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Assessment of the response of pollinator abundance to environmental pressures using structured expert elicitation

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Policy-makers often need to rely on experts with disparate fields of expertise when making policy choices in complex, multi-faceted, dynamic environments such as those dealing with ecosystem services. For policy-makers wishing to make evidence-based decisions which will best support pollinator abundance and pollination services, one of the problems faced is how to access the information and evidence they need, and how to combine it to formulate and evaluate candidate policies. This is even more complex when multiple factors provide influence in combination. The pressures affecting the survival and pollination capabilities of honey bees (*Apis mellifera*), wild bees, and other pollinators are well documented, but incomplete. In order to estimate the potential effectiveness of various candidate policy choices, there is an urgent need to quantify the effect of various combinations of factors on the pollination ecosystem service. Using high-quality experimental evidence is the most robust approach, but key aspects of the system may not be amenable to experimentation or may be prohibitive based on cost, time and effort. In such cases, it is possible to obtain the required evidence by using structured expert elicitation, a method for quantitatively characterizing the state of knowledge about an uncertain quantity. Here we report and discuss the outputs of the novel use of a structured expert elicitation, designed to quantify the probability of good pollinator abundance given a variety of weather, disease, and habitat scenarios.

Evaluación de la respuesta de la abundancia de polinizadores a las presiones ambientales mediante el uso de elicitación experta estructurada

A menudo los legisladores dependen de expertos en diversas áreas de conocimiento para tomar decisiones sobre legislación en entornos complejos, multifacéticos y dinámicos tales como los que tienen que ver con los servicios ecosistémicos. Los legisladores que quieren tomar decisiones basadas en evidencias que respalden mejor los servicios de polinización y la abundancia de polinizadores, se enfrentan al problema de cómo acceder a la información y a las evidencias que necesitan, y de cómo combinar éstas para formular y evaluar futuras leyes. Esto es aún más complejo cuando hay múltiples factores que influyen de manera combinada. Las presiones que afectan a la supervivencia y a la capacidad polinizadora de las abejas de la miel (*Apis mellifera*), a las abejas silvestres y a otros polinizadores están bien documentadas, pero de manera incompleta. Para estimar la efectividad potencial de varias opciones posibles de legislación, es necesario cuantificar el efecto combinado de varios factores sobre el servicio ecosistémico de polinización. El uso de una evidencia experimental de alta calidad es el enfoque más sólido, pero algunos aspectos clave del sistema podrían no ser susceptibles de experimentación o ser prohibitivos debido al coste, el tiempo y el esfuerzo. En tales casos, es posible obtener la evidencia requerida mediante el uso de la elicitación experta estructurada, un método para caracterizar cuantitativamente el estado del conocimiento sobre una cantidad incierta. En este estudio informamos y discutimos los resultados del uso novedoso de una elicitación experta estructurada, diseñada para cuantificar la probabilidad de una abundancia de polinizadores adecuada teniendo en cuenta una variedad de escenarios climáticos, de enfermedades y de hábitat.

Keywords: Structured expert elicitation; IDEA protocol; bees; hover flies; pollinators; conservation; ecosystem services

Introduction

The dynamics of pollinator populations and factors that impact upon these populations are a focus of attention for policy-makers concerned with conservation and vital ecosystem services like pollination. There are substantial gaps in knowledge about the status of pollinators worldwide (e.g., abundance declines, distribution,

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species declines) and the effectiveness of measures to protect them (GM crop regulation, pesticide policy, pollution control, etc.) (Becher, Osborne, Thorbek, Kennedy, & Grimm, 2013; Chauzat et al., 2014; Dicks et al., 2016; Godfray et al., 2014; Potts et al., 2016; Vanbergen & The Insect Pollinators Initiative, 2013). In order to adequately protect and preserve pollinators, such as by means of England's National Pollinator Strategy (NPS) in the UK (Defra, 2014), it is vital to know what and how much effect various key factors have on the abundance of honey bees, wild bees, and other pollinators (such as hover flies) and whether these effects act independently or in combination. A suitable monitoring framework to support the pollinator strategies is vital (Carvell et al., 2016; Defra, 2013).

It is estimated that over 70% of important food crops worldwide are dependent upon pollinators (Klein et al., 2007), and pollinator-dependent food products are important contributors to healthy human diets and nutrition (Potts et al., 2016). The status of bees and other pollinators is also of key concern in global food security (Bailes, Ollerton, Pattrick, & Glover, 2015; Blaauw & Isaacs, 2014; Jaffé et al., 2010; Lonsdorf, Kremen, Ricketts, Winfree, & Greenleaf, 2009; Lucas, 2017; Ollerton, 2012; Perry et al., 2015; Polce et al., 2013). Many agricultural businesses employ migratory bee services in order to ensure adequate pollination of crops (Bishop, Jones, Lukac, & Potts, 2016; Gordon, Bresolin-Schott, & East, 2014). However, the mere presence of bee colonies on site may not guarantee optimal pollination, if the colonies are weakened by disease or struggling for environmental or other reasons. Whilst honey bees are not the only pollinators (Breeze et al., 2014; Rader et al., 2016), they are distinctive as they are often managed by humans so can be described as livestock. As such, the direct impact of bee keepers on their survival and health, for example, by controlling levels of parasites and disease, is a potential point of intervention for policymakers. In the UK, protected crops within polytunnels, like most of the UK soft fruit industry, use bought-in boxes of bumble bees, with the health of these bees assured by the supplier. This is another potential point for policy intervention.

There are two interrelated problems facing policymakers wishing to make evidence-based decisions. The first is how to access the information and evidence they need, including quantitative statements about levels of uncertainty, for example, probabilistic estimates of pollinator distributions (Elith & Leathwick, 2009; Fithian, Elith, Hastie, & Keith, 2014; Guillera-Arroita et al., 2015; Renner et al., 2015). The second problem is how to combine evidence in a transparent, defensible, coherent, and statistically robust manner. This is especially difficult when the evidence is incomplete, and that which does exist is inherently uncertain (probabilistic) in nature, particularly with respect to estimates of future values. The latter point, how to integrate probabilistic data for policy decisions, is addressed by Smith, Barons, and Leonelli (2017), who developed a formal statistical methodology to draw on the expertise of a variety of disparate panels of experts and their diverse supporting probabilistic models and then integrate this network of information coherently in order to explore and compare the efficacy of different candidate policies. In this paper, we focus on the difficulty of accessing information that is required, but is prohibitively difficult or expensive to obtain in the form of a designed experiment, as is the case of combinations of interacting and interrelated factors affecting pollinator abundance on realistic spatio-temporal scales. For this, we harnessed the power of structured expert elicitation.

Expert elicitation

Using expert advice and opinion to support policy decision-making is commonplace (Sutherland & Burgman, 2015). Indeed, the opinions and contributions of experts and stakeholders were integral to the development of England's NPS. Expert judgment elicitation seeks to elicit a subjective probability distribution for a quantity of interest from each of several experts and to summarize these distributions to provide insight about the quantities of interest, the extent of uncertainty, the sources of the uncertainty, the extent of agreement/disagreement and reasons for any disagreement amongst the group of experts consulted. Commonly, the way in which their contributions are synthesized and amalgamated to inform the eventual decision is not very transparent. Additionally, where informal elicitation and aggregation is employed, experts are subject to a number of well-documented biases: social biases deferring to the member with the most compelling personality or who is seen as the most senior, bias towards the most readily available information and misunderstandings due to semantic differences (Kahneman & Tversky, 1984; Slovic, 1999). As a result, unstructured elicitation of expert judgments can produce results that are not reproducible and can be unreliable and heavily biased. However, the difficulties that beset unstructured expert elicitation can be substantially reduced by using structured approaches designed to mitigate the most pervasive and debilitating psychological and contextual frailties of expert judgment (Aspinall, 2010; Burgman, 2016; Cooke, 1991; Cooke & Goossens, 2008; Keeney & von Winterfeldt, 1991; O'Hagan et al., 2006).

Structured elicitation of expert opinion in pursuit of decision support is an increasingly important technique and the European Food Safety Authority recently composed a detailed guidance document on its use for food and feed safety risk assessment (EFSA, 2014). It has also been used to guide policy on safety from volcanic eruptions (Aspinall & Roger, 1998), assess health risks (Cooke et al., 2007), climate change (Granger Morgan, Pitelka, & Shevliakova, 2001), and to quantify uncertainty in the risks of herbicide-tolerant crops (Krayer von Krauss, Casman, & Small, 2004). Aggregation of experts' judgments can be behavioral (seeking consensus) or mathematical (combining individual estimates using a formula) or a mixture of the two. There are several well-established methodologies for structured expert elicitation protocols, each with its own strengths and limitations, described in detail in the EFSA guidance: namely Delphi, Cooke's and Sheffield protocols. For this elicitation, we used the IDEA protocol (Hanea et al., 2016), a recently developed elicitation method which combines the strengths of these three methods (individual estimates, group discussion, and calibration) and ameliorates some of the limitations (a requirement for consensus).

The IDEA protocol

The acronym *IDEA* arises from the combination of the key features of the protocol that distinguish it from other structured elicitation procedures: it encourages experts to *Investigate* and estimate individual first round responses, *Discuss, Estimate* second round responses, following which judgments are combined using mathematical *Aggregation*.

In the pre-elicitation stage, the information sought needs to be expressed as precisely as possible to minimize any risk of semantic or other misunderstandings arising and to aid in the identification of the suitable experts. The elicitation stage consists of three phases: investigate, discuss, and estimate. After investigating relevant background material, experts are asked to provide their private estimates for the quantities of interest in the order: lowest plausible, highest plausible and then best estimate to avoid anchoring around the central estimate. After a facilitated discussion of the anonymized results for each question in turn, experts are asked to give second private estimates for the quantities of interest. Calibration questions, which have "answers" that can be checked, are elicited using the same protocol. Finally, individual experts' estimates are aggregated into a single estimate for each question using information gained in the calibration stage. More details of the IDEA protocol are given in Online Supplementary Material Appendix 1.

Materials and methods

The IDEA protocol was used to elicit from pollinator experts the conditional probabilities required to populate a Bayesian Network (BN) (Pearl, 1985) representation of the pollinator system. BNs are probabilistic graphical models in which nodes represent variables of interest and directed arrows represent (possibly causal) relationships between the variables. This BN is to be used to provide an overarching framework for combining the probabilistic elements of the pollinator system in order to produce a decision support system for policymakers (see methodology developed in (Smith et al., 2017)). After the quantities which needed to be elicited were identified, relevant experts were invited to take part in an expert elicitation exercise. Background evidence was sought through a literature search and sent out to experts and the quantities of interest refined into specific questions. These steps were followed by the face-to-face elicitation workshop.

The experts

The selection of suitable experts is key to a successful elicitation exercise. Eleven experts agreed to attend and a list of background materials circulated to them, given in Online Supplementary Material Appendix 1. One of the experts attended for an additional working day prior to the elicitation workshop to lend domain knowledge to the refinement of the questions of interest in order to ensure that they were clear and fair.

Selection of the questions of interest

Selection of the questions of interest was based on the variables revealed as key drivers of pollinator abundance in a literature search. From these the system was represented by a BN developed with the aid of multiple experts in pollinating insects and pollination services in the UK and Australia. Whilst good evidence is available to quantify many aspects of the system, quantitative assessments of the effects of disease, habitat, and weather on pollinator abundance were weak and so we elected to supplement these with a structured expert elicitation exercise. In the full model, variables identified in the literature and by the pollination experts as impacting the abundance of pollinating insects (Brown et al., 2016; Mayer et al., 2011), include:

- land use, its incentives and costs (Baldock, Goddard, Kunin et al., 2015; Baldock Goddard, Hicks et al., 2015; Cranmer, McCollin, & Ollerton, 2012; Dicks et al., 2015; Hall et al., 2016; Hicks et al., 2016; Matheson & Carreck, 2014; Meixner et al., 2014; Ollerton, Erenler, Edwards, & Crockett, 2014; Orford, Murray, Vaughan, & Memmott, 2016; Senapathi, Goddard, Kunin, & Baldock, 2017; Tarrant, Ollerton, Rahman, Tarrant, & McCollin, 2013),
- weather and climate (Al-Ghamdi, Abou-Shaara, & Mohamed, 2014; Kerr et al., 2015; Settele, Bishop, & Potts, 2016),
- disease and pest pressure (Arundel, 2011; Bull et al., 2012; Capri, Higes, & Kasiotis, 2013; Carreck, 2011; Carreck, Ball, & Martin, 2010a, 2010b; Chandler et al., 2000; Chandler, Prince, & Pell, 2011; Datta, Bull, Budge, & Keeling, 2013; Fürst, McMahon, Osborne, Paxton, & Brown, 2014; Gordon et al., 2014; Manley, Boots, & Wilfert, 2015; Martin, Ball, & Carreck, 2010; Ryabov et al., 2014; Wilfert et al., 2016),
- pesticide, fungicide, and herbicide use (Baron, Raine, & Brown, 2014; Botias et al., 2015; Dively, Embrey,

Kamel, Hawthorne, & Pettis, 2015; EASAC, 2015; EFSA, 2012, 2013; Godfray et al., 2014; Pettis et al., 2013).
- habitat loss, degradation, and fragmentation (Connolly, 2013; Kennedy et al., 2013),
- social attitudes and incentives (Gill et al., 2015; Ollerton, Rouquette, & Breeze, 2016; Staley et al., 2012) and
- standards of beekeeping and husbandry – this is a major pressure on honey bee colonies – and agricultural inputs (Carreck & Ratnieks, 2014; Godfray et al., 2014; Hartfield, 2017).

These all change over time and are all linked directly or indirectly to the abundance of different classes of pollinator. Policies which may be adopted include incentives and regulations on various aspects of land use and agricultural inputs, policies to ameliorate the effects of extreme weather events, research investments on pests and diseases of pollinators, and social marketing and education related to societal and farming support for pollinators (Dicks et al., 2016). In order to evaluate these policies, it is necessary to agree upon suitable measures of pollinator abundance and to quantify the effects of various policies on this measure.

It is important, for a successful elicitation, to agree upon clear definitions of the variables to be quantified, depicted in Figure 1. The overarching goal was to provide decision support for policy-makers; given that disease burden is only amenable to direct human intervention – and thus to policy change – in managed honey bees, disease pressure was assumed to affect honey bees only. In order to avoid over-burdening the experts participating in the structured elicitation, the cumulative effects of weather, environment, and disease pressure on pollinator abundance needed to be restricted to two levels for each as follows: abundance of various pollinators was considered to be good or poor; weather was either average, or unusual, disease pressure was high or low and the environment was supportive or unsupportive. We then needed to define precisely what we meant by these categories and how they would be measured.

Following careful discussion with the experts at the elicitation workshop, good abundance of honey bees was defined as overwinter losses of no more than 30% as defined by the honey bee research association, COLOSS (van der Zee et al., 2013), and poor abundance corresponded to overwinter losses greater than 30%. For wild bees, abundance was considered good if the number of observations recorded in the spring season by the Bees, Wasps, and Ants Recording Society (BWARS) was within the range of averages for the spring season recorded in the last five years and poor if fewer. For other insect pollinators, hover flies were considered to be a representative taxon and so abundance was defined as good if the number of observations recorded in the spring season by the Hover fly Recording

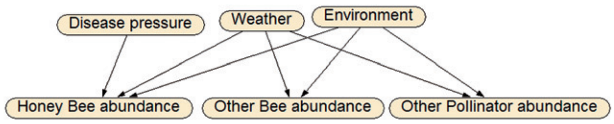

Figure 1. The effects on the honey bee, wild bee and other insect pollinator abundance of all combinations of possible states of weather, the environment and disease pressure were elicited from a panel of experts. Evidence for the link between disease and honey bees is strong, but relatively incomplete for other bees and other pollinators. For this reason, we did not ask the experts to estimate the effects of disease on other bees and other pollinators and omit the link between disease pressure and other bees and other pollinators in the schematic. Image produced in NETICA.

Scheme (HRS) was within the range of averages for the spring season recorded in the last five years and poor if fewer. Some limitations of the BWARS and HRS recording methods were noted, particularly that recordings of rare species are more likely to be made than common varieties and that survey regions are likely to be limited to easily accessible areas.

The participating experts considered the parasitic mite varroa (*Varroa destructor*) to be the key pest affecting honey bees. The UK National Bee Unit's BeeBase website provides a wide range of free beekeeping information for UK beekeepers and the threshold for varroa treatment given on BeeBase was used to delineate between good and poor varroa control and this was used as a proxy for overall disease pressure.

Following in-depth discussion, environment was defined as supportive if it had at least 15% of semi natural land, and unsupportive if the percentage was below this threshold.

The weather was categorized as average or unusual based on figures obtained from the UK Meteorological Office: average if the number of days with more than 0.2 mm of rain fell between 35 and 70, hours of sunshine fell between 240 and 480 and mean daily temperature fell between 3 and 10 °C; and unusual otherwise. See Figure 2 for representation.

Following these clarifications, the experts each gave private, individual first round estimates for the probability of good pollinator abundance given the various combination of the influencing factors in each of the elicitation questions. It was assumed that the probability of poor pollinator abundance is: (1) the probability of good abundance. The experts' estimates were plotted in anonymized form on graphs (see Online Supplementary Material Figure S1) ready for the discussion phase. The elicitation questions are listed in Online Supplementary Material Appendix 1.

During the discussion of the anonymized results, experts shared their understanding of what precisely each question was asking, discussed how they had come to their estimates and the reasons for the width of the interval between their lowest and highest plausible estimates. In particular, it was important for the facilitators to understand whether a wide interval was indicative of

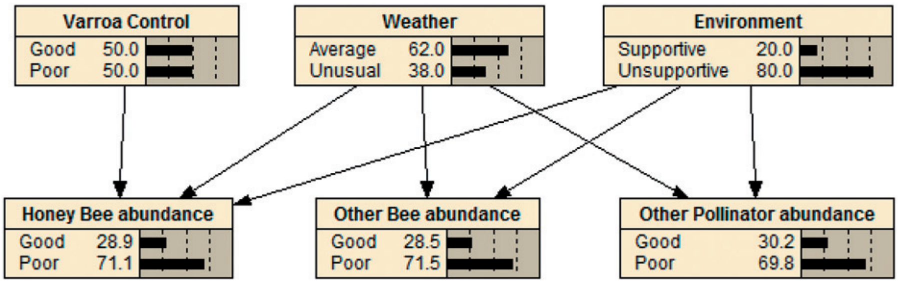

Figure 2. Bayesian network populated with the best estimate probabilities from the Table 1 with the baseline probabilities that weather is average 62% of the time and 20% of UK environment is supportive as defined previously. At baseline, no evidence has been added as to whether varroa control is good or not, so these probabilities are 50:50. The numbers and bars show the probability of each state being true. Image produced in NETICA.

the expert's perceived uncertainty in the system or a reflection of their own uncertainty, for example, where they had more expertise in honey bees than hover flies and so felt less well able to estimate quantities on the questions about hover flies. Following the discussion, the experts each gave private, individual second-round responses in line with the IDEA protocol.

After the workshop, the experts' first and second-round estimates were compared and whilst some responses were unchanged, others were changed considerably. Of particular note, many of the experts reduced the interval between highest plausible and lowest plausible values in their second-round estimates, suggesting that they were more certain about the interval within which a good estimate should lie following the discussion. For example, in Q1.7, expert 1 showed a lot of uncertainty in round one which is reduced after the discussion as seen in a reduced distance between upper and lower estimates in their round 2 estimates. Experts 4 and 5 showed a significant change of mind on the location of their estimates following discussion, but remaining experts did not change much. A similar plot was produced for each question. In Q1.6, expert 2 shows a great deal of confidence with narrow bands between the upper and lower estimates which do not change after the discussion. Expert 3, in contrast, completely relocates their estimate following the discussion, so that the upper and lower bounds do not overlap. Expert 9 shows enormous uncertainty before discussion and a greater certainty afterward, as shown by reduced bands between upper and lower values from a difference of 90% to a difference of 20% (see Online Supplementary Material Figures S2 and S3).

The calibration exercise

Following the main elicitation exercise, the experts kindly agreed to take part in a calibration exercise. Permission was generously granted by a number of authors of refereed papers (see acknowledgments) to base calibration questions on their papers after they had been accepted for publication in a journal, but ahead of their actual publication, so that these papers were unavailable to the experts at the time of giving estimates for the calibration questions. The wording of the questions and the papers on which they were based is given in Online Supplementary Material Appendix 1.

First-round estimates were received from 10 of the original eleven experts via email and these were plotted in an anonymized format on graphs, as before. The discussion phase was held by Skype, with experts who were unable to attend agreeing to read the anonymized written record of the discussion before making their own second-round estimates. During the discussion, it emerged that the experts present at the meeting felt they had insufficient expertise between them to answer calibration questions 9, 10, and 11 with any confidence, so the second-round estimates for these questions were assumed to be identical to the first and calibration scoring was done both with and without these questions as a sensitivity analysis. All 10 experts subsequently provided second estimates by email by an agreed date. These were analyzed using the following measures of performance (see Online Supplementary Material Appendix 1 and (Hanea et al., 2016) for details):

- The Brier score (per question, per expert).
- The average Brier score (per expert).
- The length of the uncertainty interval (per question, per expert).
- The calibration term of the Brier score (per expert calculated from all questions).
- Relative informativeness (per expert calculated from all answers).

These analyses showed that the differences in calibration scores were not significant between experts. This means that the estimates of the quantities of interest from the original elicitation workshop can be combined using an equal-weighting scheme of the second-round estimates.

Results

Using an equally weighted combination average, the aggregated lowest plausible, highest plausible, and best estimates for the probability of good abundance of honey bees, other bees, and hover flies were calculated from the of the second-round estimates. These are given in Table 1.

Table 1. The best estimate (lowest plausible, highest plausible) for the probability that abundance of honey bees, other bees and hover flies is good, under all combinations of environment, weather and disease pressure.

Environment	Weather	Varroa control	Probability abundance is good		
			Honey bees	Other bees	Hover flies
Supportive	Average	Good	0.77 (0.57, 0.89)	0.73 (0.49, 0.87)	0.71 (0.48, 0.87)
Supportive	Average	Poor	0.27 (0.16, 0.45)	0.73 (0.49, 0.87)	0.71 (0.48, 0.87)
Supportive	Unusual	Good	0.52 (0.29, 0.76)	0.47 (0.29, 0.73)	0.51 (0.32, 0.71)
Supportive	Unusual	Poor	0.24 (0.13, 0.44)	0.47 (0.29, 0.73)	0.51 (0.32, 0.71)
Unsupportive	Average	Good	0.38 (0.21, 0.59)	0.21 (0.11, 0.42)	0.25 (0.12, 0.43)
Unsupportive	Average	Poor	0.14 (0.07, 0.29)	0.21 (0.11, 0.42)	0.25 (0.12, 0.43)
Unsupportive	Unusual	Good	0.33 (0.15, 0.51)	0.18 (0.07, 0.41)	0.17 (0.06, 0.37)
Unsupportive	Unusual	Poor	0.11 (0.05, 0.23)	0.18 (0.07, 0.41)	0.17 (0.06, 0.37)

Using these values in the Bayesian network, we can now perform “what-if” analysis for all possible scenarios. The first scenario is a baseline, populated with the best estimate probabilities from Table 1 with the baseline probabilities that weather is average 62% of the time and 20% of UK environment is supportive as defined previously and that there is a 50/50 chance of good varroa control (Figure 2). The following scenarios are produced by asserting that one or more aspects of weather, environment, or varroa control have been observed, by setting these to 100%, also called “adding evidence”.

With a supportive environment the probability of good abundance increases from baseline values, but with a smaller improvement for honey bees as these are still impacted by the quality of varroa control. Similarly, with an unsupportive environment the probability of good pollinator abundance reduces from baseline values, but less so for honey bees (Figure 3).

With good varroa control, the probability of good honey bee abundance increases significantly from baseline values whilst the probability of good abundance of other bees and hover flies is unaffected since only honey bees are affected by the quality of varroa control and analogously for poor varroa control (see Online Supplementary Material Figure S4).

A combination of good varroa control and unusual weather captures the balance of the influencing factors on different classes of pollinators. The values for hover flies and other bees are the same as unusual weather alone. The effect on honey bees of the combination of good varroa control with unusual weather shows probability of good abundance higher than baseline values, reflecting the experts’ assertion that varroa control has a stronger influence on honey bee abundance than weather. Similarly, the effect on honey bees of the combination of poor varroa control with unusual weather shows probability of good abundance much lower than baseline values, reflecting the strong effect of poor varroa control exacerbated by unusual weather (Figure 4). A combination of good varroa control and supportive environment shows a probability of good abundance of all pollinator classes much higher than baseline values (Figure 3), which persists even in the event of unusual weather (see Online Supplementary Material Figure S5).

Finally, using the BN we can determine what the probabilities of good varroa control, average weather, and supportive environment need to be in order to be certain of good pollinator abundance. For good abundance of all classes of pollinators, varroa control would need to be good with 73% probability in combination with 82% probability of average weather and 82% probability of supportive environment (Figure 5). For good honey bee abundance, this level varroa control along with probabilities of supportive environment and average weather raised slightly from baseline values would be sufficient. Under these conditions, the probability of good abundance of hover flies and other bees is also slightly improved. For good other bee abundance, a further slight increase in the probability of average weather in combination with a probability of supportive environment of 45% would be required. Honey bees and hover flies would also be expected to have an increased probability of good abundance under these conditions. For good hover fly abundance, a further increase in the probability of average weather is required. The probability of supportive environment is lower than for other bees, but still more than double the baseline values (see Online Supplementary Material Figure S6).

Discussion

We have estimated the probability of good pollinator abundance under various combinations of weather conditions, environmental circumstances, and disease pressure profiles using structured expert judgment, overcoming the prohibitive difficulties of obtaining these by designed experiment. Structured expert judgment provides a way to estimate these quantities in a transparent and defensible manner. In the elicitation of quantities from experts, we have also shown that the differences in expertise between acknowledged specialists can be properly and robustly dealt with and reduced by the careful use of facilitated discussion, avoiding the severe problems associated with unstructured elicitation.

We have shown that these quantities can be used to quantify the likely effects of changes in drivers on the abundances of various classes of pollinating insects. This leads to the ability to test policy interventions alone

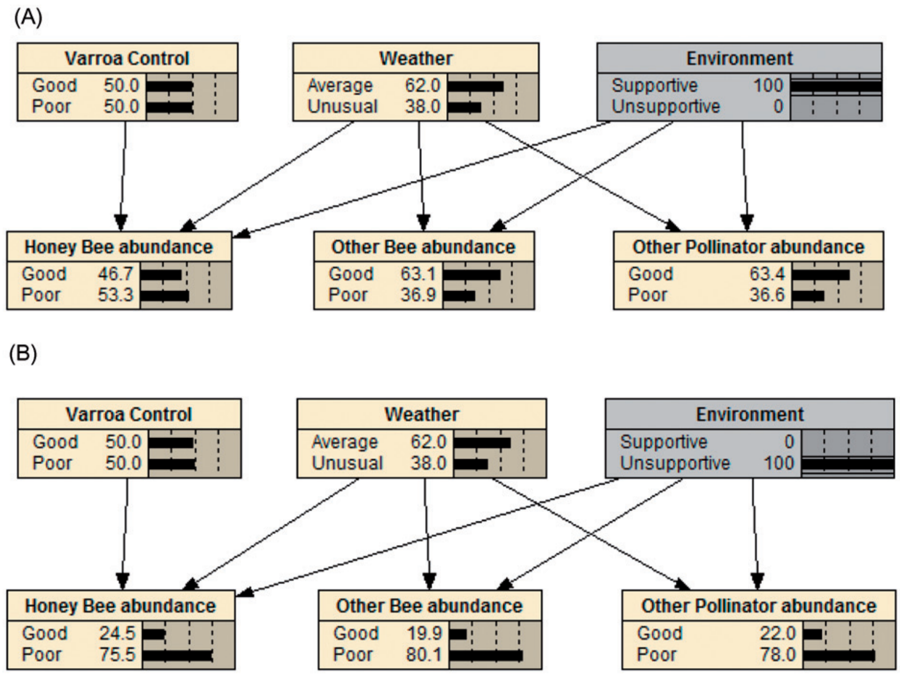

Figure 3. Bayesian network populated with the best estimate probabilities from the Table 1 with (a) a supportive environment, (b) an unsupportive environment. The numbers and bars show the probability of each state being true. Image produced in NETICA.

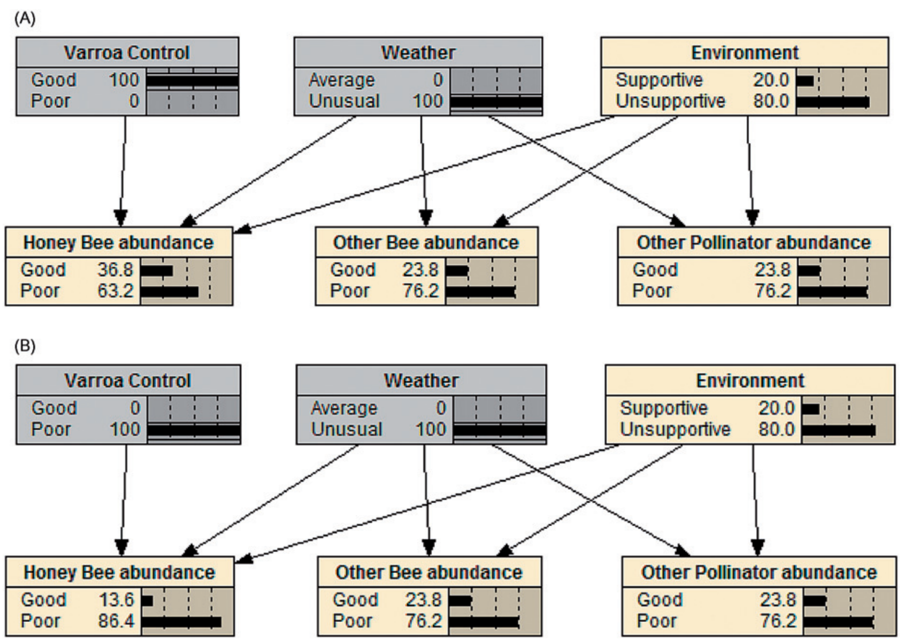

Figure 4. Bayesian network populated with the best estimate probabilities from the Table 1 with a combination of unusual weather and (a) good Varroa control and (b) poor Varroa control captures the balance of the influencing factors. The numbers and bars show the probability of each state being true. Image produced in NETICA.

and in combination for the likely impact on pollinator abundance to inform policy choice or pilot studies. For example, the quantities provided by the experts show that varroa control has an enormous effect on the abundance of honey bees, so interventions which include assistance in good varroa control are likely to be supportive of good honey bee abundance (Online Supplementary Material Figure S4). We see that a supportive environment is good for all pollinators, but its effect is more constrained for honey bees as these are still influenced by the quality of varroa control (Figure 3). We can also determine likely effect of policies on pollinator abundance under the effects of uncontrollable drivers, like weather. As more evidence becomes available, for example evidence on disease pressure for other pollinators, this can be incorporated

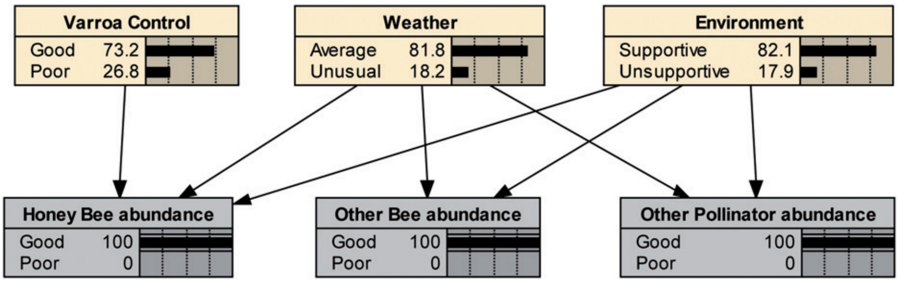

Figure 5. Bayesian network populated with the best estimate probabilities from Table 1 showing the values for Varroa control, weather and environment which would be required to ensure good abundance of honey bees and other bees and hover flies. The numbers and bars show the probability of each state being true. Image produced in NETICA.

into this model to refine the estimates of pollinator abundance. This approach can also be extended to include other drivers. For example, estimating the effect of climate change on weather variability could be used to adjust the probability of unusual weather (as defined here) and so quantify the knock-on effect on pollinator abundance. Work to do this using the methods in (Smith et al., 2017) is currently under way and will be reported separately.

By eliciting not only best estimate values for the probability of good abundance but also the lowest and highest plausible values (Table 1), it becomes evident that not all these influencing factors have a symmetrical effect. For example, unusual weather has the effect of lowering the lowest plausible probability of good abundance for all pollinator classes more than the highest plausible probability of good abundance, with other factors constant. The notable exception to this is for honey bees when varroa control is poor; here additional weather effects are small.

Further interesting patterns can be seen in the similar and different responses of different classes of pollinators. Whenever the environment is unsupportive, the highest plausible value for the probability of good abundance in all pollinator classes is less than 43%, except in the case of honey bees with good varroa control, where it is still under 60%. This suggests that a supportive environment is a key modifiable factor to support pollinator abundance. Whenever varroa control is poor, the highest plausible value for the probability of good abundance of honey bees is below 45%, regardless of the other factors, suggesting that varroa control is a key modifiable factor to support honey bee abundance. Using the BN to determine what the probabilities of good varroa control, average weather and supportive environment need to be in order to be certain of good pollinator abundance, we have shown how the different classes of pollinator have differing requirements. Since, in the short term at least, weather is not a controllable factor, we return to the scenario in Online Supplementary Material Figure S5 and show that in areas where the environment is supportive and varroa control is good, then we can expect a probability of good abundance of pollinators of all classes in excess of 60%.

Important policy conclusions from this work are:

- Actions to improve the effectiveness of varroa control should be a priority for the honey bee policy area. The results demonstrate the importance of varroa management for individual beekeepers, but given that varroa management was by far the most important driver for honey bee abundance identified in this study, it suggests also that improvements to government policy on varroa management would also be a useful way forward,
- Improving the amount of supportive environment will have large benefits for wild bees and other pollinators, with some benefits also for honey bees – the results suggest this should be a priority policy area.

This study adds an estimate of how much change in pollinator abundance might be expected form implementation of policy recommendations.

The strengths of this study are the use of established and validated methods to derive quantities of interest, making this a unique contribution. The provision of the likely effect of combinations of factors on pollinator abundance is of great importance within ecosystem service management and conservation as well as policy design. In particular, the preservation of pollinators is of such importance that there are national strategies in the UK and elsewhere and these findings can be used to evaluate candidate policies in order to support policy-makers in making evidence-based choices. The experts who contributed to the workshop and provided estimates are recognized as top experts in the field, and many have already given evidence to the UK government in the development of the national strategy, giving confidence that these estimates are likely to be reliable given the current state of knowledge.

The limitations of the study are the rough discretization of the continuous variables and the choice of calibration questions. We had to reduce the levels of weather, disease pressure, and environment to two levels each in order to complete the elicitation in the time available. Ideally a more nuanced categorization would be preferred. However, more levels per variable lead to a rapid rise in the number of conditional probabilities to be elicited, hence in an increased elicitation burden. Future work could include the use of continuous BNs which can drastically reduce the number of parameters to be elicited (Hanea, Kurowicka, & Cooke, 2006; Morales, Kurowicka, & Roelen, 2008). Also only a subset of drivers were chosen which excluded some others known to be major stressors on pollinators, such as climate change and pesticides. Finding evidence on which to base calibration questions was enormously difficult and the calibration questions are not as similar to the elicitation questions as we would have liked. In our implementation of the protocol, the difficulty was increased by having the calibration exercise remotely; for practical reasons, the calibration discussion was carried on by Skype and not face to face. It is likely that the intervals between the highest and lowest plausible estimates would have been smaller following a face-to-face discussion. Three questions were deemed beyond the experts' domain knowledge. However, by undertaking sensitivity analysis with respect to these questions, we have shown that the calibration score and so the weighting between experts is not significantly affected. To undertake structured expert elicitation well takes time and is very demanding for experts. These compromises, whilst not ideal, enabled the study to take place.

Future work will include the incorporation of these values with other evidence on major drivers of pollinator abundance to provide a proof of concept decision support system which could be used by policy-makers to evaluate the effect on pollinator abundance of plausible scenarios and policy interventions, based on new methodology for coherent inference in networked systems (Smith et al., 2017). We conclude that when evidence based decision-making is required, structured expert judgment can provide useful, transparent, and defensible evidence, including in the ecosystem services domain.

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No potential conflict of interest was reported by the authors.

Supplementary material

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