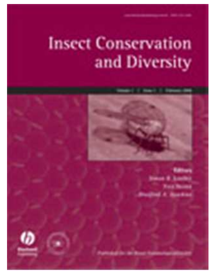
Neonicotinoids, bees and opportunity costs for conservation

by Walters, K.F.A.

DOI: http://dx.doi.org/10.1111/icad.12177

Walters, K.F.A. 2016. Neonicotinoids, bees and opportunity costs for conservation. *Insect Conservation and Diversity*, 9 (5), pp. 375-383.



Neonicotinoids, bees and opportunity costs for conservation

Journal:	*Insect Conservation and Diversity*
Manuscript ID	ICDIV-16-0008.R1
Manuscript Type:	Forum & Policy
Date Submitted by the Author:	n/a
Complete List of Authors:	Walters, Keith; Harper Adams University, Crop Sciences
Keywords:	Neonicotinoids, Neonicotinoid insecticides, EU Moratorium, IPM, Sustainable pest management, Ecosystem services, Conservation

Neonicotinoids, bees and opportunity costs for conservation

K. F. A. Walters

Harper Adams University, Newport, Shropshire, TF10 8NB, UK

Tel: 07552 689357

Email: kwalters@harper-adams.ac.uk

Running title: Neonicotinoids, bees and conservation costs

Abstract

1. Restrictions on the use of neonicotinoid insecticides in the European Union are widely debated in relation to bee decline, but their potential consequences at the interface between sustainable crop production and conservation are less frequently discussed.
2. This paper raises issues to be considered if we are to achieve a balanced consensus in this contentious area.
3. The common legal framework governing testing and environmental impact for all chemical crop protection products is highlighted, leading to concerns that the current focus on impact of neonicotinoids is diverting attention from other drivers of bee decline to the detriment of a balanced conservation strategy.
4. The evidence for the causal relationship between neonicotinoid use and bee decline is considered and information gaps requiring further work identified.
5. How research into the parallel use of pesticides and beneficial invertebrates in integrated pest management (IPM) can inform the pollinator debate is highlighted. The importance of the neonicotinoids in major IPM systems is illustrated, leading to discussion of potential consequences for conservation of biodiversity and sustainable crop protection if they were lost and we revert to reliance on other pest management tools.
6. Increasing agricultural production and conservation are sometimes viewed as being contradictory and the paper concludes by calling for a broadening of the debate to consider the complimentary objectives of bee conservation and sustainable crop production, so that advances in both fields can hasten consensus on the way forward, rather than perpetuating the current rather polarised debate.

Introduction

In a note to the 1884 edition of Old Mortality, Robert Louis Stevenson observes that "sooner or later everybody sits down to a banquet of consequences", a relevant warning when we consider the wider impacts of the current debate on the effect of neonicotinoid insecticides on pollinators.

The decline of bee species during the last 60 years has been attributed to various stressors including habitat loss, loss of floral diversity in key landscapes, predators, parasites, disease and pesticides (Goulson *et al*., 2015; Vanbergen *et al*., 2013; Ollerton *et al*., 2014). A key driver of public and environmental concern relating to bee decline has centred around the loss of the ecosystem services they provide, principally crop pollination, and conservation issues. It is, however, often not recognised that although wild bees contribute significantly to production of insect pollinated crops, this service delivery is limited to a small subset of known bee species (Kleijn *et al*., 2015). As these do not include many threatened species, the exposure to insecticides of those at-risk species is severely limited. The importance of diversity, however, in providing resilience through species redundancy or complementarity should be recognised (Brittain *et al*., 2013; Hoehn *et al*., 2008; Rader *et* al., 2012, 2013). Although bee decline has been more fully documented in Europe and North America, it is likely that common global drivers might be expected to produce similar outcomes in other continents (Carvalheiro *et al*., 2013; Koh *et al*., 2015). The decline in Europe commenced long before the introduction of neonicotinoids (Bonmarco *et al*., 2011; Carvalheiro *et al*., 2013) and they have been subject to and met the same registration requirements as all other pesticides currently used in EU crop production. Despite these observations, neonicotinoid insecticides have become a focus of attention as a potential driver of the decline (Blacquiere, 2012; Godfray *et al.*, 2014; Goulson, 2013). This led in 2013 to the European Union announcing a restriction on the use as seed treatments of three active ingredients (Imidacloprid, Thiamethoxam and Clothianidin) in bee attractive crops (EC, 2013), which is now commonly referred to as a moratorium.

Registration testing and conservation

To obtain registration for use in the EU, candidate active ingredients/products are subject to harmonised registration requirements (EC, 2009a) that can only be met after environmental hazard and safety has been established by extensive laboratory and field research. This work has to be generated under Good Laboratory Practice (GLP) or other stringent auditable quality standards, and conform to detailed guidelines originally established by independent experts (EPPO, 2010; OECD, 2013). The data are assessed by independent specialist scientists at national registration authorities, and use (subject to legally enforceable label restrictions) is allowed only after multiple criteria have been satisfied, including acceptably low risk of environmental damage. Unfortunately, such data are rarely published due to commercial considerations, thus this large body of evidence is not available or discussed by academics or environmental interest groups. This may have contributed to an imbalanced debate, with the strong focus on perceived impacts of a single class of insecticides drawing attention away from other key (perhaps more dominant) drivers of bee decline such as landscape change reducing floral resources and nest sites for bees, pests and disease (Vanbergen *et al*, 2013). Critically this has also detracted from research into, and development of, agricultural techniques that mitigate pesticide effects (Matthews *et al*., 2014). If such mitigation factors have significant effects on resultant risk then conservation efforts will not be well served by a narrow focus on neonicotinoids that draws attention away from achievable goals of improving landscapes to enhance botanical biodiversity.

Given the common legal framework enforces equally high environmental standards for all chemical crop protection products, why are the neonicotinoids so prominent in the debate when many authors suggest that other stressors (particularly landscape change/habitat) are more dominant drivers of pollinator decline (Vanbergen *et al*, 2013)? Many other questions arise but key issues include:

Is the evidence regarding hazards and risks posed by neonicotinoids conclusive?

Is the moratorium, which in the UK is leading to use of older (arguably more hazardous) chemistries (Nicholls, 2015), itself inadvertently raising serious concerns for conservation of biodiversity and sustainable crop production?

Such issues are of global, not just European importance as many countries are considering their future policy on neonicotinoid use.

Evidence and information gaps

If there is clear evidence that neonicotinoid insecticides on their own constitute a major factor in bee declines, then irrespective of the relative importance of other drivers the EU moratorium would be justified on conservation grounds.

The use of the products as seed treatments leading to pollinator exposure through translocation into nectar and pollen has received most attention in the current debate. Very low levels of the three active ingredients subject to the moratorium have been reported in pollen and nectar in treated commercial fields (EFSA 2013a, b, c), and some of these records undoubtedly result from improved analytical technology that has reduced detection limits (Walters, 2013). Exposure to low levels of these active ingredients does not necessarily result in significant risk as the dose delivered is often too low to stimulate either acute or chronic lethal or sub-lethal responses (Carreck & Ratnieks, 2014). This partly explains why predicted risks surrounding their use have not been confirmed in most field investigations (Cutler *et al*., 2014; Godfray *et al*., 2015; Rundlof *et al*., 2015).

Another aspect of use of treated seed has, however, led to some well reported large scale incidents in Germany, Italy and Slovenia in which acute honeybee losses resulted from dust generated during drilling of maize (Forster, 2012). If repeated across wider proportions of the agricultural landscape, such incidents would represent a serious challenge to conservation of biodiversity. Following investigation of the causes (which included poorly/improperly treated seed), legislators responded immediately to address the risk with extra registration requirements limiting dust generation and requiring use of deflectors to reduce contamination of surrounding vegetation with airborne dust (EU, 2010). These mitigation procedures were intended to prevent recurrence of similar incidents and contribute to the safeguarding of bee populations. The results of some widely discussed laboratory and field studies have, however, added to concerns fuelled by these incidents and some of these have been enhanced by sensationalist reporting in the media. Responses have also been demonstrated using a wide range of sub-lethal endpoints some of which have not been related to consequences at the colony or free-flying individual levels in either the laboratory or field but still were used in arguments favouring the moratorium (IPBES, 2016). Thus discussion in the popular press often conflates two issues, dust from drilling and sub-lethal effects that may result from oral exposure, and assumes colony level effects where these have not been definitively demonstrated, a point that is rarely recognised. None-the-less, if some of the resultant claims of neonicotinoid impacts on pollinators are correct then perhaps we should be worried, so how strong is the published evidence supporting the EU moratorium?

Worryingly, significant gaps in datasets used to defend the decision to introduce the moratorium have now been recognised. The research conducted has a narrow focus; most studies have investigated Imidacloprid (>70% laboratory studies and >85% field studies), but this active ingredient had to large extent been superseded in Europe as a seed treatment for relevant crops prior to the introduction of the moratorium (Walters, 2013**)**. Reliable extrapolation of the effects reported for imidacloprid to other neonicotinoids is prevented by variable characteristics of the active ingredients (Blacquiere *et al.,* 2012; Godfray *et al.*, 2014). For example, unlike thiamethoxam and clothianidin, imidacloprid displays wide variation in acute oral toxicity of (4-400 ng/bee). It also has several toxic plant metabolites in the pollen and nectar, differing again from thiamethoxam and clothianidin. In addition microsomal mono-oxygenase P450 enzymes do not appear as a major route of metabolism in bees, whereas P450 enzymes feature strongly in the metabolism of thiamethoxam and clothianidin, potentially reducing impact on bees (Thompson et al, 2014a). These differences, and others, underline the importance of considering such active ingredients individually to maximise our understanding of their impact on conservation issues

Additional gaps in the evidence-base presented in support of the moratorium are also evident; most studies investigate *Apis* species with few on other pollinators (including wild bees) despite the greater importance of wild pollinators as providers of ecosystem services (Blacquiere *et al.*, 2012; Garibaldi *et al.*, 2013; Godfray *et al*., 2014). This is important as there is growing evidence for variable responses to neonicotinoid exposure between bee taxa (Rundlof *et al*., 2015; Piiroinen & Goulson, 2016). For example, differential sensitivity of honeybees and bumblebees to a dietary insecticide (imidacloprid) have been reported, whereby following exposure bumblebees progressively developed a dose-dependent reduction in feeding rate, whereas honeybees did not (Cresswell, 2012). Further, the EFSA collations of data on neonicotinoid contamination of nectar and pollen under commercial field conditions demonstrate that bees showing effects in many laboratory experiments have been exposed to unrealistically high levels of pesticides when three key dosage characteristics (concentration, duration and choice) are taken into account (Carreck & Ratnieks, 2014). Complications in replicating field exposure are also magnified by the range of application technology used by farmers, which target insecticides at pests whilst reducing the exposure of non-target organisms (Matthews *et al*., 2014). This is a key but rarely discussed consideration if we are to simultaneously meet our essential conservation and sustainable food production targets.

Legislation governing pesticide use has also been strengthened to reduce environmental risk, coupled with operator training (a legal requirement in the UK aimed at maintaining both environmental and operator safety), that compliment these technological advances (EC 2009b; Matthews *et al*., 2014). Such rules governing pesticide use have not, however, been considered when interpreting the findings of many studies of pesticide impacts on pollinators. This exacerbates the problems associated with both extrapolation of experimental results to commercial field conditions, and drawing clear conclusions on conservation risk and mitigation.

A sub-set of these problems, particularly usage characteristics and dose rates, have beset field and semi-field studies, possibly explaining very different responses reported following exposure to neonicotinoids in commercial crops, with some authors recording no impact at either individual or colony levels whilst others note detrimental effects (Cutler & Scott-Dupree, 2014; Cutler *et al.,* 2014; Gill, R. J., *et al.*, 2012; Rundlöf *et al*., 2015). For example, high dose rates of two pesticides (a neonicotinoid and a pyrethroid) were used in a study investigating the effect of these active ingredients individually and in combination (Gill *et al*., 2012). In this case the imidacloprid dose rate was nearly an order of magnitude greater than the highest residue reported in nectar in any European commercial crop (data on commercial field residues from EFSA, 2012). The correct full label rate dilution for the pyrethroid spray was used but the volume applied per unit area resulted in a greater than permitted (in the EU) dose rate, resulting in over-exposure. A second example is provided by a study of effects of clothianidin applied to spring oilseed rape (Rundlöf *et al*., 2015). In this case the residues in pollen and nectar were again an order of magnitude higher than reported in any commercial fields in the EU, or in any previous field studies of this active ingredient (e.g. Cutler & Scott-Dupree, 2014). Although such investigations provide evidence of responses at very high exposure rates it is difficult to determine their significance within the more typical range encountered in commercial fields. Thus, if the outcomes are to be used in support of conservation decision making, it is essential that such studies be repeated at realistic exposure rates or scenarios.

The difficulties of reaching an overall consensus on future neonicotinoid use are also exacerbated by the challenge of publishing studies showing no-effects in high impact factor journals, which prevents the full range of evidence being placed in the public arena. If balanced conclusions on hazards posed are to be arrived at, editors should counter the bias towards publishing results showing positive effects which can lead to a misleading overview of real-environment responses due to promotion of data generated using supra-field exposure rates.

These problems with the evidence base, coupled with a failure to publish data generated for registration portfolios, may partly explain why an increasing number of studies appear to challenge the original decision to register the neonicotinoids for use. This is worrying as failure to accurately characterise and quantify hazards and risks posed by this class of insecticides, may give the appearance that the moratorium will have greater impact in halting bee decline than might ultimately occur. This would impede rather than support conservation efforts by diverting attention away from other critical drivers such as landscape change which require urgent and immediate research and action. Thus further well targeted, well designed and conclusive research is needed to fill the above data gaps. In addition, monitoring over time is required to understand the full consequences of either use or a ban on the use of neonicotinoids. Only then can the relative importance of neonicotinoid insecticides and other drivers be assessed and conservation responses properly reflect this balance. Failure to do so may result in our addressing the wrong problems. Currently, monitoring of the impact on crop production of the EU neonicotinoid ban in the UK is in its early stages and requires further time before clear conclusions emerge (Dewar & Walters, 2016).

There is growing concern that the resultant loss of neonicotinoids following the EU ban, and the consequential increased reliance on alternative pest management products may lead to increased rather than decreased environmental impacts on non-target organisms. If it does, it could impede efforts to develop sustainable pest management practices. Is this the case and what can be learnt from the extensive research relating to integrated pest management (IPM) that could inform this debate?

Perspectives from Integrated Pest Management

With the approaching review of the EU moratorium Raine & Gill (2015) correctly concluded that we must balance the risks of neonicotinoid exposure for insect pollinators and the value these pesticides provide to ensure crop yield and quality; does it matter if we lose these products?

As illustrated by the lack of publications, the highly focussed debate and large literature on the impact of this class of crop protection products on pollinators has hitherto not been matched by similar debate on their wider importance in crop production. The wide scale use of neonicotinoid pesticides in all major and many minor crops worldwide, and their importance in resistance management, illustrates their central role in agricultural production (Blacquiere *et* al., 2012; Goulson, 2013). It is therefore worrying that the relative environmental impact of possible alternative pest management products is rarely raised. Whereas occasional calls for us to evaluate alternative options for pest control (including IPM) have been made (Goulson *et al*., 2015), current use and importance of neonicotinoids in such systems is rarely highlighted (Budge *et al*., 2015; North *et al*., 2016). Further, the wider value of information on their impact on or compatibility with natural enemies is almost never considered when assessing impact on pollinators. With an increasing global population sustainable crop production is a priority concern which should complement not compete with conservation objectives, so what can be learnt from IPM research?

Transferable Biology: Narrow interpretation of outcomes of pollinator research can in some cases be avoided by considering information generated by IPM research. A recent study by Kessler *et al* (2015) investigating the proposal that bumblebees could detect and avoid neonicotinoid treated crops, came to the apparently contradictory conclusions that for imidacloprid and thiamethoxam they could not detect the active ingredient, consumed less contaminated nectar, but none-the-less foraged preferentially on treated nectar. In this case, irrespective of whether the bees consumed treated nectar preferentially, long established natural enemy research has shown that detection of a pesticide is not always necessary for reduction of predator exposure to treated food (Singh, 2001; Singh *et al*., 2004; Thornham *et al*., 2007). For example in well controlled laboratory experiments *Coccinella septempunctata* consumed fewer pesticide resistant aphids that had been pre-treated with active ingredients from other pesticide groups than untreated aphids, but choice tests indicated that they were unable to detect the low residue (approximately 19 nL) deposited on the aphid cuticle (Thornham *et al.,* 2007). It was concluded that physiological processes resulted in the observed temporary reduction in feeding rate while metabolic detoxification takes place thus protecting the biological control agent. This response has been used to facilitate IPM strategies when insecticides and *C. septempunctata* are used simultaneously. This is potentially important for interpretation of the bumblebee study (Kessler *et al*., 2015), as a similar reversible reduction in consumption of imidacloprid and thiamethoxam treated nectar substitute to those noted for Coccinellids had been demonstrated previously in bumblebees, using bioassays that generated no evidence of behavioural avoidance (Thompson *et al*., 2014b). Thus reference to the Coccinellid study may suggest a partial explanation of some of Kessler *et al*. findings without the need to invoke behavioural attraction or avoidance. Such work conducted on natural enemies for IPM can strategically inform work on pollinators in relation to responses to neonicotinoid (and other) insecticides. Similar improved integration of findings of IPM and pollinator research may support the avoidance of narrow interpretation, reducing the risk of misleading or incomplete information being used as a basis for conservation policy.

Compatibility with natural enemies and IPM: Research into IPM is, however, more central to the debate over the impacts of this insecticide class on pollinators and our mitigation strategy, than the simple provision of transferable biology. A little discussed consideration is the many reports of compatibility of neonicotinoid active ingredients with a wide range of biological control agents. Many studies have been conducted on the lethal and sub-lethal effects of a wide range of natural enemies or bio-control agents, from a broad range of taxonomic groups, which consider impact on both individual species and the natural enemy complexes that occur on crops (e.g. Cuthbertson *et al*. 2012; Roubos *et* al., 2014a; Shah *et al*. 2007; Smith & Krischik 1999; Vincent *et al.* 2000). The findings of these studies record widespread compatibility with non-target beneficial organisms at field realistic exposure rates, as is the case for many insecticides that have passed through current registration processes. As a result the neonicotinoids have been found to be both suitable for, and frequently are used as components of commercial IPM systems. The environmental impact of such compounds can also be further reduced by application methods that target the pest more closely, and availability in both spray and seed treatment formulations offers IPM specialists more options to reduce exposure of non-target organisms (Matthews, 2014), including pollinators. This should be taken into account when balancing conservation and crop production decision making.

In addition there is extensive research on farming approaches, operating at different scales, that facilitate combined use of naturally occurring predators and parasitoids (and potentially pollinators) with conventional insecticides (Roubos *et al*. 2014b). For example, at the farm scale, techniques that can be used to reduce impact of pesticide applications on non-target invertebrates include low doses, application method, spatial and temporal targeting of applications, selection of formulation and creation of refugia, amongst many others (Oakley *et* al., 1996; Roubos *et al*. 2014b). At the landscape scale, habitat quality and composition affect the magnitude of ecological services available, and also mitigate against the effects of pesticides on natural enemies. Current research is establishing the relative importance of local and landscape effects of pesticides on natural enemies and other ecosystem service provision to support government policy development and development of improved land management strategies (e.g. Kennedy *et al*. 2013; Roubos *et al*. 2014b). This work is yielding information of potential value to the pollinator debate.

IPM is context sensitive and locally adapted; to tailor such dynamic systems to local needs requires the availability of a range of insecticide products/classes to facilitate their use, and neonicotinoids often feature. The loss of a significant sub-set of this class of insecticides may thus impair the development of sustainable pest control approaches at the time when they have never been more important in crop production.

Such concerns would, of course, be lessened if key sustainable pest control systems for the major crops that rely on this class of insecticides did not currently exist. There are, however, multiple examples of key control systems that utilise these products. The concept of integrated control has been applied in Arizona (Naranjo and Ellsworth 2009); for example for more than 15 years *Bemisia tabac*i has been controlled on cotton using a strategy based on neonicotinoid insecticides. This has resulted in an estimated 70% reduction in foliar insecticide use, promoting both conservation/enhanced utilization of ecosystem services, with a saving to the industry of >$200 million (encouraging uptake). The system simultaneously promotes conservation of biodiversity and sustainable crop production and is thought to be so important that cross commodity guidelines for managing the use of the insecticide class are now in place to sustain efficacy (Palumbo *et al*. 2003).

This is by no means the only example of the use of neonicotinoids in sustainable management systems. Control strategies aimed at temperate climate fruit crops in Michigan have been effective against aphids, leafhoppers, and true fruit flies (depending on active ingredient) and have driven grower transition from broad spectrum insecticides to reduced-risk classes. Neonicotinoids are key to sustainable strategies for cotton in Australia (fundamental to successful IPM especially for control of secondary sucking pests such as mirids and *Aphis gossypii*, where emergence of neonicotinoid resistance resulted in substantial efforts to recover efficacy). Products based on this class of insecticides are central to sustainable pest management in cotton in India, grapes in Tunisia, invasive pests transported on world trade in plants and plant products, and many others (Chen et al. 2013; Cuthbertson *et* al., 2012; Daane *et* al., Herron & Wilson 2011; Mansour *et al*. 2010). Loss of neonicotinoids where no reduced-risk alternatives (tested for environmental hazard and registered for major commodities) are available will undermine continued use of such sustainable systems, progressive development of new ones, the ecosystem services they rely on, and drive the continued use of more broad-spectrum products. Such an eventuality would be to the detriment of efforts to conserve biodiversity in the agricultural landscape. We must consider that sustainable crop production and conservation of biodiversity should be complementary and not competitive, and management and conservation strategies must both be developed to reflect this principle if we are to make progress in solving the complex issues that we face.

Disruption of sustainable crop protection: This is not a theoretical problem but one that we already begin to encounter. Concerns are already being raised regarding the disruption of existing pest management strategies following the EU moratorium (e.g. Bird, 2015; Pucci, 2015), due to both loss of effective pest control and potential detrimental impact on natural enemy populations that exert incidental background pest suppression.

Nicholls (2013) reviewed the implications of the restriction of use of the neonicotinoids imidacloprid, clothianidin and thiamethoxam on crop protection in oilseeds and cereals in the UK.

Prior to the moratorium on their use UK crop production specialists recommended a single neonicotinoid seed treatment to control damage caused each year on oilseed rape by both cabbage stem flea beetle (CSFB; *Psylliodes chrysocephala)*, and aphid vectors of turnip yellows virus (*Myzus persicae*). Both species display pyrethroid resistance, and aphids are resistant to pirimicarb, the alternative registered active substances available for use. Consequently in the first two years after the moratorium was introduced many crops have received multiple sprays of older (potentially more environmentally hazardous) products. Despite such multiple treatments, CSFB incidence in key oilseed growing areas has significantly increased leading to substantial establishment failure (Nicholls, 2015; Pucci, 2015, Walters & Dewar, 2016).For example, initial figures have shown that 5% of the national crop sown in 2014 was lost during the establishment phase due to CSFB damage, 1.5% was replanted but 3.5% was abandoned (Nicholls, 2015). To this will be added any losses accrued from the impact of the aphid borne viruses transmitted in autumn (HGCA, 2013). Such losses vary between years dependent on a range of factors, important amongst which are aphid population size and weather at the time the crop is susceptible to infection. Yield depressions of up to 30% occur and result in farmers using insecticides to reduce transmission rates. The loss of neonicotinoid seed treatments has resulted in farmers now having to rely on more intensive use of older products despite the associated resistance problems noted above (HGCA, 2013).

There are also concerns that the current situation in UK oilseed rape might present challenges to our ongoing efforts to conserve the wild pollinator populations we are attempting to protect? Discussions in the farming press indicate that the increase in crop failure described above, an expectation that significant yield losses have resulted from reduced pest control, and worries about the resistance status and environmental effects of alternatives to neonicotinoid seed treatments, may lead to a reduction in the OSR acreage sown in the UK and elsewhere. Although Kleijn *et al*. (2015) suggest that many at-risk pollinator species do not appear frequently in mass flowering crops, such crops have been shown to be beneficial to bees such as non-*Bombus* generalist pollinators (Riedinger *et* al., 2015) thus loss of a proportion of the already restricted forage in the farming landscape may exacerbate conservation challenges.

The impact of the moratorium on the use of these products or, as some start to call for, its' broadening to encompass other neonicotinoid insecticides, must also be considered against the ongoing trend of increasing loss of available plant protection products. The report of The Anderson Centre on "The effect of the loss of plant protection products on UK agriculture and horticulture and the wider economy" identifies three main policies that they conclude threaten their availability in Europe/the UK (The Anderson Centre 2014). These include the approval process leading to pesticide registration at EU level, the implementation of the Water Framework Directive at national level which will influence/restrict the use of pesticide products, and restrictions on neonicotinoid seed treatments. They identify 87 of the current approximately 250 active substances as being threatened but suggest this is probably an underestimate. Of these, 59% of insecticides were classified as being at high risk of loss, and 41% as medium; none were low risk (The Anderson Centre 2014). As environmentally sustainable crop management requires the availability of a range of modes of action, then serious consideration must be given to this report when scientific advice is provided to policy makers reviewing the moratorium. A reversion to a narrow range of older chemistries is likely to risk the emergence of wider challenges and threats to both the natural environment and conservation efforts, particularly in agroecosystems. This problem is significantly under-represented in discussions and planning of the conservation of biodiversity and as a result may lead to serious unintended consequences if it emerges as a threat to worldwide food security through yield reductions. Under such circumstances it might, for example, lead to pressure for increasing the proportion of land devoted to agriculture to the detriment of natural environments.

Broadening the debate; risks and consequences

In conclusion, UN estimates that to keep pace with growing demand there needs to be a 70% increase in global food production by 2050 are widely reported (Godfray, 2010). The agricultural industry currently, therefore, faces a complex of contradictory challenges. Production targets need to be increased but this is made more difficult by the limited availability of land. The problem is exacerbated by the essential need to devote large areas of suitable land for conservation of biodiversity. In addition the impact of climate change (e.g. energy crops competing for land), a decreasing number of pesticides leading to frequent resistance problems (and associated damage to some ecosystem services), and financial constraints on production research (Godfray, 2010) add to the issues. To achieve the overall aim without causing unacceptable environmental damage requires sustainable intensification without making the mistakes of the 1960s (when application of crop protection products that have since been superseded, using approaches that have been changed and improved, resulted in significant non-target impact). Thus the targets have to be achieved in conjunction with associated (complimentary) conservation and biodiversity objectives. These challenges can be met within the important constraints imposed by conservation principles and objectives, but sustainable combined strategies will require a broad focus and balanced judgements based (in some cases) on more robust scientific evidence, that take account of a wide range of factors. Against a background of issues illustrated above, however, conservation outcomes are currently not well served by a too narrow focus on a single class of insecticides, particularly as they are widely considered not to be the principle driver of bee decline (Vanbergen *et al.*, 2013). Broadening of the debate to consider the complimentary objectives of bee conservation and sustainable crop production would therefore enable advances in both fields to be more readily used to hasten consensus on the way forward, surely preferable to our current polarised debate that reduces the prospect of such consensus being achieved.

If the narrowly focused European debate regarding the future of the neonicotinoids is not broadened to recognise the limitations of the current evidence base, take account of the full range of impinging issues, and adopt a balanced overview of the consequences accruing from the loss of a substantial proportion of a class of modern insecticides, then it will only add to the problems we face. If the evidence ultimately indicates that the risks identified outweigh the advantages of their use then the way forward is clear, but Raine and Gill (2015) are correct, we must "find the right balance between the risks of neonicotinoid exposure for insect pollinators and the value these pesticides provide to ensure crop yield and quality". Otherwise we may be at risk of making decisions which have far reaching impacts without taking a sufficiently holistic overview. Let us heed the warning of Robert Louis Stevenson.

References

Bird, J. (2015) EU Farmers blame 11% oilseed yield drop on neonic ban. *Agrow,* www.agra-net.com/agra/agrow/markets-regulatory/Europe/EU-farmers-blame-11-oilseed-yield-drop-on-neonic-ban--1.htm

Blacquiere, T., Smagghe, G., van Gestel, C.A.M. & Mommaerts, V. (2012) Neonicotinoids in bees: a review on concentrations, side effects and risk assessment. *Ecotoxicology*, **21**, 973–992.

Bonmarco, R., O. Lundin, H. G. Smith, and M. Rundlöf. (2011) Drastic historic shifts in bumble-bee community composition in Sweden. *Proceedings of the Royal Society B: Biological Sciences* **279**, 309-315.

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

Budge, G.E., Garthwaite, D., Crowe, A., Boatman, N.D., Delaplane, K.S., Brown, M.A., Thygesen, H.H. & Piretravalle, S. (2015) Evidence for pollinator cost and farming benefits of neonicotinoid seed coatings on oilseed rape. *Scientific Reports* **5**, 12574DOI:10.1038/srep12574

Carreck, N.L & Ratnieks, F.L.W. (2014) The dose makes the poison: have "field realistic" rates of exposure of bees to neonicotinoid insecticides been overestimated in laboratory studies? *Journal of Apicultural Research*, **53**, 607-614.

Carvalheiro L.G., Kunin W.E., Keil P., Aguirre-Gutiérrez J., Ellis W.N., Fox R., Groom Q., Hennekens S., Van Landuyt W.,Maes D., van de Meutter F., Michez D, Rasmont P., Ode B., Potts S.G., Reemer M., Roberts S.P., Schaminée J., WallisDeVries M.F., & Biesmeijer J.C (2013) Species richness declines and biotic homogenisation have slowed down for NW-European pollinators and plants**.** *Ecological Letters* **16**(7) 870-878.

Chen, Y., Vanlerberghe-Masutti, F., Wilson, L.J., Barchia, I., McLoon, M.O., Smith, T. & Herron, G.A. (2013) Evidence of superclones in Australian cotton aphid Aphis gossypii Glover (Aphididae: Hemiptera). *Pest Management Science*, **69**, 938-948.

Cresswell, J.E., Page, C.J., Uygun, M.B., Holmbergh, M., Li, Y., Wheeler, J.G., Laycock, I., Pook, Ibarra, N.H. de., Smirnoff, N. & Tyler, C.R. (2012) Differential sensitivity of honey bees and bumblebees to a dietary insecticide (imidacloprid). *Zoology* **115**, 365-371.

Cuthbertson, A.G.S., Mathers, J.J., Croft, P., Nattriss, N., Blackburn, L.F., Luo, W., Northing, P., Muari, T., Jacobson, R.J. & Walters, K.F.A. (2012) Prey consumption rates and compatibility with pesticides of four predatory mites from the family Phytoseiidae attacking *Thrips palmi* Karny (Thysanoptera: Thripidae). *Pest Management Science*, **68**, 1289–1295.

Cutler, G.C. & Scott-Dupree, S.D. (2014) A field study examining the effects of exposure to neonicotinoid seed-treated corn on commercial bumble bee colonies *Ecotoxicology*, **23**, 1755–1763.

Cutler, G.C., Scott-Dupree, C.D., Sultan, M., McFarlane, A.D. & Brewer, L. (2014) A large-scale field study examining effects of exposure to clothianidin seed-treated canola on honey bee colony health, development, and overwintering success. *PeerJ* 2, e652 https://dx.doi.org/10.7717/peerj.652

Dewar, A.M. & Walters, K.F.A. (2016) BCPC Pests and Beneficials Group Inaugural Review Meeting – Can we continue to grow oilseed rape? A report of the recent meeting on oilseed rape pest control at NIAB Park Farm, Cambridge, UK. (in press).

EC (2009a) EC 1107/2009 Regulation (EC) No 1107/2009 of the European Parliament and of the Council of 21 October 2009 concerning the placing of plant protection products on the market and repealing Council Directives 79/117/EEC and 91/414/EEC.

EC (2009b) DIRECTIVE 2009/128/EC of the European Parliament and of the Council of 21 October 2009 establishing a framework for Community action to achieve the sustainable use of pesticides. *Official Journal of the European Union*, 309/71-86.

EC (2013) Commission implementing regulation (EU) No 485/2013 of 24 May 2013 amending Implementing Regulation (EU) No 540/2011, as regards the conditions of approval of the active substances clothianidin, thiamethoxam and imidacloprid, and prohibiting the use and sale of seeds treated with plant protection products containing those active substances. *Official Journal of the European Union*, 139/12–26.

EFSA (2013a) Conclusion on the peer review of the pesticide risk assessment for bees for the active substance imidacloprid. *EFSA Journal* **11(1)**, 3068, 55pp.

EFSA (2013b) Conclusion on the peer review of the pesticide risk assessment for bees for the active substance clothianidin. *EFSA Journal* **11 (1)**: 3066, 58pp.

EFSA (2013c) Conclusion on the peer review of the pesticide risk assessment for bees for the active substance thiamethoxam. *EFSA Journal* **11 (1)**: 3067, 68pp.

Ellsworth, P.C., Palumbo, J.C., Naranjo, S.E., Dennehy, T.J. & Nichols, R.L. (2006) Whitefly Management in Arizona Cotton 2006. [Online]. *IPM Series 18, Publ. No. AZ1404, University of Arizona, College of Agriculture and Life Sciences, Cooperative Extension, Tucson, AZ*, 4 pp. Available: http://cals.arizona.edu/pubs/insects/ az1404.pdf [accessed: 26 June 2016].

EPPO (2010) Environmental risk assessment scheme for plant protection products; Honeybees. *OEPP/EPPO Bulletin*, **40**, 323–331.

EU (2010) Commission Directive 2010/21/EU of 12 March 2010 amending Annex 1 to Council Directive 91/414/EEC as regards the specific provisions relating to clothianidin, thiamethoxam, Fipronil and Imidacloprid. *Official Journal of the European Union*, **L65/27**

Forster, R. (2012) Risk mitigation measures for seed treatments using neonicotinoids. Proceedings 11th International Symposium of the IC-PBR Bee Protection Group, Wageningen (The Netherlands), November 2-4, 2011. *Julius-Kühn-Archive* **437**, 63-68. http://dx.doi.org/10.5073/jka.2012.437.013

Garibaldi, L.A., Steffan-Dewenter, I., Winfree, R., Aizen, M.A. *et al*. (2013) Wild pollinators enhance fruit set of crops regardless of honey bee abundance. *Science*, **33**, 1608-1611.

Gill, R. J., Ramos-Rodriguez, O. & Raine, N. E. (2012) Combined pesticide exposure severely affects individual- and colony-level traits in bees. *Nature*, **491**, 105–108.

Godfray, H.C.J., Beddington, J.R., Crute, I.R., Haddad, L., Lawrence, D., Muir, J.F., Pretty, J., Robinson, S., Thomas, S.M. & Toulmin, C. (2010) Food security: The challenge of feeding 9 Billion People. *Science*, **327 (5967)**, 812-818.

Godfray, H.C.J., Blacquière, T., Field, L.M., Hails, R.S., Petrokofsky, G., Potts, S.G., Raine, N.E., Vanbergen, A.J. & McLean, A.R. (2014) A restatement of the natural science evidence base concerning neonicotinoid insecticides and insect pollinators. *Proceedings Royal Society B* **281**, http://dx.doi.org/10.1098/rspb.2014.0558

Godfray, H.C.J., Blacquière, T., Field, L.M., Hails, R.S., Potts, S.G., Raine, N.E., Vanbergen, A.J. & McLean, A.R. (2015) A restatement of recent advances in the natural science evidence base cocerning neonicotinoid insecticides and insect pollinators. *Proceedings Royal Society B* **282**, http://dx.doi.org/10.1098/rspb.2015.1821

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) Bee declines driven by combined stress from parasites, pesticides, and lack of flowers. *ScienceExpress* http://dx.doi.org/10.1126/Science.1255957

Herron, G.A. & Wilson, L.J. (2011) Neonicotinoid resistance in *Aphis gossypii* Glover (Aphididae: Hemiptera) from Australian cotton. *Australian Journal of Entomology*, **50**, 93–98.

HGCA (2013) Will aphid borne virus problems increase? HGCA Hand Out No. 6. www.cereals.ahdb.org.uk/hgca/cereals 2013/handouts/ho6.pdf

Hoehn P., Tscharntke T., Tyianakis J.M., & Steffan-Dewenter I. (2008) Functional group diversity of bee pollinators increases crop yield. *Proceedings of the Royal Society - B- Biological Sciences,* **275,** 2283-2291

IPBES, 2016 IPBES (2016): Summary for policymakers of the assessment report of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services on pollinators, pollination and food production. S.G. Potts, V. L. Imperatriz-Fonseca, H. T. Ngo, J. C. Biesmeijer, T. D. Breeze, L. V. Dicks, L. A. Garibaldi, R. Hill, J. Settele, A. J. Vanbergen, M. A. Aizen, S. A. Cunningham, C. Eardley, B. M. Freitas, N. Gallai, P. G. Kevan, A. Kovács-Hostyánszki, P. K. Kwapong, J. Li, X. Li, D. J. Martins, G. Nates-Parra, J. S. Pettis, R. Rader, and B. F. Viana (eds.). IPBES, Bonn, Germany pp. 1–28.

Kennedy, C.M., Lonsdorf, E., Neel, M.C., *et al*. (2013) A global quantitative synthesis of local and landscape effects on wild bee pollinators in agroecosystems. *Ecology Letters*, **16**, 584–599

Kessler, S.C., Tiedeken, E.J., Simcock, K.L., Derveau, S., Mitchell, J., Softley, S., Stout, J.C., Wright, G.A. (2015) Bees prefer foods containing neonicotinoid pesticides. *Nature*, http://dx.doi.org/10.1038/nature14414 (2015)

Kleijn, D., Winfree, R., Bartomeus, I., Carvalheiro, L.G. *et al*. (2015) Delivery of crop pollination services is an insufficient argument for wild pollinator conservation. *Nature Communications*, DOI: 10.1038/ncomms8414

Mansour, R., Youssfi, F.E., Lebdi, K.G. & Rezgui, S. (2010) Imidacloprid applied through drip irrigation as a new promising alternative to control mealybugs in Tunisian vineyards. *Journal of Plant Protection Research*, **50**, 314-319.

Matthews, G., Bateman, R. & Miller, P. (2014) Pesticide Application Methods, 4th Edition. Wiley-Blackwell 536pp. ISBN: 978-1-118-35130-7

Naranjo, S.E. & Ellsworth, P.C. (2009) Fifty years of the integrated control concept: moving the model and implementation forward in Arizona. *Pest Management Science*, **65**, 1267–1286.

Nicholls, C. (2013) Implications of the restriction on the neonicotinoids: imidacloprid, clothianidin and thiamethoxam on crop protection in oilseeds and cereals in the UK. *HGCA Research Review No. 77*. www.cereals.ahdb.org.uk

Nicholls, C. (2015) Assessing the impact of the restrictions on the use of neonicotinoid seed treatments. www.hgca.com/media/632560/Neonicotinoids-planting-survey-report

North, J.H., Gore, J., Catchot, A.L., Stewart, S.D., Lorenz, G.M., Musser, F.R., Cook, D.R., Kerns, D.L. & Dodds, D.M. (2016) Value of neonicotinoid insecticide seed treatments in mid-south soybean (glycine max) production systems. *Journal of Economic Entomology* doi10.1093/jee/tow035

Oakley, J.N., Walters, K.F.A., Ellis, S.A., Green, D.B., Watling, M. & Young, J.E.B. (1996) Development of selective aphicide treatments for integrated control of summer aphids in winter wheat. *Annals of Applied Biology*, **128**, 423-436.

OECD (2013) OECD Guidelines for the testing of chemicals, Section 2 *Effects on biotic systems*. www.oecd-ilibrary.org/environment/oecd-guidelines-for-the-testing-of-chemicals-section-2-effects-on-biotic-systems_20745761

Ollerton J., Erenler H., Edwards M., & Crockett R. (2014) Extinctions of aculeate pollinators in Britain and the role of large scale agricultural changes. *Sciences* **346**, 1360-1362.

Palumbo J.C., Ellsworth P.C., Dennehy T.J. & Nichols R.L. (2003) *Cross commodity guidelines for neonicotinoid insecticides in Arizona*. [Online]. *IPM Series 17, Publ. No. AZ1319, University of Arizona, College of Agriculture and Life Sciences, Cooperative Extension, Tucson, AZ, 4 pp*. Available: http://cals.arizona.edu/pubs/insects/az1319.pdf [accessed: 26 June 2016]

Piiroinen, S. & Goulson, D. (2016) Chronic neonicotinoid pesticide exposure and parasite stress differentially affects learningin honeybees and bumblebees. *Proceedings of The Royal Society B* 20160246.

Pucci, J (2015) EU Farmers feel first hit of neonicotinoid ban. Farm Chemicals International. November 2015, 12-15.

Rader R., Howlett B.G., Cunningham, S. A., Westcott, D.A. & Edwards, W. (2012) Spatial and temporal variation in pollinator effectiveness: do unmanaged insects provide consistent pollination services to mass flowering crops? *Journal of Applied Ecology* **49**, 126-134.

Rader R., Reilly J., Bartomeus I., & Winfree, R. (2013) Native bees buffer the negative impact of climate warming on honey bee pollination of watermelon crops. Global Change Biology **19**, 3103-3110.

Raine, N. & Gill, R.J. (2015) Ecology: Tasteless pesticides affect bees in the field *Nature*, http://dx. doi:10.1038/nature14391

Riedinger, V., Mitesser, O., Hovestadt, T., Steffan-Dewenter, I., Holzschuh, A. (2015). Annual dynamics of wild bee densities: attractiveness and productivity effects of oilseed rape. Ecology**,** 1351–1360.

Roubos, C.R., Rodriguez-Saona, C., Holdcraft, R., Mason, K.S. & Isaacs, R. (2014a) Relative toxicity and residual activity of insecticides used in blueberry pest management: Mortality of natural enemies. *Journal of Economic Entomology*, **107**, 277-285.

Roubos, C.R., Rodriguez-Saona, C. & Isaacs, R. (2014b) Mitigating the effects of insecticides on arthropod biological control at field and landscape scales. *Biological Control – Special Issue on Impact of Environmental Change on Biological Control*, **75**, 28-38.

Rundlöf, M., Andersson G.K.S. & Bonmarco, R., Fries, I. et al. (2015) Seed coating with a neonicotinoid insecticide negatively affects wild bees. *Nature*, **521**, 77–80.

Shah, F.A., Ansari, M.A., Prasad, M. & Butt, T.M. (2007) Evaluation of black vine weevil (*Otiorhynchus sulcatus*) control strategies using *Metarhizium anisopliae* with sublethal doses of insecticides in disparate horticultural growing media. *Biological Control*, **40**, 246–252.

Singh, R.R. (2001). The behaviour of the ladybird, *Coccinella septempunctata*, in response to sub-lethal doses of insecticide. *PhD Thesis, University of Newcastle-upon-Tyne, UK.*

Singh, SR; Walters, KFA; Port, GR; Northing, P (2004). Consumption rates and predatory activity of adult and fourth instar larvae of the seven spot ladybird *Coccinella septempunctata* (L.), following contact with dimethoate residues and contaminated prey in laboratory arenas. *Biological Control* **30,** 127-133.

Smith, S.F. & Krischik, V.A. (1999) Effects of Systemic Imidacloprid on *Coleomegilla maculata* (Coleoptera: Coccinellidae). *Environmental Entomology*, **28**, 1189-1195.

The Anderson Centre (2014). The effect of the loss of plant protection products on UK agriculture and horticulture and the wider economy. www.nfuonline.com/andersons-final-report/

Thompson, H.M., Fryday, S.L., Harkin, S. & Milner, S. (2014a) Potential impact of synergism in honeybees (*Apis mellifera*) of exposure to neonicotinoids and sprayed fungicides in crops. *Apidologie*, **45**, 545-553.

Thompson, H.M., Wilkins, S., Harkin, S., Milner, S. & Walters, K.F.A. (2014b) Neonicotinoids and bumble bees (Bombus terrestris): Effects on nectar consumption in individual workers. *Pest Management Science,* DOI: 10.1002/ps.3868

Thornham, D.G., Stamp, C., Walters, K.F.A., Mathers, J.J., Wakefield, M., Blackwell, A. & Evans, K.A. (2007) Feeding responses of adult seven-spotted ladybirds, *Coccinella septempunctata* (Coleoptera, Coccinellidae), to insecticide contaminated prey in laboratory arenas. *Biocontrol Science and Technology*, **17**, 983-994.

Vanbergen, A.J. and The Insect Pollinators Initiative (2013) Threats to an ecosystem service: pressures on pollinators. *Frontiers in Ecology and the Environment*, http://dx.doi.org/10.1890/120126

Vincent, C., Ferran, A., Guige, L., Gambier, J. & Brun, J. (2000) Effects of imidacloprid on *Harmonia axyridis* (Coleoptera: Coccinellidae) larval biology and locomotory behaviour. *European Journal of Entomology*, **97**, 501-506.

Walters K.F.A (2013). Data, data everywhere but we don't know what to think? Neonicotinoid insecticides and pollinators. *Outlooks Pest Management*, **24**, 151–155.