age	1				
Experience	0.48***	1			
Education	0.22*	0.09	1		
Farm size	-0.14*	0.09	0.12	1	
Income	-0.18***	0.16**	-0.11	0.36***	1

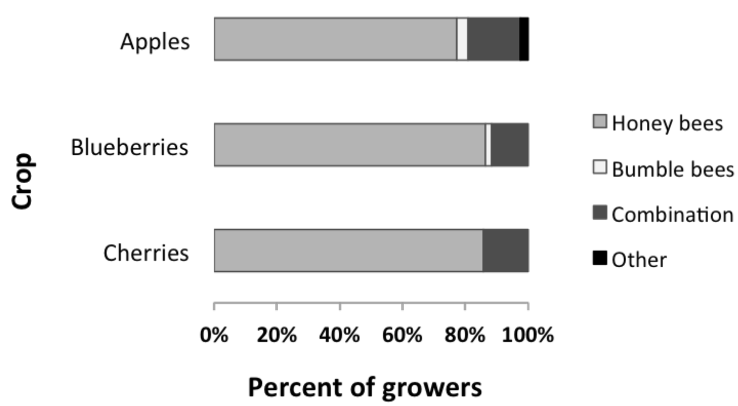
Pearson's r, df = 364. Significance at the 95% confidence level: * $p < 0.05$, ** $p < 0.001$, and *** $p < 0.0001$.

3. Results & Discussion

3.1 Pollination management and priorities

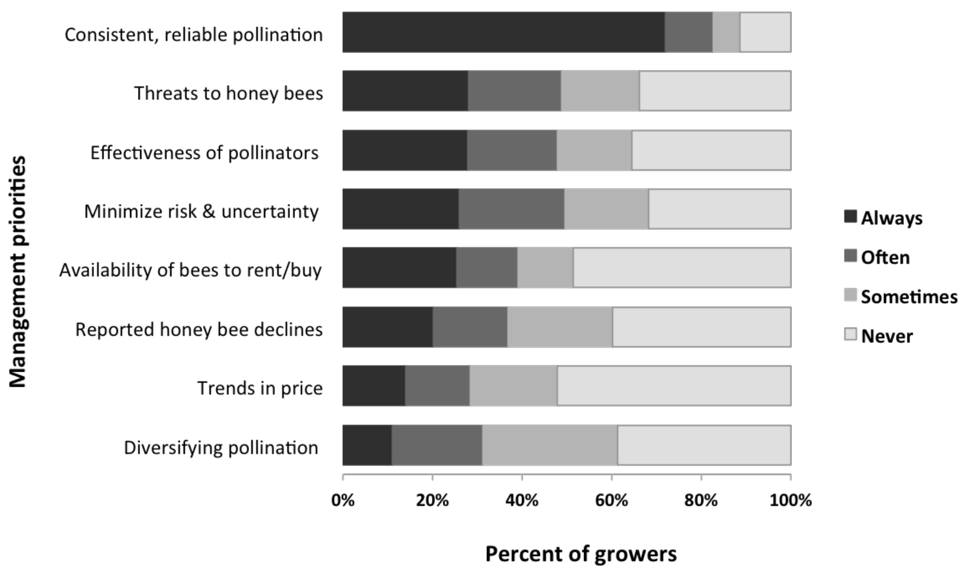
Two-thirds of growers buy or rent bees annually to pollinate their most important crop, comprising: 59% of growers reporting apple, 71% of growers reporting blueberry, and 61% of growers reporting cherry as most important to their farm's gross income from crop production. There was no detectable difference in the frequency with which growers of different crops reported buying or renting pollinators ($\chi^2 = 0.56695$, df = 2, p-value = 0.7532). Among growers that don't buy or rent pollinators (n = 109), the most common strategy for crop pollination was relying on wild bees that naturally occurred in the landscape (62% of respondents that do not buy/rent). Growers also reported that they relied on pollination from bees sourced by neighbors (12%), owned their own bees (6%), reduced or ceased pesticide application during crop bloom (6%) or actively managed habitat to support bees (5%).

Figure 2: Primary pollinator by crop. Survey respondents by crop type are: apple, n = 107; blueberry, n = 240; cherry, n = 20.



Growers reported honeybees as the primary pollinator of their most important crop most frequently; honey bees are used by 77% of apple growers and 86% of blueberry growers and 86% of cherry growers (Figure 2). Growers also relied on combinations of bees, comprising honey bees and wild bees or honey bees and managed bumble bees; 17% of apple growers, 12% of blueberry growers, and 14% of cherry growers reported using combinations of bees. Managed bumblebees were named as the primary pollinator by 4% of apple growers and 2% of blueberry growers (Figure 2). As there were no significant differences in frequency of use of pollinator types across different crops ($\chi^2 = 7.7253$, df = 6, p = 0.2589), or other key pollination practices, we grouped the three crops for further analysis.

Figure 3. Management priorities. Growers reported eight management priorities, indicating whether they were as Always, Often, Sometimes or Never a priority in their management decisions. These list of considerations included: consistent, reliable crop pollination; threats to honey bee populations; effectiveness of pollinator species; minimizing risk and uncertainty in crop pollination; availability of managed pollinators for rental or purchase; reported declines in honey bee populations; trends in pollinator rental and purchase price.

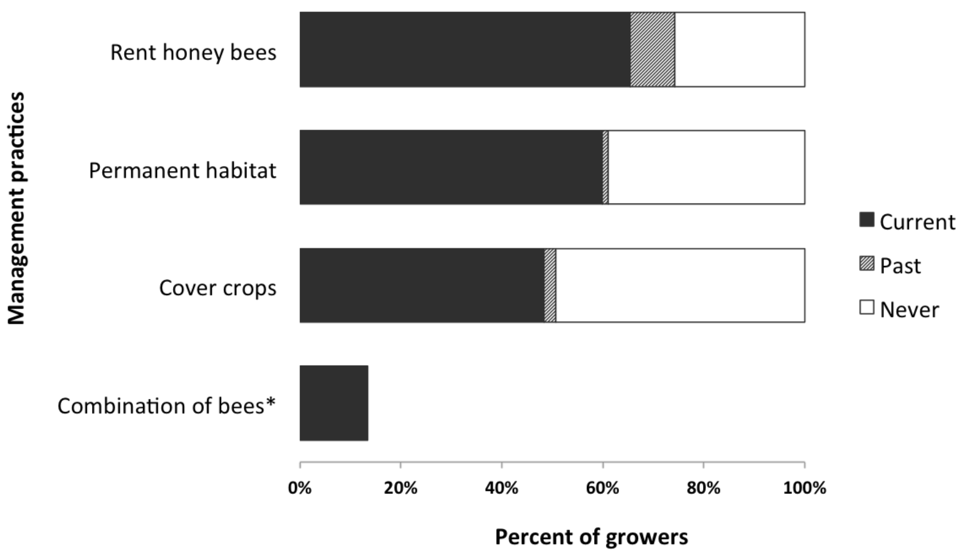


Consistent, reliable crop pollination was the top-rated management priority for growers (Figure 3), which did not differ among crop types (range 0-4, ANOVA $F_{2, 228} = 1.14$, $p = 0.16$). However, growers on large (≥180 acres) and medium sized farms (10-179 acres) were significantly more likely to rate this management priority more highly than growers with small farms of 9 acres or less (ANOVA $F_{2, 228} = 5.14$, $p = 0.007$). One plausible explanation is that larger commercial operations may keep formal records of pollination investment and variation in crop set, growers on small acreage may include "hobby farmers" and part-time operations. Another important consideration is that pollination services by wild bees are more variable on large farms, which tend to have larger field sizes with field centers that are difficult to access for small-bodied bees; small farms are more likely to receive adequate pollination from wild bees (Isaac and Kirk, 2010). However, the amount of overall variation in ratings of this management priority explained by farm size is very modest (< 5%).

There was a trend at 90% confidence level towards growers on large vs. small farms to report that availability of managed pollinators for rental or purchase, and effectiveness of pollinator species, were always or often a management priority (availability, $F_{3, 222} = 2.34$, $p = 0.096$; effectiveness, $F_{2, 221} = 2.506$, $p = 0.083$). Growers with large farms ranked effectiveness of pollinator species as a higher priority, on average, than growers with small farms (large farms, 2.6 vs. small farms, 1.8, of 4 possible).

Taken together, the priorities data suggest three tiers of management priorities for Michigan specialty fruit growers: consistent, reliable crop pollination represented a top tier priority. A second tier of considerations includes effectiveness of pollinator species, threats to honey bee populations, minimizing risk and uncertainty in crop pollination, and availability of managed pollinators for rental or purchase. Reported declines in honey bee populations, trends in price, and diversifying pollination strategies were less frequently named as "always" or "often" management priorities, reflecting a third tier of priorities.

Figure 4. Management practices. Growers indicated the practices that were currently used, those that were used in the past but discontinued, and the practices that were never used. *Data were not collected regarding whether growers had used combination of bees in the past, or had never used the practice; data on current use of combination of bees are presented.

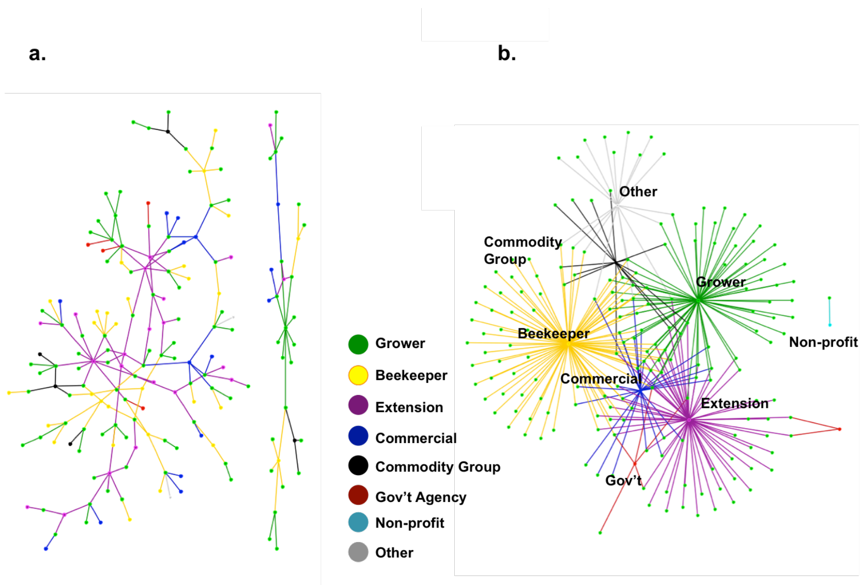


Buying or renting honey bees was the most commonly reported pollination management practice (65% current practice, Figure 4). Sixty percent of growers reported currently retaining areas of permanent habitat, including wooded lots and farm edges, old fields, swamps and marshes. Site visits and follow-up conversations with growers suggest that relatively few growers were actively creating new areas of permanent habitat (e.g., planting hedgerows of perennial shrubs and/or native wildflowers), thus we interpret this practice as retaining areas of existing habitat rather than the practice of restoring or creating habitat intended to be a permanent feature of the farm. Forty-eight percent of growers report using flowering cover crops to encourage pollinators and 13% of growers report using combinations of bees. The bee species used in combination were often honey been plus wild bees that were present in the landscape, growers reported using honey bees in combination with managed bumble bees in only a modest number of cases (< 10%).

3.2 Grower networks and innovation

We visualized the networks with each grower represented as a node, and the links among nodes indicating partners with whom growers report sharing information on pollination management (Figure 5a). The characteristic path length, 2.148, indicates that any actor (grower or grower contact) could reach all others within this in approximately two to three hops, which suggests that information can move quickly via the partner of a partner, or the partner of a partner of a partner. The network diameter, 7, indicates that the two furthest nodes could be reached through seven hops along network ties. However, the network density is relatively modest, 0.039, indicating that approximately 4% of the total connections possible are named by survey respondents. This likely reflects the challenge of sparse data coverage in a voluntary survey; less than 5% of respondents provided two or more contacts with whom they exchange information on pollination management. Nevertheless, with the available data there are several sub-structures of interest in this network, suggesting that Michigan specialty crop growers in the study area may have several large 'advice networks' which have few shared connections. One of the subgroups is connected to a crop commodity group for blueberry growers; another to a promotion commission for apples.

Figure 5a. Shared partners across Michigan specialty crop growers; **b.** Key roles in networks of Michigan specialty crop growers. Each node represents a communication partner with whom growers exchanged information on pollination management. The role types are grouped together by color; proportional representation of each type is reported.

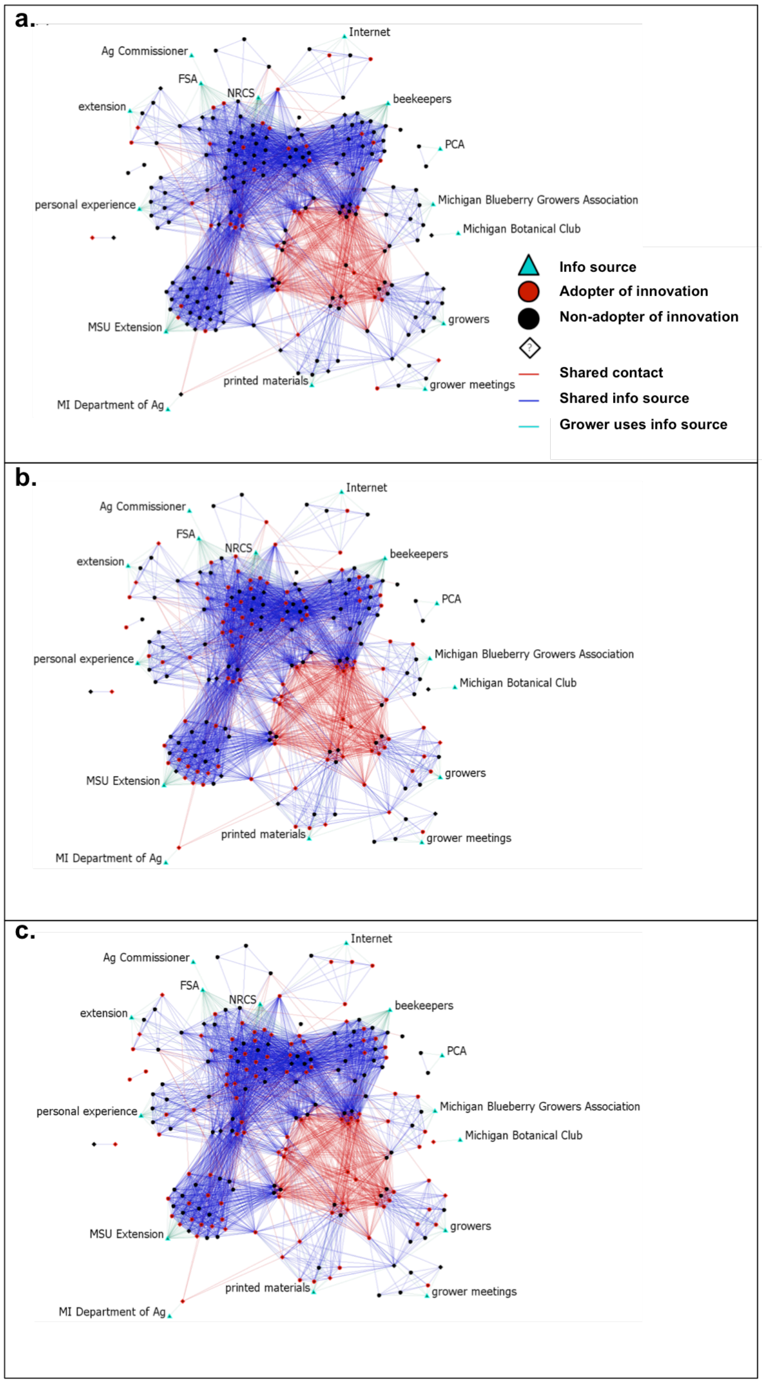


We also identified key organization types and roles of contacts, exploring the proportional representation of each in growers' networks (Figure 5b). Beekeepers were an important source of information, representing 28% of connections. Responses also highlight the importance of grower-to-grower communication, reflected in 26% of connections. Information from Extension was also critical, representing 25% of grower networks. Commercial suppliers, commodity groups, government agencies, non-profit organizations, and other organizations were represented less frequently.

We considered the three focal innovative management practices—combinations of bees, flowering cover crops, retaining permanent habitat—by considering transformed networks (matrix algebra described in Supplemental Information), which facilitate analysis of direct and indirect connections to innovative growers that use the focal practices (red nodes), non-adopters that do not use the focal innovative practices (black nodes) and shared information sources in Figure 6 a, b, c, for each respective practice. Red (lighter) ties are those shown above in Figure 5a. Blue (darker) ties describe a share information source (triangle nodes, labeled).
Across the three practices, there are several sub-regions visible in the grower networks (Figure 6). Growers who receive information from the government tend to be clustered in the top left,

while those who get information from beekeepers tend to be clustered in the top right. Growers, meanwhile, who get their information from Michigan State University (MSU) Extension specialists were clustered in the bottom left, and growers who were willing to report working with others on pollination management were in the bottom right.

Figure 6. Grower networks with adopters of innovative practices shown in red nodes; non-adopters shown in black nodes. Red links indicated shared contacts within networks, blue shared information sources for growers that have adopted use of: **a.** combinations of bees; **b.** cover crops; and **c.** retention of permanent habitat.



Combinations of bees: Growers that adopted combinations of bees (Figure 6a) had networks with significantly more connections to government contacts, represented in 30% of adopters' networks, compared with 13% of non-adopters. Additionally, adopters had more connections with *both* MSU Extension and government, which were represented in 8% of adopters' networks compared to 1% of networks of non-adopters (χ^2= 10.677, df = 1, p < 0.001). However, connections with only MSU Extension did not differ between the two groups (adopters, 16%; non-adopters, 10%, χ^2 = 1.4117, df = 1, p = 0.2348), nor did the count of connections with innovative neighbors (adopters, 25%; non-adopters, 14%, χ^2= 2.1199, df = 1, p = 0.1454). One possible explanation for the lack of difference with innovative neighbors is that only 17% of growers adopted this practice, which may make it more challenging to detect differences between adopters and non-adopters due to the difficulty associated with restricted data coverage of a relatively sparse network measured using a voluntary survey. We also explored the proportion of networks that had connections to *both* MSU extension and innovative neighbors, finding no detectable difference representation in adopters' networks, 8%, relative to non-adopters' networks, 5% (χ^2 = 0.30701, df = 1, p-value = 0.5795). In networks of growers that adopted combination of bees had significantly more connections to *both* government agencies and innovative neighbors, 18%, versus non-adopters, 2% (χ^2 = 4.3226, df = 1, p = 0.03).

Cover crop: The number of growers currently using cover crops (Figure 6b) was split nearly evenly between adopters (49%) and non-adopters (51%). The proportion of adopters with connections to any government agency (18%) was slightly but not significantly larger than non-adopters (14%; χ^2 = 0.47228, df = 1, p = 0.4919). However, adopters reported significantly more links with the USDA Natural Resource Conservation Service (NRCS) (16%) than non-adopters (9%; χ^2 = 4.0847, df = 1, p = 0.0148). The adopters and non-adopters had similar proportions of innovative neighbors currently using cover crops (19% and 18%, respectively; χ^2 = 2.1199, df = 1, p = 0.1454), an intuitive result given that the number of adopters and non-adopters of cover crops was nearly equal. It did not make a detectable difference if a grower reported more connections to innovative neighbors relative to non-innovative neighbors (χ^2 = 0.043546, df = 1, p = 0.8347), this may be due to a relatively modest number of nodes in the network as well as nearly equal representation in networks of adopters and non-adopters (13% and 12% respectively). Extension connections were similar across adopter and non-adopters.

Permanent habitat: The networks of growers that adopted the practice of retaining permanent habitat (Figure 6c) did not differ significantly from non-adopters with respect to number of contacts to MSU extension (χ^2 = 0.38129, df = 1, p = 0.5369), the broader category of extension (χ^2 = 0.06689, df = 1, p = 0.7959), government (χ^2 = 0.036431, df = 1, p = 0.8486) and NRCS (χ^2 = 0.06689, df = 1, p = 0.7959), or innovative neighbors (χ^2= 0.14602, df = 1, p = 0.7024).

Results of regression analysis provided further support that distinct factors have significant relationships with innovation adoption for practices in different stages of the process. Evaluating the three practices individually—adopting use of combinations of bees (early adopters), adopting use of flowering cover crops (early majority), adopting retention of permanent habitat (late majority)—provided additional insight into types of key contacts, personal experience with benefits and concerns, controlling for farmer demographics, farm size, and production type, organic vs. conventional (Table 3).

In particular, we found that connections with the Natural Resources Conservation Service (NRCS), a key government agency providing technical support related to pollinator conservation and on-farm habitat enhancements had a significant positive correlation with adopting use of combinations of bees, and adopting flowering cover crops (detectable at 90% confidence level, Table 3). There was not a detectable relationship between NRCS and retention of permanent habitat; one plausible explanation is that this relationship may become less influential over time relative to personal experience, personal characteristics, and farm capital. Another consideration is that retaining permanent is a less active practice that the other two (e.g., retaining existing habitat does not take seed or mechanical inputs in the same way as cover crops, nor purchase of organisms).

Connection to innovative neighbors had a detectable positive correlation with adopting use of combinations of bees, but did not have a detectable relationship with the two other practices. It may be more difficult to detect as the percent of the overall population adopting the practice increases (Supplemental Information, Figure S1). Connections with extension did not have a detectable relationship with adoption of any of the three practices; this may be attributable to the fact that growers connect with extension for many reasons, including but certainly not limited to the innovative pollination management practices that are the focus of this study. Another important consideration is that growers considering adoption of innovative management practices may connect with extension (among other contacts) prior to adoption, thus the task of detecting significant relationships and potential differences across adopters and non-adopters is complex.

Growers' personal experience with potential benefits and concerns with practices to attract and retain diverse pollinators had significant positive and negative correlations, respectively, with adoption of all three innovative practices (confidence levels varied by practice, Table 3). These results emphasize the importance of personal experience, and its influence on practice adoption, while controlling for the broader context of key network connections and demographic variables. On this front, we did not find a detectable relationship between grower age and adoption of innovative practices. Larger farm size had a significant negative correlation with adoption of combination of bees, but a positive correlation with retaining permanent habitat areas. Growers on large farms may are expected to have more financial capital to buy or rent pollinators; additionally the ability of combinations of bees to delivery synergistic benefits of crop pollination is not well known (but see Brittain *et al.* 2013 for data on almonds); field studies on the synergistic interactions and area requirements for pollinators and their services are still relatively few and may not be well known throughout grower communities. In contrast, large acreage may have the land and financial capital to preserve areas of existing permanent habitat. Reporting organic production had a significant, positive relationship with adoption of all three innovative practices.

Each of the three innovative practices investigated in this study is in a different stage of adoption, and is thus influenced by different stakeholders in growers' networks; however the influence of personal experience was consistent across practices, with higher perceptions of benefits positively correlated with adoption and higher perceptions of concerns negatively correlated (Table 3).

Table 3. Results of regression analysis. Factors influencing adoption of combinations of bees, cover crops, and permanent habitat.

	Combination of bees		Cover crop		Permanent habitat	
	Estimate (SE)	**z-value**	**Estimate** (SE)	**z-value**	**Estimate** (SE)	**z-value**
Intercept	-1.436 (0.774)	-1.855.	-1.422 (0.571)	-2.492*	-0.936 (0.573)	-1.63.
Government (NRCS)	0.941 (0.433)	2.170*	0.539 (0.379)	1.422.	0.224 (0.386)	0.581
Innovative neighbors	0.698 (0.376)	1.853.	0.003 (0.294)	0.010	-0.201 (0.292)	-0.689
Extension	0.192 (0.381)	0.614	-0.178 (0.296)	-0.602	-0.033 (0.299)	-0.689
Benefits perception	0.517 (0.494)	1.047.	1.312 (0.373)	0.000***	1.233 (0.387)	3.181**
Concerns perception	-1.015 (0.739)	-1.373.	-0.897 (0.478)	-1.873.	-1.251 (0.492)	-2.544*
Grower age	-0.01 (0.131)	-0.079	0.074 (0.094)	0.793	0.001 (0.095)	0.016
Farm size	-0.193 (0.116)	-1.663.	0.119 (0.086)	1.38	0.190 (0.088)	2.145*
Organic production	1.131 (0.383)	2.95**	1.275 (0.388)	3.288**	1.670 (0.463)	0.000***

Combinations of bees: McFadden $R^2 = 0.18$, AIC = 269.43, residual deviance 269.43, and df = 331.
Cover crop: McFadden $R^2 = 0.15$, AIC = 450.62, residual deviance 430.62, and df = 331.
Permanent habitat: McFadden $R^2 = 0.16$, AIC = 422.01, and df = 331; Values are significantly different between adopters and non-adopters: "." $0.05 < p < 0.10$; * $p < 0.05$; ** $p < 0.001$; *** $p < 0.0001$

Adoption of using combinations of bees (adopted by 17 % of growers) is positively linked to government, to interaction with other innovators (through shared partners in discussions of pollination management). Growers that adopted combinations of bees named Internet resources as the most useful source of information on pollination management with significantly greater frequency than non-adopters and adopters of other practices ($\chi^2 = 5.0847$, df = 2, p = 0.013). The internet primarily supplements other forms of interaction, but can make it easier to stay involved with others (Wellman *et al.*, 2001). On line resources may help information, such as findings from field trials, to travel quickly even when users are separated by physical distance. Adoption of flowering cover crops represents, a practice with wider adoption (49% of growers), appears to benefit from continued government support, but social support and other factors are no longer germane, reflecting that the practice is now becoming more common. Adoption of retaining permanent habitat, the practice with the most widespread adoption of the three evaluated in this study (55% of growers), no longer appears to benefit from government support or social support, rather personal experience and farm capital characteristics may be more influential.

These results suggest that different types of information brokers may be important for distinct practices, which are at different stages of adoption. The importance of information brokers in natural resource management has been discussed extensively in the literature (Folke *et al.*, 2003), including the importance of thought leaders which are often extension specialists and other formal experts, and champions, which are fellow growers that can share information that supports adopting new practices (Risgaard *et al.*, 2007). Scholars have used network structure to explain roles of actors (Scott, 1988; Bodin *et al.*, 2006), with some highlighting the importance of brokers in particular (Bodin *et al.*, 2006). Brokers comprise individual or organizational actors that carry many unique links, connecting groups that would otherwise not be in contact with each other (Burt, 2002). Brokers can be described as the actors that help form bridging links across dissimilar types of actors in the community (Bodin *et al.*, 2006) because of this position brokers can learn a great deal about many different groups, attaining the advantageous position of knowing which groups to connect (and which not to connect), approaches to connect them and appropriate timing (Burt, 2002). This can be critical knowledge under circumstances of uncertainty (Bodin *et al.*, 2006), including those represented by management challenges related to ecosystem services and the organisms that provide them.

Information brokers has the ability to navigate a complex, dynamic social landscape and coordinate actions across diverse actors in a network (Burt, 2002). In this study, two information brokers that have unusually high numbers of unique links: Michigan State University Extension and beekeepers. Given the mission of cooperative extension, it is clear that it plays a variety of roles in offering information and technical support to the agricultural community, we see that it may be particularly important in networks of early adopters (Figure 5a). Extension provides information on implementation (e.g., publications), and personal communication through extension specialists (Garbach *et al.,* 2016), both of which can provide critical support when considering new practices (Lubell and Fulton, 2008).

4. Conclusions

A network perspective can facilitate analysis of individual relationships and cross-scale interactions that how these may ultimately influence availability and distribution of ecosystem services. This contribution may be of value in natural resource management ranging from the extent of one farm to broader regional contexts. This critical understanding is needed to support innovative practices to help respond to challenges in managing pollination and other ecosystem services.

Our results suggest that different types of contacts play critical roles at different stages of adoption. Adoption of innovative pollination management practices is an important example of a management innovation that can help sustain an essential ecosystem service in agricultural landscapes. Together with landscape context, management can have significant influence—either positive or negative—on pollinators and their ability to sustain pollination services. With this in mind, a core question is how to catalyze and strategically support use of innovative management practices. Understanding the importance of connections with innovative neighbors in the early stages of adoption, and the potentially powerful influence of farm capital characteristics in the later stages of adoption can help guide outreach and extension efforts.

Additionally, grower networks that describe links between growers and their key contacts can describe a set of distinguishable subgroups, which may be especially important in natural resource management (see Bodin and Crona, 2009). In this study, grower network diagrams revealed sub-groups that receive information from the government; those getting information from beekeepers; those getting information from Extension specialists; and those getting information primarily from other growers. Importantly, these connections often exist across scales, or management units such as counties, for example with individual nodes between growers and the contacts with whom they interact with on one scale, and the networks of subgroups visible at another scale.

This study demonstrated the links of links that bridge across growers, linking multiple managers at the scale of individual farms, through direct and indirect connections with institutions (e.g., Extension), commercial suppliers (e.g., beekeepers) and crop commodity groups (e.g., cooperative groups for growing and or processing a crop). A number of processes may be at work at different scales, potentially providing different functions across the system (Bodin and Crona, 2009); among the most important function is information sharing. The way in which individual actors interact within tight-knit subgroups (e.g., high density of connections) may be quite different from how two subgroups with few bridging connections between them interact. Importantly, the different scales are not isolated; rather they are continually influencing one another through feedbacks (or lack of connection) between actors.

There is a pressing need to continue building understanding of cross-scale interactions (Cash *et al.*, 2006; Berkes, 2008). Studies on resource extraction suggest the importance for outcomes for resource governance, using resource extraction as an example. Specifically, local resource users are increasingly linked to global trade and commodity networks (large scale), but the structure of the local communication networks (small scale) largely determines the conditions of who participates, when, and how (Taylor *et al.*, 2007 in Bodin and Crona, 2009). Yet, to date, less work has focused on management practices and the networks of contacts relevant for management of critical ecosystem services, such as pollination.

This study contributes to understanding the need to bridge this critical knowledge and action gap. And unlike resource extraction, ecosystem services can respond in the short or medium term to management innovations at the individual level (e.g., pollinator response to floral enhancement, see Blaauw and Isaacs, 2014). Thus, management designed to enhance ecosystem services merit additional investigation and policies that provides support for adoption of innovative management practices and the communication networks that help inform and shape decision making.

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Grower networks support adoption of innovations in pollination management: the roles of social learning, technical learning, and personal experience

Supplemental Information

Information source features: To use a network formalism to examine information sources, we consider two distinct sets, the set of participants P and the set of information sources S. We are interested in which participants P are connected to information sources S. To do this, we arrange these sets in a matrix so that each participant Pi represents a row in the data, with each information source S_j representing a column in the data. A non-zero value in M_{ij} indicates that participant Pi uses information source S_j. Because we are interested in converting this data to a feature vector, we binarize the data so that all cell values are either 0 or 1. Because these are two different sets, the resulting network graph will be bipartite. The total number of data cells in the resulting matrix is $|P| * |S|$. The density of the resulting matrix is the count of the non-zero cell values divided by the total number of data cells.

Our consistent roles for pollination information sources across the study are based on functional groups identified in the data, and are 1) Beekeeper, 2) Commercial, 3) Commodity Group, 4) ConservationOrg, 5) Extension, 6) Farming Coop, 7) Government, 8) Grower, 9) GrowerOrg, 10) Meetings, 11) Non-Profit, 12) Pest Control Agents, 13) Personal Experience, 14) Published Materials (both online and print), and 15) Other.

In each state, the organizations of interest vary, but are primarily 1) university extension services, 2) dominant crop organizations, 3) federal organizations, 4) and pest control advisors. We keep the number of organizations limited to avoid unnecessary regression comparisons.

In each case, we develop the bipartite network graph to serve as a feature vector, based on each participant's answer to a specific survey prompt, "Please list the most important information source on pollinator management practices." Although the question suggests a single most important information source, some participants provided multiple answers, while others refused to answer. The preponderance of participants provided one "important information source".

We supplement the given answers provided by the respondents with supplementary information from other elements of the survey. Another question asked whether the participant is currently receiving financial and technical support in creating a more pollinator friendly farm from various government and conservation organizations. We assume that if they do receive financial or technical support from a specific program, that this program's supporting agency also counts as an important source of information on pollination management practices. We use the following table to transform current participation in a specific program to inform our bipartite network.

Table S1. Specific programs, organizations, and information source and related roles.

Program	Information Source	Information Source Role
Environmental Quality Incentive Program (EQUIP)	NRCS	Government
Conservation Stewardship Program (CSP)	NRCS	Government
Conservation Reserve Program		Government
Cooperation Extension & Local Universities		Extension
Non-Profit Conservation Organizations		Non-Profit
Farm Service Agency (FSA)	FSA	Government
Natural Resource Conservation Service (NRCS)	NRCS	Government

The bipartite network that results is participant by information source. When we did the role analysis, we grouped information sources according to their roles; this produces a much denser network and resulting feature vector.

Viewed as a binarized matrix (which is then converted to a feature vector for statistical regression), if a link exists, then the value in the appropriate cell of the matrix is a ‘1’, while if a link does not exist, the value in the appropriate cell is ‘0’. We merge this feature vector with a set of outcome variables of interest for each respondent.

When we examine these features, we use logistic regressions to examine each feature and its outcome. We use the logistic regression to determine whether the feature offers useful clarity in identifying innovative practitioners. This has four elements, two of which offer evidence in support of the positive result (i.e., adoption of an innovative management practice), and the other two offering evidence against the result (Figure S1).

Figure S1. Logistic regression interpretation diagram.

	Innovative	Non-Innovative
Has feature X	Evidence For	Evidence Against
Does not have feature X	Evidence Against	Evidence For

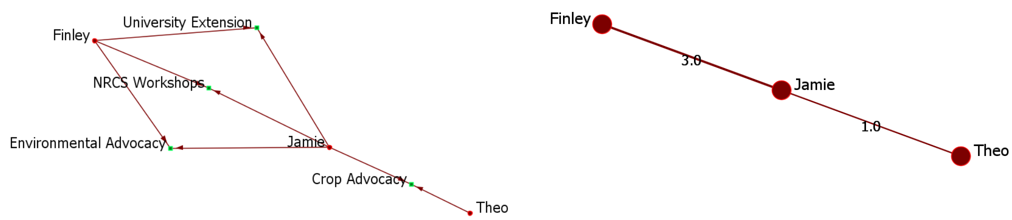
Thus, every innovative grower that does not have feature X offers evidence against the logistic, as well as every grower that does have feature X who is non-innovative. When comparing results between innovative practices, such as combinations of bees versus flowering cover crops, we keep this factor in mind.

Partner Features: Another possible source of adoption of innovative practices by growers is through interactions with innovative growers, some practices may be more transferable than others. However, we do not have direct interaction data between growers. Instead, we asked growers to identify people and their role with whom they have recently discussed pollinator management. We anonymized these names consistently for each state, first using a Levenstein correction procedure (Okuda, Tanaka, & Kasai, 1976) to handle subtle spelling mistakes common to oral interviews.

Thus, there exists a set P, participants, and a set C, of contacts. Each participant may list up to five contacts. The network, Pollination Management Discussion, is a P x C matrix (M), with a '1' in the M_{ij} cell indicating a link between P_i and C_j. We can create a link between participants in set P by multiplying P x C by its transpose, (P x C) * (C x P). The resulting matrix is P x P, with a link representing a shared contact. This matrix multiplication procedure is called folding.

Social network scientists use folding to infer social structure when direct inquiry into the social network of interest is unfeasible; these inferences are often quite useful (Han, 2009). Folding creates a link between two actors based on a shared common tie. An illustrative example: Finley and Jamie both attend University Extension meetings, go to NRCS-sponsored workshops, and are both in the same environmental advocacy group. Theo, meanwhile, is not part of these groups but Finley and Theo are both officers in their local crop advocacy group. If we fold this network, using the multiplication procedure described above, we see that Finley and Jamie share three organizations in common, while Jamie and Theo share one. We depict this social structure graphically, below (Figure S2).

Figure S2. Folded networks derived through matrix algebra.



For each innovative feature, we can create two subsets of the participants, which we shall Innovative Participants, the set I, and Non-Innovative Participants, the set N. By separating this subset from the full set of participants, we can create the matrices P x I and P x N. We can then calculate the out-degree (Wasserman & Faust, 1994) of each Participant in the P x I and P x N matrix. The out-degree is the number of connections of each participant in each matrix. For convenience, we will use the notation pi to indicate out-degree for participant p in the P x I matrix, while pn will use out-degree for participant p in the P x N matrix. From this, we generate three meta-features:

- Connected to Innovative Growers (IG_Connect): a binary feature, with a 1 if pi > 0, and a 0 otherwise.
- Innovative Growers outnumber Non-Innovative Growers (IG>NG): a binary feature, with a 1 if pi > pn.
- Innovative Grower Count (IG_Count): a scalar feature equal to pi.

When examining these three features, we can consider the null hypothesis of each and its implications for policy proposals. The null hypothesis, in each case, is that these features are not related to whether the participant uses innovative practices. If IG_Connect is statistically significant, it suggests that practices to encourage cross-collaboration between innovative and non-innovative growers may help spread innovative practices. If IG>NG is statistically significant and IG_Connect is not, then policies to strongly encourage cross-collaboration will be necessary, but also suggest that care will be needed to avoid practice "regression" through too much collaboration with non-innovative growers. If IG_Count is significant, then it suggests that more interactions with innovative growers reinforce the adoption of the innovative practice.

References

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