Rapid rise in toxic load for bees revealed by analysis of pesticide use in Great Britain

Dave Goulson Corresp., [1] , **Jack Thompson** [1] , **Amy Croombs** [1]

[1] School of Life Sciences, University of Sussex, University of Sussex, Falmer, E Sussex, United Kingdom

Corresponding Author: Dave Goulson
Email address: d.goulson@sussex.ac.uk

A strong argument can be made that the European Union has the most rigorous regulatory system for pesticides in the world, and that modern pesticide use poses fewer environmental threats than older regimes. Nevertheless, the impacts of pesticides on bees and other non-target organisms is much debated in Europe as elsewhere. Here we document changing patterns of pesticide use in arable and horticultural crops in Great Britain from 1990 to 2015. The weight of pesticides used has approximately halved over this period, but in contrast the number of applications per field nearly doubled. The total *potential* kill of honeybees (the total number of LD_{50} doses applied to the 4.6 million hectares of arable farmland in Great Britain each year) increased six-fold to approximately 3 x 10^{16} bees, the result of the increasing use of neonicotinoids from 1994 onwards which more than offset the effect of declining organophosphate use. It is important to acknowledge that our simple analysis does not take into account many factors such as differences in persistence, and timing and mode of application of pesticides, that will affect actual exposure of non-target organisms. Nonetheless, all else being equal, these data suggest that the risk posed by pesticides to non-target insects such as bees, other pollinators and natural enemies of pests, has increased considerably in the last 26 years.

PeerJ Preprints | https://doi.org/10.7287/peerj.preprints.26856v1 | CC BY 4.0 Open Access | rec: 15 Apr 2018, publ: 15 Apr 2018

Rapid rise in toxic load for bees revealed by analysis of pesticide use in Great Britain

D Goulson[1]*, Thompson, J.[1] & Croombs, A.[1]
1 School of Life Sciences, Sussex University, Falmer BN1 9QG, UK
*Corresponding author, email: d.goulson@sussex.ac.uk

Abstract

A strong argument can be made that the European Union has the most rigorous regulatory system for pesticides in the world, and that modern pesticide use poses fewer environmental threats than older regimes. Nevertheless, the impacts of pesticides on bees and other non-target organisms is much debated in Europe as elsewhere. Here we document changing patterns of pesticide use in arable and horticultural crops in Great Britain from 1990 to 2015. The weight of pesticides used has approximately halved over this period, but in contrast the number of applications per field nearly doubled. The total *potential* kill of honeybees (the total number of LD_{50} doses applied to the 4.6 million hectares of arable farmland in Great Britain each year) increased six-fold to approximately 3 x 10^{16} bees, the result of the increasing use of neonicotinoids from 1994 onwards which more than offset the effect of declining organophosphate use. It is important to acknowledge that our simple analysis does not take into account many factors such as differences in persistence, and timing and mode of application of pesticides, that will affect actual exposure of non-target organisms. Nonetheless, all else being equal, these data suggest that the risk posed by pesticides to non-target insects such as bees, other pollinators and natural enemies of pests, has increased considerably in the last 26 years.

Introduction

There is widespread concern regarding the health of populations of insect pollinators including domestic honey bees (*Apis mellifera*) and wild pollinators such as bumblebees (*Bombus sp*). There is clear evidence for significant declines in the abundance and distribution of many pollinators, with some local and global extinctions (reviewed in Goulson *et al.* 2015). This has given rise to concerns over the future supply of pollination services for crops, currently valued at about €153 billion globally (Gallai *et al.* 2009). There is a broad consensus that these declines are due to a combination of factors including habitat loss, emergent diseases, exposure to pesticides, and

PeerJ Preprints | https://doi.org/10.7287/peerj.preprints.26856v1 | CC BY 4.0 Open Access | rec: 15 Apr 2018, publ: 15 Apr 2018

climate change, although the relative importance of these factors is debated (Goulson *et al.* 2015). The role of pesticides is the most controversial, since the debate impinges directly on farmers and the crop production industry.

In Europe, the regulatory system for pesticides is widely regarded as the most rigorous in the world, with a complex system in place to review the safety of new plant protection products and re-evaluate their safety at intervals (Handford *et al.* 2015). Although pesticides are known to have wrought considerable environmental damage in the past, as was famously exposed by Rachel Carson's book "Silent Spring" (1962), there is a perception that modern pesticides are much safer (Dudley *et al.* 2017). The European Union (EU) has been promoting reduced pesticide use and increased adoption of Integrated Pest Management (IPM) practices (Hillocks 2012; Handford *et al.* 2015). Notably, the EU introduced a moratorium in 2013 which prevents the use of some neonicotinoid insecticides on flowering crops, a measure specifically intended to reduce risks to bees. Use of these chemicals elsewhere in the world is much less restricted. One might thus expect the EU to be a relatively benign region for bees, at least with regard to exposure to pesticides.

Nonetheless there are concerns that the landscape scale, industrial use of multiple pesticides poses risks to the environment that are not captured by regulatory tests which largely focus on short-term studies in which test organisms are exposed to a single chemical (Dudley *et al.* 2017; Milner & Boyd 2017). Recent studies suggest that environmental contamination with neonicotinoid insecticides in particular is contributing to declines in wild bees (e.g. Woodcock et al. 2016), aquatic insects (Van Dijk et al. 2013), butterflies (Gilburn *et al.* 2015; Forister *et al*. 2016) and insect-eating birds (Hallmann et al. 2014) (reviews in Goulson 2013; Pisa et al. 2015; Wood & Goulson 2017). All but one of these studies (Forister *et al*. 2016) were conducted in Europe.

Here we use a novel approach to evaluate whether the risks to bees posed by pesticide use in farming are decreasing or increasing, focussing on Great Britain for the simple reason that detailed pesticide use data are available for this region from 1990 to the present. Similar data are not available for any other region, but we would expect similar patterns elsewhere, particularly across the EU (of which Great Britain remains part for the moment). We examine patterns of change in the mass of pesticides used, the area sprayed, and the total number of honey bees that could potentially be killed, in the period 1990-2015. Pesticide usage data was obtained from the Food and Environment Research Agency (FERA 2018). We then calculated the number of honey bee LD_{50} doses applied each year for each chemical, by dividing the mass applied by the LD_{50}. This indicates the *potential* kill due to use of the chemical, assuming all of it was consumed by or came into contact with honeybees, and serves as a comparative measure of how the toxic load entering the environment has changed over 26 years..

Methods

Pesticide usage data was obtained from the Food and Environment Research Agency website (Defra, 2018). All 416 pesticides on the Defra database were initially included, but those for which total usage over the 1990-2015 survey period was below 100kg were subsequently discarded, leaving 396 chemicals. Pesticide usage is recorded as both the mass applied each year, and the area treated. For the latter, a treatment of 10 ha with one application of a product, or the treatment of 1 ha with 10 applications of a product in a year would both give a value of 10.

We obtained LD_{50} data for honey bees for each chemical from the existing literature. Wherever available, we used 48 h LD_{50} values, but in a few cases these were not available and were substituted with 24 h or 96 h studies. For each pesticide the typical mode of application and mode of action of the pesticide was used to determine whether the primary route of exposure of bees was likely to be via contact or consumption, and appropriate LD_{50} values were then used. For 66 of the most obscure pesticides no LD_{50} values were publicly available. Thirty-six of these were members of chemical groups for which LD_{50} values were available for closely related compounds, and for these the mean LD_{50} value for other members of the chemical group was substituted. The remaining 30 chemicals were excluded from further analysis. Together they accounted for considerably less than 1% of all pesticides used by weight. We then calculated the number of honey bee LD_{50} doses applied each year for each chemical, by dividing the mass applied by the LD_{50}. This indicates the potential kill due to use of the chemical, assuming all of it was consumed by or came into contact with honeybees.

PeerJ Preprints | https://doi.org/10.7287/peerj.preprints.26856v1 | CC BY 4.0 Open Access | rec: 15 Apr 2018, publ: 15 Apr 2018

Results

Between 1990 and 2016 the total weight of pesticides used in Great Britain fell by 48% from 34.4 to 17.8 thousand tons per year (Figure 1). In contrast, the area treated almost doubled, from 45 million hectares to 80 million hectares. The area of cropped land has remained approximately stable throughout this period at around 4.6 million hectares (Defra 2016). Thus in 1990 each hectare of cropped land on average received a total of 7.5 kg of pesticide active ingredient delivered in 9.8 applications. By 2015 each hectare of land received 3.9 kg of pesticide in 17.4 applications, a marked change in practice [note that several active ingredients may be applied at once, so this does not mean farmers actually spray fields 17.4 times].

The potential number of bees killed by these applications (the number of LD_{50} doses that could be delivered) rose approximately six-fold over the 26 year period, from 5 x 10^{15} to 30 x 10^{15} (Figure 2). Toxicity due to herbicides declined over time, largely due to decreased usage of triazines such as simazine, while declines in use of carbamate and organothiophosphate insecticides also reducing the toxic load. However, these reductions were more than offset by increases in toxicity due to an approximately five-fold increase in the weight of pyrethroid insecticides applied, and a very large increase in toxicity due to the introduction and widespread adoption of neonicotinoid insecticides from 1994 onwards. Eighty seven percent of the total toxic load in 2015 was due to neonicotinoids, and >99% of this was due to three compounds: imidacloprid, clothianidin and thiamethoxam. All three compounds have become widely used and have very low LD_{50} values, in the region of 4 to 5 ng per bee via oral exposure.

Discussion

These data on the number of potential LD_{50} doses must be interpreted with considerable caution. Thirty x 10^{15} is enough to give 10,000 lethal doses to each of the approximately three trillion honeybees in the world. In reality, the very large majority of the pesticides applied will not come in to contact with any bee; if this were not so, there would be no bees left in Britain. The total toxic load entering the environment is just part of the story. The probability of a pesticide coming into contact with a bee will depend on many factors, such as how and when it is applied, what crops it is applied to, its persistence, whether it acts systemically in plants (and hence enters nectar and pollen) and so on. If neonicotinoids were being used in place of more persistent chemicals, or those that were more likely to find their way into nectar and pollen, then this might offset their higher toxicity. However, the opposite appears to be the case; neonicotinoids are persistent in the environment, and being systemic are regularly found in the pollen and nectar of both flowering crops and also wildflowers in farmland (Krupke *et al.* 2012; Bonmatin *et al.* 2015; Botias *et al.* 2015, 2017; Mogren & Lundgren 2016). As a result, they are often the most common pesticides found in honey and pollen stores in honey bee and bumblebee colonies (Lambert *et al.* 2013; Sanchez-Bayo & Goka 2014; David et al. 2015, 2016), and in wild bees themselves (Hladick *et al.* 2016). Indeed, a recent study found neonicotinoids in 75% of honey samples collected from diverse locations around the globe and including remote Pacific islands, suggesting that honey bees do routinely come into contact with these chemicals (Mitchell *et al*. 2017).

Although it is clear that bees are chronically exposed to pesticides, most of the time they are likely to receive sublethal doses. Our approach does not directly capture such effects, but if we make the reasonable assumption that, for each chemical, the doses causing sublethal effects are lower but proportional to the doses causing acute mortality, then our analysis should indicate the likely changes over time in the relative frequency with which bees receive a dose that does them sublethal harm.

We focus here on honey bees for the reason that LD_{50} values are available for honey bees and they are of course major pollinators, but neonicotinoids are highly toxic to all insects that have been tested, both pests and beneficials (Pisa *et al.* 2014). More broadly, toxicity of pesticides to insects tends to be broadly similar across insect species. It is thus likely that all non-target insects including other pollinators are likely to be similarly at risk, which may explain the apparent links between patterns of pesticide use and declines of aquatic insects, butterflies and insect-eating birds (Van Dijk *et al.* 2013; Gilburn *et al.* 2015; Forister *et al.* 2016; Hallmann *et al.* 2014). It is also noteworthy that this six-fold increase in potential toxicity to insects in the period 1990 to 2015 corresponds closely with the timing of the 76% decline in flying insect biomass recorded in Germany in the period 1989-2014 (Hallmann et al. 2017).

In conclusion, while acknowledging that our analysis makes many simplifying assumption, nonetheless it suggests that the risks that pesticides pose to bees and other beneficial insects may have considerably increased in the last 26 years in Great Britain, despite a complex regulatory system and a push from the EU for reduced pesticide use and a move towards Integrated Pest Management.

Acknowledgements

We are very grateful to the Pesticide Usage Statistics team at the Farmed Environment Research Agency, who conduct the pesticide use surveys and make the data freely available.

References

Bonmatin J-M., Giorio C., Girolami V., Goulson D., Kreutzweiser D., Krupke C., Liess M., Long E., Marzaro M., Mitchell E., Noome D., Simon-Delso N., Tapparo A. 2015. Environmental fate and exposure; neonicotinoids and fipronil. Environ. Sci. Pollut. Res. 22: 35-67.

Botias, C., David, A., Hill, E., Goulson, D., 2017. Quantifying exposure of wild bumblebees to mixtures of agrochemicals in agricultural and urban landscapes. Environ. Pollut. 222: 73-82.

Botías, C., David, A., Horwood, J., Abdul-Sada, A., Nicholls, E., Hill, E., Goulson, D. 2015. Neonicotinoid residues in wildflowers, a potential route of chronic exposure for bees. Environ. Sci. Technol. 49, 12731-12740.

Carson, R. 1962. Silent Spring. Houghton Mifflin, USA.

David, A., Botías, C., Abdul-Sada, A., Goulson, D., Hill, E.M., 2015. Sensitive determination of mixtures of neonicotinoid and fungicide residues in pollen and single bumblebees using a scaled down QuEChERS method for exposure assessment. Anal. Bioanal. Chem. 1–12.

David, A., Botías, C., Abdul-Sada, A., Nicholls, E., Rotheray, E.L., Hill, E.M., Goulson, D., 2016. Widespread contamination of wildflower and bee-collected pollen with complex mixtures of neonicotinoids and fungicides commonly applied to crops. Environ. Int. 88, 169–178.

Defra, 2016. Farming statistics, Final crop areas, yields, livestock populations and agricultural workforce at June 2016 - United Kingdom. www.statistics.gov.uk.

Defra 2018. https://secure.fera.defra.gov.uk/pusstats

Dudley, N., Attwood, S.J., Goulson, D., Jarvis, D., Bharucha, Z.P., Pretty, J. 2017. How should conservationists respond to pesticides as a driver of biodiversity loss in agroecosystems? BIOLOGICAL CONSERVATION 209: 449-453.

Forister, M.L., Cousens, B., Harrison, J.G., *et al*. (2016) Increasing neonicotinoid use and the declining butterfly fauna of lowland California. Biology Letters, 12, 20160475

Gallai, N., Salles, J-M., Vaissiere, B.E. 2009. Economic valuation of the vulnerability of world agriculture confronted with pollinator decline. Ecological Economics 68: 810-821.

Gilburn, A.S., Bunnefeld, N., Wilson, J.M., Botham, M.S., Brereton, T.M., Fox, R. and Goulson, D. (2015) Are neonicotinoid insecticides driving declines of widespread butterflies? PeerJ, 3, e1402

Goulson, D. 2013. An overview of the environmental risks posed by neonicotinoid insecticides. Journal of Applied Ecology 50: 977-987.

Goulson, D., Nicholls E., Botías C., & Rotheray, E.L. 2015. Combined stress from parasites, pesticides and lack of flowers drives bee declines. Science 347: 1435-+.

Hallmann CA, Foppen RPB, van Turnhout CAM, de Kroon H, Jongejans E. 2014. Declines in insectivorous birds are associated with high neonicotinoid concentrations. *Nature* 511: 341-343.

Hallmann, CA, Sorg, M, Jongejans, E, Siepel, H, Hofland, N, Schwan, H, Stenmans, W, Müller, A, Sumser, H, Hörren, T, Goulson, D & de Kroon, H. 2017. More than 75 percent decline over 27 years in total flying insect biomass in protected areas. PlosONE 12: e0185809.

Handford, CE, Elliot, CT, Campbell, K. 2015. A review of the global pesticide legislation and the scale of challenge in reaching the global harmonization of food safety standards. Integrated Environmental Assessment and Management 11: 525-536.

Hillocks, R.J. 2012. Farming with fewer pesticides: EU pesticide review and resulting challenges for UK agriculture. Crop Protection 31: 85-93.

Hladick, M.L., Vandever, M., Smalling, K.L. 2016. Exposure of native bees foraging in an agricultural landscape to current-use pesticides. Science of the Total Environment. 542: 469-477.

Krupke, C.H., Hunt, G.J., Eitzer, B.D., Andino, G. and Given, K. (2012) Multiple route of pesticide exposure for honeybees living near agricultural fields. PLoS One, 7, e299268

Lambert, O., Piroux, M., Puyo, S., Thorin, C., L'Hostis, M., Wiest, L., Buleté, A., Delbac, F., Pouliquen, H., 2013. Widespread Occurrence of Chemical Residues in Beehive Matrices from Apiaries Located in Different Landscapes of Western France. PLOS ONE 8, e67007.

Milner, A.S. & Boyd, I.L. Toward pesticidovigilance. Science, 357: 6357.

Mitchell, E.A.D., Mulhauser, B., Mulot, M., Mutabazi, A., Glauser, G., Aebi, A. 2017. A worldwide survey of neonicotinoids in honey. Science 358: 109-111.

Mogren, C.L. and Lundgren, J.G. (2016) Neonicotinoid-contaminated pollinator strips adjacent to cropland reduce honey bee nutritional status. Scientific Reports, 6, 29608

Pisa, L.W., Amaral-Rogers, V., Belzunces, L.P., *et al*. (2015) Effects of neonicotinoids and fipronil on non-target invertebrates. Environmental Science and Pollution Research, 22, 68-102

Sanchez-Bayo, F., Goka, K., 2014. Pesticide Residues and Bees – A Risk Assessment. PLOS ONE 9, e94482.

Van Dijk, T.C., Van Staalduinen, M.A. and Van der Sluijs, J.P. (2013) Macro-invertebrate decline in surface water polluted with imidacloprid. PLoS One, 8, e62374

Wood, T. & Goulson, D. 2017. The Environmental Risks of neonicotinoid pesticides: a review of the evidence post-2013. ENVIRONMENTAL SCIENCE & POLLUTION RESEARCH 24: 17285-17325.

Woodcock, B.A., Isaac, N.J.B., Bullock, J.M., Roy, D.B., Garthwaite, D.G., Crowe, A. and Pywell, R.F. (2016) Impacts of neonicotinoid use on long-term population changes in wild bees in England. Nature Communications, 7, 12459

Figure 1

(on next page)

Area of crop treated(blue line, hectares) and mass of pesticide applied (red line, kilograms) from1990 to 2015.

The total area of crop remained approximately constant at 4.6 million hectares. In 1990 each hectare of cropped land on average received a total of 7.5 kg of pesticide active ingredient delivered in 9.8 applications. By 2015 each hectare of land received 3.9 kg of pesticide in 17.4 applications.

Figure 1. Area of crop treated (blue line, hectares) and mass of pesticide applied (red line, kilograms) from 1990 to 2015. The total area of crop remained approximately constant at 4.6 million hectares. In 1990 each hectare of cropped land on average received a total of 7.5 kg of pesticide active ingredient delivered in 9.8 applications. By 2015 each hectare of land received 3.9 kg of pesticide in 17.4 applications.

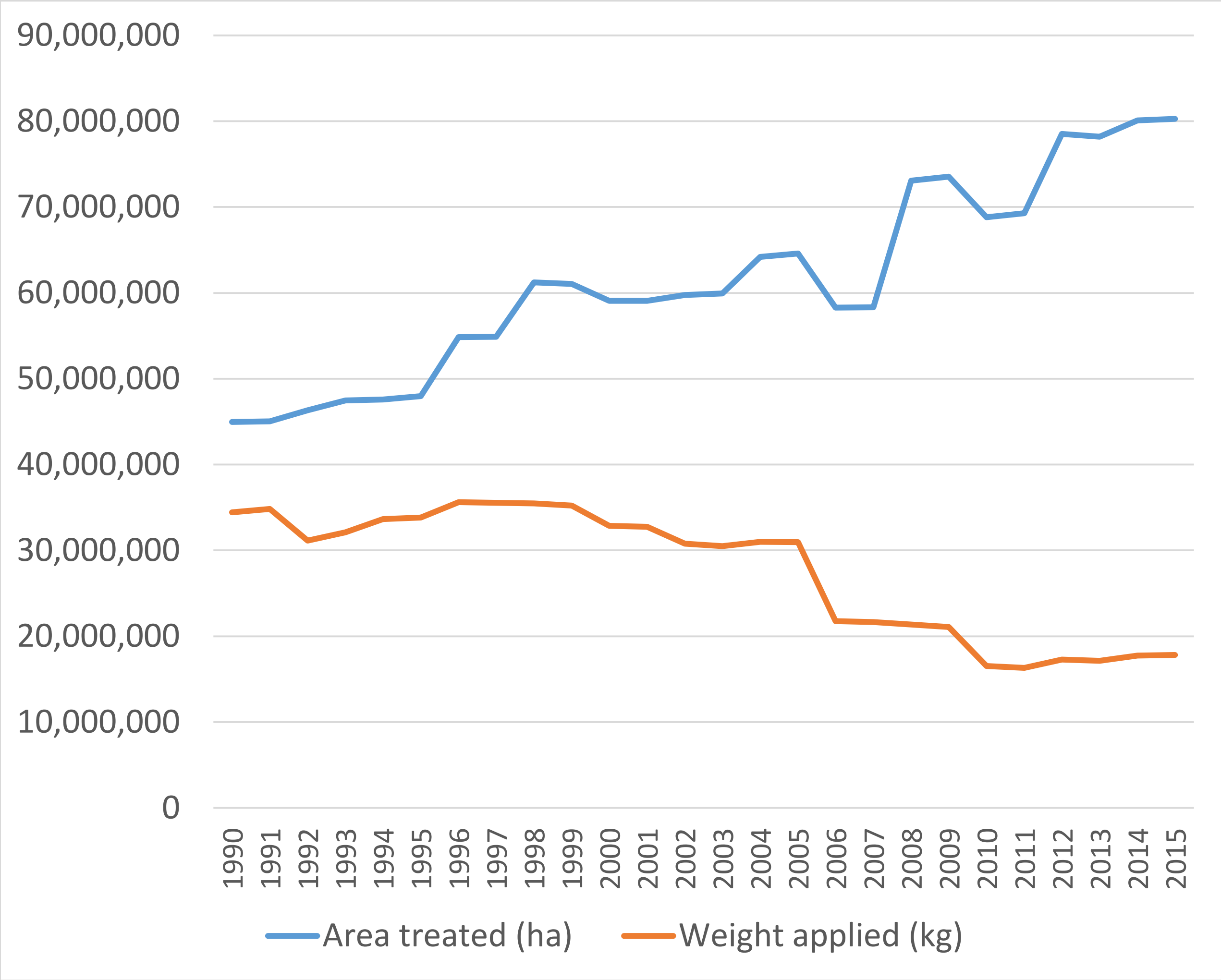

Figure 2 (on next page)

Potential number ofhoney bee LD_{50}s in pesticides applied to Great British farmland eachyear.

Data on pesticide use are collected by Department for the Environment, Farming and Rural Affairs (Defra 2018), UK.

PeerJ Preprints | https://doi.org/10.7287/peerj.preprints.26856v1 | CC BY 4.0 Open Access | rec: 15 Apr 2018, publ: 15 Apr 2018

Figure 2: Potential number of honey bee LD_{50}s in pesticides applied to Great British farmland each year.