Institution: University of Exeter		
Unit of Assessment: UoA 5 Biological Sciences		
Title of case study: Ecological "BEEHAVE" models deliver benefits for pollinators - improving European regulation, reducing risks and informing land management.		
Period when the underpinning research was undertaken: 2012 – Aug 2020		
Details of staff conducting the underpinning research from the submitting unit:		
Name(s):	**Role(s) (e.g. job title):**	**Period(s) employed by submitting HEI:**
Prof Juliet Osborne	Chair in Applied Ecology, P.I.	2012 – present
Dr Matthias Becher	Research Fellow	2013 – August 2020
Dr Peter Kennedy	Research Fellow	2013 – present
Dr Grace Twiston-Davies	Research/Impact Fellow	2015 – present
Dr Rosalind Shaw	Research/Impact Fellow	2012 – present
Period when the claimed impact occurred: 2014 - Present		
Is this case study continued from a case study submitted in 2014? N		

1. Summary of the impact

Pollinator populations are declining, posing a threat to global food production and to insect and plant biodiversity. Exeter's award-winning bee research has directly addressed an urgent need for decision-support tools to manage risks to pollinators and deliver pollinator-benign land management. Osborne's team has created innovative ecological models of managed and wild bee colony dynamics, unique in allowing large scale and long-term assessment of multiple stressors on bee populations. The models have:

A. **Changed how EU regulators assess risks** to bees and how they set specific bee protection goals.
B. **Changed practice and perspectives in the global agrochemical industry** and **informed and improved plant protection risk assessment** to reduce risks to pollinators.
C. **Transformed policy and practice** to boost pollinator populations in landscapes by enabling the delivery of pollinator-friendly land management plans for stakeholders responsible for >900km^2 of the UK.

2. Underpinning research

Bees and other pollinators are in decline globally, threatening food security and the survival of ecosystems dependent on their services. Prof Juliet Osborne and colleagues have played a pivotal role in identifying threats to pollinators through their research into loss of habitat, increased pesticide use, invasive species and disease [3.1], developing the science needed to underpin national pollinator policy to improve pollinator resilience.

We focus on a key element of this research: the development of a suite of innovative ecological models for use by a wide range of stakeholders (regulators, policy makers, the agrochemical industry and land stewards) as decision-support tools in pursuit of strategies to improve the environment for pollinators. Osborne's team identified that solutions to creating good pollinator policy, practice and safer plant protection products would only be found if we are able to predict the impact of multiple stressors over long time frames (years) and across large spatial scales (km) - beyond the scope of field or lab experiments. These forecasts are needed to set and evaluate "bee protection goals" set by regulators to guide the risk assessment of agrochemical products.

Osborne's team have directly addressed this need to examine the effect of stressors on pollinator population dynamics by developing three novel, complex and biologically realistic models of bee colony survival, which can be applied in any landscape: **BEEHAVE** [3.2], **Bumble-BEEHAVE** [3.3] and **BEESCOUT** [3.4]. These freely available models [3.5] were designed in collaboration with industry and end-users.

BEEHAVE: In order to understand the complexity of interactions between stressors within and

outside of a honeybee colony that might lead to tipping points and colony failure, Osborne, Becher and Kennedy (in collaboration with Dr Pernille Thorbek at Syngenta and Prof Volker Grimm, UFZ, Leipzig) created BEEHAVE [3.2] - a detailed, behaviourally explicit agent-based model to simulate honeybee colony growth and survival in any mapped landscape over time. This work was initiated at Rothamsted Research in 2009 and completed when Osborne moved to UoE in 2012 (BBSRC/Syngenta Industrial Partnership Award 2009-2012). BEEHAVE was developed in open-source software (NetLogo) with a user-friendly interface so it could be used by the widest variety of people [3.2]. The model has been used by researchers in Europe and North America to predict the effects of disease, forage availability, varroa mite infestation, pesticide effects, weather patterns, invasive Asian hornet predation pressure, and beekeeping interventions on colony health and survival and to simulate thresholds of colony failure in different conditions [citation list in 3.5]. Osborne's team have further developed BEEHAVE to simulate the lethal and sublethal effects of pesticides on colonies [3.6].

Bumble-BEEHAVE: Following the success of BEEHAVE, stakeholders requested a similarly robust and flexible tool for wild bumblebees so the Exeter team developed Bumble-BEEHAVE [3.3]: the first published model of wild bumblebee colonies at population level, with detailed landscape patterning (**BEESCOUT** [3.4]). The priority for this model was to be able to predict the effects of landscape management on wild populations. Habitat loss is one of the biggest factors affecting wild bee populations so, to support and encourage land managers to undertake land management options that promote pollinators, a software tool integrating Bumble-BEEHAVE and BEESCOUT with a user-friendly dashboard, called **BEE-STEWARD**, was developed in 2017 [details in 3.5]. It was devised in collaboration with Natural England, the National Farmers Union, and the National Association of Areas of Outstanding Natural Beauty to run scenarios of land management options on farm maps, with outputs demonstrating how these options will affect local bee populations.

3. References to the research

3.1 Fürst, M. A., McMahon, D. P., **Osborne, J. L.**, Paxton, R. J., & Brown, M. J. F. (2014). Disease associations between honeybees and bumblebees as a threat to wild pollinators. *Nature*, *506*(7488), 364-366. doi:10.1038/nature12977

3.2 **Becher, M. A.**, Grimm, V., Thorbek, P., Horn, J., **Kennedy, P. J.**, & **Osborne, J. L.** (2014). BEEHAVE: A systems model of honeybee colony dynamics and foraging to explore multifactorial causes of colony failure. *Journal of Applied Ecology*, *51*(2), 470-482. doi:10.1111/1365-2664.12222

3.3 **Becher, M. A.**, **Twiston-Davies, G.**, Penny, T. D., Goulson, D., Rotheray, E. L., & **Osborne, J. L.** (2018). Bumble-BEEHAVE: A systems model for exploring multifactorial causes of bumblebee decline at individual, colony, population and community level. *Journal of Applied Ecology*, *55*(6), 2790-2801. doi:10.1111/1365-2664.13165

3.4 **Becher, M. A.**, Grimm, V., Knapp, J., Horn, J., **Twiston-Davies, G.**, & **Osborne, J. L.** (2016). BEESCOUT: A model of bee scouting behaviour and a software tool for characterizing nectar/pollen landscapes for BEEHAVE. *Ecological Modelling*, *340*, 126-133. doi:10.1016/j.ecolmodel.2016.09.013

3.5 BEEHAVE website: www.beehave-model.net.

3.6 Rumkee, J.C., **Becher, M.A.**, Thorbek, P., **Kennedy, P.J**. & **Osborne, J.L.** (2015). Predicting honeybee colony failure: using the BEEHAVE model to simulate colony responses to pesticides. *Environmental Science & Technology*, *49*, 12879-12887. doi: 10.1021/acs.est.5b03593.

4. Details of the impact

Osborne et al's BEEHAVE models [3.5] were built to make a practical difference to decision-making at all scales - from European regulators (EFSA) and global agrochemical companies making strategic bee health decisions, to individual farmers or beekeepers making local management decisions to positively improve the farmed environment for pollinators. In the six years since the publication of BEEHAVE they are being used by all these stakeholder groups.

The BEEHAVE models' significance for environmental benefit, across multiple diverse sectors, was recognized when Osborne's team was awarded the BBSRC Innovator of the Year Award for Social Impact in 2017 [5.1]. Specifically, the team's ecological models [3.5], simulating the population dynamics of both honeybees (worth £150mill to the UK economy alone) and wild bumblebees, have: **A.** changed how EU regulators assess risks to bees and how they set specific bee protection goals [5.2, 5.3]; **B.** shifted perspective and informed and improved plant protection risk assessment by the global agrochemical industry to reduce risks to pollinators [5.4 - 5.6], and **C.** enabled the delivery of pollinator-friendly land management plans for stakeholders responsible for >900km^2 of the UK [5.7 - 5.10].

A. European Regulatory Guidance and Bee Protection Goals

The European Food Standards Agency (EFSA) oversees the regulation and risk assessment of agrochemicals in the EU. In 2014 EFSA set up the Must-B working group to develop an "*integrated approach to environmental risk assessment of multiple stressors on bees*" to secure the future of bee health in Europe; and they published a thorough evaluation of BEEHAVE in 2015 [5.2] stating that: "*The Panel recommends that BEEHAVE should be adopted as the basis for modelling the impact on honeybee colonies of pesticides and other stressors*". As a direct result, EFSA have now embedded BEEHAVE into their development of improved regulatory tools and guidance as follows:

i. EFSA commissioned a new regulatory model (in development by 3rd party [September 2020]) based on the design of BEEHAVE. This will be a quantitative tool for regulatory risk-assessment purposes to better understand the (relative) risks and impacts of multiple stressors on honeybee colonies which agrochemical companies will be expected to use in their risk assessment of new plant protection products [5.2]
ii. In May 2020 EFSA reviewed its Guidance Document for assessing risks of chemicals to bees, which sets the Specific Protection Goals for bees defining the magnitude of effect (e.g. on colony survival) that would be 'safe' for field trials. EFSA proposed four 'approaches' to setting new Specific Protection Goals to the EU risk managers in member states [5.3], and two of these involved using BEEHAVE & Bumble-BEEHAVE. In August 2020 the European Commission confirmed in a written Question & Answer to the European Parliament that "*A majority of Member States supported to conduct further work based on approach 2, which considers natural variability in colony size. It is based on scientific population modelling, in particular the BEEHAVE model, which EFSA found in 2015 to predict well colony dynamics*." [5.3]

Thus, BEEHAVE was the foundation for, and remains central to, EU regulators revising bee protection goals and developing improved regulatory risk assessment [5.2, 5.3].

B. Changed practice and perspectives in the global agrochemical industry to improve plant protection risk assessment to reduce risks to pollinators,

Syngenta, Bayer and BASF, the three largest global agrochemical companies operating across 5 continents (spending >$6billion in R&D each year; achieving >$25bill in crop product sales/year according to 5.4, company R&D sites and sales reports 2019) are all now using BEEHAVE [5.4, 5.5, 5.6] calling it "*A game-changing ecological model for risk assessment and regulation"* [5.4], even beyond its application to bees. The Global Head of Environmental Safety at Syngenta states that *"BEEHAVE changed the industry and the regulators' perspective on how such models could be used to evaluate large scale and long-term effects of multiple and interacting stressors, beyond the capability of field trials"* [5.4].

As pressure to understand the sub-lethal impacts of pesticides on non-target organisms grows, Syngenta, BASF and Bayer have all invested in ecological modelling expertise (in house, consultants and PhD students) [5.4 - 5.6] to evaluate how BEEHAVE can simulate complex field scenarios and predict likely long-term effects of the impact of pesticides on honeybees [5.6]. Bayer stated that it is "*committed to investigating the potential effects of plant protection products under realistic field conditions by means of monitoring studies and the BEEHAVE model*" [5.5]. The companies and consultancies (Ibacon GmbH and Waterborne Environmental) are developing their own ecotoxicology modules to extend BEEHAVE to

simulate field risk assessments and avoid negative outcomes [5.4 - 5.6].

Pesticide development and regulation costs an average of $286 million for each active ingredient to market (European Crop Protection, 2016), and Syngenta state that use of BEEHAVE *"will result in more efficient use of resources for field trials, potentially saving costs, and will provide more robust evidence to avoid and mitigate the negative impacts of plant protection products on honeybee health"* [5.4].

C. Transformed policy and practice to boost pollinator populations in landscapes in the UK A large body of research evidence on pollinator ecology and management from Osborne's research group has contributed to changing pollinator policy and practice in the UK, including the UK National Pollinator Strategy [5.11]. This wider research, the recommendations it led to, as well as the bee models, are embedded in environmental policy and practice in the South West UK: in particular that of Cornwall Council [5.7], The Duchy of Cornwall Estates [5.8] and the National Associations of Areas of Outstanding Natural Beauty (NA-AONB) [5.9]. Cornwall Council launched the Cornwall Pollinator Action Plan in 2019 which refers to BEE-STEWARD and states that "*advice and information from (…) Osborne's team were included in the development and writing of this Plan."* [5.7].

To deliver pollinator-friendly landscape management in line with the UK National Pollinator Strategy, Twiston-Davies and Shaw have worked with 142 stakeholders since 2015 [5.10], including partnering with the largest landowners in the South West of the UK with combined land holdings of ~973km^2 (9.5% of land area in Cornwall, Devon and Isles of Scilly) [5.10] and with the NA-AONB which covers 18% of UK countryside [5.9]; as well as a wide range of businesses and charities [5.10]. The BEE-STEWARD tool has been used with these stakeholders to visualize the effect of adding pollinator-friendly habitats to their landscape maps and predict effects on bumblebee populations; thus aiding land stewards to create and implement management plans.

Examples of how this work has changed stakeholder practice:

- The team's collaboration on Cornwall Council's Green Infrastructure for Growth project has transformed >40 Ha of public green spaces (parks, road verges) to boost biodiversity in Cornwall. It was considered: "*an example of best practice for regional green space management"* and won the Ciria BIG biodiversity challenge award in 2019 for the Best Biodiversity Project in the country [5.7].
- The Duchy of Cornwall, the largest landowner in SW, state that Bee-Steward reports have *"delivered a quantified prediction of bumblebee population growth",* feeding into an evidence base for *"management plans which will be rolled out across our entire 38,000ha estate."* They state that *"as a consequence we are better placed to successfully deliver the Duchy of Cornwall Estate natural capital plans."* [5.8].
- With the NA-AONB, the 'Farms for AONBees' project used BEE-STEWARD to demonstrate the impacts of pollinator friendly management on 125 km^2 of Cornwall. They stated that "*the BEE-STEWARD model is supporting and enhancing the impact of our prioritised work outline in the Cornwall AONB 2016-2021 Management Plan"* [5.9]. The project received a Bowland Award nomination for the most outstanding contribution to the wellbeing of Areas of Outstanding Natural Beauty (2018). Also *"The Bee-Steward tool has been vital in engaging key members of the farming community which are generally more challenging to engage within protected landscapes where nature conservation and business need to work hand in hand"* [5.9].
- The NA-AONB and the Duchy of Cornwall have won contracts from the Department for Environment, Food and Rural Affairs (Defra) and Natural England to use BEE-STEWARD to develop the new Defra ELMS (Environmental Land Management Schemes) post-Brexit [5.8, 5.9]. The Bumblebee Conservation Trust also won funds to use BEE-STEWARD in Cornwall, as a pilot to using the model in their conservation work across the UK [5.10].
- 61 BEE-STEWARD reports have been created for businesses (farms, holiday parks, hotels, breweries, food and drink companies) [5.10]. As a direct result the stakeholders

have pledged to create 545ha of new pollinator habitat (flowering cover crops, perennial wildflower meadows, trees and hedgerows), and enhance 391ha by seeding or management [5.10].

In summary: The suite of models and strong translation activities of Osborne's team are actively building pollinator resilient environments both locally and globally. They have underpinned European regulation on bee protection, enhanced the ability of global industry to reduce the environmental damage of pesticides, and changed the practice of land stewards and local government to manage landscapes to maximize pollinator survival.

5. Sources to corroborate the impact

5.1 National recognition: BBSRC Innovator Prize for Impact 2017 https://tinyurl.com/mxnezf2w (See mid-page)

5.2 EFSA: EFSA Evaluation of BEEHAVE for risk assessment (2015) & plan for its use in design of new regulatory model, https://efsa.onlinelibrary.wiley.com/doi/epdf/10.2903/j.efsa.2015.4125; 'Risk assessment of pesticides and other stressors in bees: Principles, data gaps and perspectives from the European Food Safety Authority', Rortais et al; EFSA slides 'MUST-B Developing a holistic and integrated risk assessment approach of multiple stressors in bees', Management Board Meeting, 2018.

5.3 EFSA & European Parliament: Confirmation of EFSA proposal & EU member states decision to use BEEHAVE, and Bumble-BEEHAVE models to update bee guidance on bee risk assessment by improvement of the EU Specific Bee Protection Goals. https://www.efsa.europa.eu/sites/default/files/topic/EFSA-Supporting-document-for-RMs-in-defining-SPGs.pdf & https://www.europarl.europa.eu/doceo/document/P-9-2020-004368-ASW_EN.html

5.4 Syngenta: Letter from Global Head of Environmental Safety at Syngenta dated 3 March 2020 demonstrating impact of BEEHAVE model on agrochemical industry

5.5 BASF & Bayer: Evidence from BASF and Bayer Crop Science demonstrating impact of BEEHAVE model on companies' risk assessment of bee health. BASF email from Pernille Thorbek (Team leader Global Modelling); Bayer blog by Julian Little, Head of Communications and Government Affairs, May 2018 and 'BEENOW: The Bee Health Magazine', 2016, Issue 2, pages 28-31.

5.6 Industry-led papers 7 papers led by Bayer, Ibacon GmbH, Syngenta or Waterborne authors, with BASF contributions. They use the BEEHAVE model to understand and develop the risk assessment process for agrochemicals and pharmaceuticals for bee health. All papers written independently of University of Exeter staff or input.

5.7 Cornwall Council: Letter confirming Dr Shaw & Osborne's team influence on the writing of the Cornwall Pollinator Action Plan, and contribution to delivering 40Ha of enhanced green space on the award-winning Green Infrastructure for Growth project.

5.8 Duchy of Cornwall: Letter confirming impact of Dr Twiston-Davies research on their thinking, planning and delivery of enhanced pollinator habitat across the Estate's land.

5.9 National Association of AONBs: Letter confirming deep impact of BEE-STEWARD and Exeter's pollinator research on AONBs prioritized land management for pollinators and Farm for AONBees project website.

5.10 Wide reach to land stewards: Evidence of the area of influence of University of Exeter BEE-STEWARD work via documentation of stakeholder land ownership; businesses engaged and consequent land-owner commitments to undertake pollinator-friendly land management.

5.11 UK National Pollinator Strategy: Osborne's research cited in Supporting Document.