Available online at www.sciencedirect.com

ScienceDirect

Current Opinion in Insect Science

Pollinator conservation requires a stronger and broader application of the precautionary principle☆

Laura Drivdal[1] and Jeroen P van der Sluijs[1,2]

The accumulating scientific evidence on global insect and pollinator decline is fuelling calls for pollinator conservation policies. A broad range of regulating and incentivising policies is undoubtedly needed to address the diverse threats to pollinator abundance and diversity, but implementing policies and regulations is beset by socio-political challenges. Lessons could be learned from the past and current applications of concepts central to biodiversity conservation. Given the uncertainties and data gaps, the concept of the Precautionary Principle (PP) is particularly important. The PP means that when it is scientifically plausible that human activities may lead to morally unacceptable harm, actions shall be taken to avoid or diminish that harm: uncertainty should not be an excuse to delay action. This paper reviews the role of the PP in pollinator conservation. The current research front is fragmented: the PP is briefly mentioned as relevant in literature on biodiversity conservation because of the scientific uncertainties regarding insect decline and their diverse drivers. A separate strand of literature contains studies on specific cases where the PP has played a role in the regulation of specific threats to pollinators: systemic insecticides and global trade in bees. Although limited to two significant threats to pollinator abundance and diversity, these studies provide important lessons on the challenges of implementing precautionary pollinator conservation policies and underline socio-political aspects of the 'human-dimensions' of pollinator conservation. Specifically, they highlight that ambiguity is a greater challenge than scientific uncertainty, which may be heightened when policies are intended to regulate specific economic sectors. We suggest that more attention should be paid to the discrepancy between the PP as formally included in policies or regulations and its inadequate implementation (too little too late) in a context of scientific uncertainty and societal conflict.

Addresses
[1] Centre for the Study of the Sciences and the Humanities, University of Bergen, PB 7805, 5020 Bergen, Norway
[2] Department of Chemistry, University of Bergen, PB 7805, 5020 Bergen, Norway

Corresponding author: van der Sluijs, Jeroen P (jeroen.sluijs@uib.no)

Current Opinion in Insect Science 2021, **46**:95–105

This review comes from a themed issue on **Pollinator decline: human and policy dimensions**

Edited by **Jeroen P van der Sluijs**, **Stéphane Foucart** and **Jérôme Casas**

For a complete overview see the Issue and the Editorial

Available online 28th April 2021

https://doi.org/10.1016/j.cois.2021.04.005

Introduction

Pollinator decline, and more broadly global insect decline, is increasingly recognised as an emerging global environmental risk urgently requiring an internationally coordinated and integrated policy response [1•,2–5]. Major data gaps prevail, limiting our knowledge on the global status of insects. The best studied declining entomofauna of concern are the insect pollinators, of which the best studied are bees. A recent study indicates that worldwide, between 2006 and 2015, 25% fewer species of wild bees were seen than was the case before 1990 [6•]. The European Red List for bees shows that the populations of 46% of Europe's bumblebees (the best studied subgroup) are declining [7]. Despite the calls from scientists and the public to develop international and national policies to address pollinator declines, governments have not delivered on legislation [2]. Pollinator decline constitutes a typical post-normal science [8] problem: being essential for global food security and ecosystem resilience [1•,2] the stakes for pollinator conservation are high, while facts are uncertain and contested, values are disputed and decisions are urgently needed. In such situations, science advisers and policymakers typically struggle to make sense of science under conditions of uncertainty and complexity [9••], which can lead to *paralysis by analysis*: continuous calls for better knowledge and prevailing hesitancy to act despite ever-stronger warning signals. The literature presents a wide range of drivers and causes

☆ Given his role as Guest Editor, Jeroen van der Sluijs had no involvement in the peer-review of this article and has no access to information regarding its peer-review. Full responsibility for the editorial process for this article was delegated to Jérôme Casas.

of insect decline and there does indeed appear to be limited consensus about their relative importance [1•,4,10•,11]; they include the intensification of agriculture with its accompanying loss of natural habitats and loss of foraging and nesting resources, the large-scale use of agrochemicals (such as insecticides, fungicides, herbicides and fertilisers), nitrogen deposition, land-use change (especially deforestation), climate change, invasive species, spread of pathogens, urbanisation and widespread nocturnal light pollution.

Suggestions are emerging for policies to conserve and restore insect and pollinator populations and diversity [1•,12,13•,14••,15], but it is clear that a diverse set of policies and regulations is needed to protect and restore pollinator abundance and diversity. Dicks *et al.* [12] stress that conventional conservation policies of creating protected areas and identifying threatened species are not sufficient and that a broad range of regulating and incentivising policies is necessary to address the myriad of threats to pollinator abundance and diversity. For the successful development and implementation of policies, we need to pay more attention to human dimensions [16•] and the variation of local policies [13•]. One aspect of this, are the socio-political challenges that may appear in risk management and the implementation of regulations or policies, especially in a context of prevailing scientific uncertainty. Insights on this aspect could be found in literature describing applications of concepts central to biodiversity management. In this paper, we focus on the literature that mentions or discuss the Precautionary Principle (PP) in pollinator/insect conservation issues. We further build on our earlier [17,18••,19] and ongoing [20,21] work on the precautionary principle and the second author's 15-year track-record in studying risk assessment and risk governance of neonicotinoid insecticides. The PP can be seen both as a general approach, for example, conserving biodiversity, and as a legal principle that enables decision makers to regulate risks that threaten environment or health despite prevailing scientific uncertainty. It has been incorporated into national and international biodiversity-related law and policies [22] and is particularly relevant to environmental law, which depends on complex and often uncertain science [23].

The precautionary principle

Initially, national and international environmental policies typically adopted a curative approach to environmental damage caused by human activities, in the form of the Polluter Pays Principle [24••]. That principle turned out to be practicable only if accompanied by a preventive policy aiming at limiting damage to what can be repaired or compensated for: for instance, species extinction cannot be repaired. Subsequently, the curative approach was complemented with a 'prevention is better than cure' model. This stage was characterised by the idea that science can reliably assess and quantify risks and can know all the consequences of human activities, and the Principle of Prevention could be used to avoid or diminish further damage. The emergence of increasingly unpredictable, uncertain, unquantifiable and possibly catastrophic risks with irreversible impacts, such as those associated with biodiversity loss, gene drives, climate change, and so on, has confronted societies with the need to develop a third, anticipatory model to protect humans and the environment against the uncertain risks of human action: the PP [24••]. The PP is used to justify policy interventions in cases where scientific evidence of risk is insufficient, inconclusive or uncertain and preliminary objective scientific evaluation has indicated that there are reasonable grounds for concern that the potentially dangerous effects on the environment, human, animal or plant health may be unacceptable (Communication from the Commission on the Precautionary Principle). It means that when it is scientifically plausible that human activities may lead to morally unacceptable harm, actions shall be taken to avoid or diminish that harm [17]. The application of the PP does not prescribe a particular course of action: varying degrees of precaution may be taken, from strong to weak.

As a legal principle, the PP particularly pertains to the making of law and policy intended to protect the environment, which depends on complex and often uncertain science [23]. Formally, the PP has been incorporated into laws and policies on biodiversity conservation at international, regional and national level, with a focus on biodiversity, fisheries, forestry, invasive alien species, and trade [22]. In Principle 15 of the 1992 Rio Declaration (Rio Declaration on Environment and Development), the United Nations jointly declared that its member states shall widely apply the PP to prevent further environmental degradation. Principle 10 of the Rio Declaration recognizes that the PP requires that individuals have full access to information concerning the environment, which has later been implemented in the UN Aarhus Convention on Access to Information, Public Participation in Decision-making and Access to Justice in Environmental Matters (Aarhus Convention). While the Rio Declaration is in a way morally binding, it is not legally binding, and the extent to which the PP has been incorporated into regulatory law varies substantially between different countries and regions [25]. In the EU, it has become a core principle in environmental law and has also been incorporated into secondary legislation (EU Regulations and EU Directives). A recent comprehensive study on the implementation of the PP in Europe found that environment and agriculture were among the three policy fields in the EU in which the PP was mentioned most often [20]. Both these policy fields are relevant to pollinator conservation. Surprisingly, the PP is not mentioned in the Bird Directive or the Habitats Directive [23].

In practice, the PP can be invoked in regulations of products or processes that may have poorly foreseeable negative consequences for human health or the environment. In the context of the conservation of biodiversity, new technologies or processes sometimes do indeed pose novel risks [22]. However, because it can be used to regulate economic initiatives and innovations, and because placing the burden of proof on companies increases their costs and involves them in lengthy bureaucratic procedures before they can place a product on the market, the PP has come under fire from large corporations and industry: for example, in relation to trade agreements [26]. Such challenges are also found in case studies on the applicability and use of the PP in biodiversity conservation and natural resource management [27]. Further, an inherent problem of implementing the PP as a legal principle in environmental law is that jurists and scientists can be said to have different approaches to uncertainty: *while legal rules are meant to provide predictability, nature is unpredictable; while the jurist seeks certainty, the scientist points to the uncertainty inherent in ecological risk* [23, p. 4].

PP as a general approach in pollinator conservation

Pollinator conservation is part of the broader field of biodiversity conservation, and it has been argued that the PP basically underlies all international conservation efforts [22,27]. However, the PP is rarely mentioned in current literature on pollinator and/or insect decline. Some recent papers on policies for pollinator conservation do not mention it at all, one being the paper in which Dicks *et al.* suggest 10 policies for governments to consider in pollinator conservation [12]. These are broad and general policies and include both regulative and incentivising policies. Two of these policies concern risk regulation where the PP has been applied in practice: pesticide regulation and regulation of transboundary pollinator trade. As we will show in the following sections, these are the two issues where we have found empirical studies mentioning the application of PP in relation to topics relevant to pollinator conservation.

A few books and articles on pollinator/insect conservation do mention the PP. In these brief mentions, the PP is understood more as a **general approach** relevant to the conservation of insect biodiversity because of the great uncertainty and lack of knowledge on insect species and their functions. Hawksworth, for instance, notes: *as we know so little of the possible consequences of the loss of any single species, the precautionary approach is possibly the only pragmatic and responsible one when considering the conservation of biodiversity in such groups* [28, p. 2865]. In the recent comprehensive book on insect conservation by Samways [29], the PP is mentioned briefly a few times. Samways argues that the PP is a starting point for conservation planning and that we need to conserve as many species as possible because we do not know their function. We should not wait until more knowledge has been acquired. Similarly, a recent paper also urges us to act despite our imperfect knowledge of the complexity of the drivers of pollinator decline [30]. All the aforementioned recent papers highlight the urgency to act even though there is scientific uncertainty — and the PP is relevant in that sense because it fundamentally aims at enabling action despite such uncertainty. On the other hand, it has recently been argued [31] that the decrease in scientific uncertainty about the reasons for the decline of wild bees justifies moving on from the PP; instead, it would be logical to apply the Principle of Prevention when formulating policy to conserve pollinators. However, the more empirically based studies we discuss below show that scientific uncertainty is perceived very differently by different scientists and stakeholders and in different sectors, and that the same body of (limited) evidence can be interpreted differently. This brings us into the domain in which the PP can best guide policy making.

The PP in the regulation of specific threats to pollinators

Two strands of literature contain case studies in which the PP played a role in regulating pollinator threats: studies on the regulation of neonicotinoid insecticides due to their adverse effects on bees, and studies on the regulations regarding the international trade in managed bees that are a threat to local biodiversity and the health of native bees. It should be noted that this does not imply that the PP is not applied in the regulation of other pollinator threats in practice, but it was only in these two fields where we found peer-reviewed academic studies that explicitly analyse, describe, or mention the PP.

The first topic concerns the role of the PP in the regulation of **neonicotinoids** (henceforth referred to as neonics), a specific class of insecticides that are neurotoxic to insects and have been found to cause serious unintended harm to beneficial insects like pollinators. When used as a seed-coating, these systemic pesticides are taken up by the roots of the germinating seed and enter the plant sap; as the plant grows, the neonic is translocated to all parts of the plant, making the plant toxic to insects, with the aim of providing long-term protection against insect pests. As a direct consequence of the systemic action of neonics, the pollen and nectar of treated crops and of wildflowers in or around the fields of treated crops also contain traces of the nerve poison in non-deadly, yet harmful concentrations. Thus, not only insect pests but also beneficial insects such as bees and other pollinators are exposed to low doses as they forage. Neonics are over 7000 times more toxic to honeybees than the insecticide DDT [32]. At field-realistic exposure levels, neonics are known to produce a wide range of adverse sublethal effects in honeybee colonies and bumblebee colonies, affecting colony performance by impairing navigation, foraging success, brood and larval development, memory and learning, by disturbing vision and sleep, by damaging the central nervous system and immune system, by increasing susceptibility to diseases and parasites, impairing hive hygiene, reducing bumblebee queen-production, and so on [32]. Further, chronic exposure to very low doses is ultimately fatal for insects because, unusually, the toxicity of neonics is amplified by exposure time [32].

Since the 1990s, neonics have become the most widely used class of insecticides globally and have dramatically transformed the agrochemical landscape for pollinators as a consequence of their large-scale prophylactic use in combination with their unprecedentedly high toxicity for bees [33]. Recent studies have shown that neonics are by far the greatest toxic threat to insects of farmland [33,34•,35]: considering all the agrochemicals applied to farmland (fungicides, herbicides and insecticides), neonic insecticides alone are responsible for a sixfold increase in the toxicity of farmland to bees in the UK in the period 1990–2015 [33]. In the US, toxicity of farmland to bees increased 48-fold from 1992 to 2014, and 92% of that increase is solely attributable to neonics [34•]. No other proclaimed cause of pollinator decline has risen so sharply.

Numerous articles have been published on the risk that neonics pose for bees and other non-target species. More than 1800 of these publications are reviewed in the 2015 Worldwide Integrated Assessment on the risks of neonicotinoids and fipronil to biodiversity and ecosystem functioning [36,37], and its recent update [38•,39]. These studies concluded that there is extensive world-wide environmental contamination by neonics of water, soils, wild plants, beehives and honey and that this contamination has large scale negative impact on pollinators, aquatic invertebrates, beneficial terrestrial invertebrates and insectivorous birds at the population and community levels. Wild pollinators are more severely harmed than honeybees because the extraordinary large colony size of honeybees makes them more resilient.

Here we will focus on the neonic studies that mention the application of the PP. Particularly relevant here are the studies that analyse socio-political processes and controversies surrounding the precautionary actions. They include studies on the partial bans of the three most problematic neonics in 2013 and 2018 in the EU [40–42,43••], and national neonic policy controversies in specific countries, including Italy [44], the UK [45•], France [18••,19] and the US [46•]. There are also studies comparing precautionary approaches and regulations of neonics in France versus the US [47] and in the EU compared to the US, Canada and UK [48•]. Fundamentally, these articles underline the relevance of deploying the PP to restrict neonic use in a situation where, despite prevailing scientific uncertainty, regulatory action is needed to avert the possible irreversible damaging effects of these insecticides on significant ecosystem services such as pollinating insects. Vogt [48•] argues that the European bans on neonic use illustrate how precautionary policies can assist pollination conservation despite stakeholder controversies, as they provide an opportunity to act to protect pollinators despite prevailing scientific uncertainty. However, in our recent case study on neonics and the PP in the context of the European (H2020) project 'REconciling sCience, Innovation and Precaution through the Engagement of Stakeholders' (RECIPES) we found that controversies in this case prevail and that this hampers timely and effective application of the PP [21]. In the proceedings of the agrochemical companies court cases against the bans, stakeholders promote different opinions on validity and details of the risk assessments, on the degrees of scientific uncertainty and the role of the PP, and on what all this should imply for decision making. Some of the studies reviewed in this paper provide similar insights. The study on the process voting on the EU ban of neonics in the UK, indicates that the politician's perceptions on scientific uncertainty and what a precautionary approach implies, mattered for the outcome [45•]. The studies on the case of banning Guacho® (seed coating based on the neonic imidacloprid) in France [18••,19] describe the social process behind applying the PP and illustrate how stakeholders framed science and scientific uncertainty to influence policy. They thereby highlight the role of social interpretation of evidence in a context of scientific uncertainty. Another paper describes the 'politics of expertise' around neonics assessments in the US, which resulted in a non-precautionary approach [46•]. These studies reflect central lessons found both in early studies on the PP in biodiversity conservation [27] and in literature on the PP in general [26]; that different interpretations and controversies on knowledge/ science, and on what precaution implies, may emerge and hamper precautionary risk management in practice, especially when powerful industries become involved. A recent analysis on corporate capture of regulatory science includes the case of neonics and highlights the close contacts between industry and regulatory authorities and the use of the same 'merchants of doubt' strategies previously used by the tobacco industry [49] (see also the paper on conflict of interests in IPBES by Arnold in this special issue). The analysis further identifies a worrisome convergence of anti-precautionary narratives on innovation between the European Commission and the industrial interests that lobby against the precautionary principle.

Further, there are diverging accounts on both the legal processes and on the more general effects of these regulations. Some — including one of the authors (EU Ban on Neonics: Too Little, Too Late) — have argued that the PP was applied too little and too late: too little, as the bans on the three neonics allowed for exceptions, loopholes and regrettable substitution, and too late because regulatory risk assessment protocols were and are persistently not updated in response to new scientific findings, while the first early warnings date from the mid 1990s [42,43••]. Somehow resembling central arguments posed by agrochemical companies in their court case appeal [50], others claim that the PP was wrongly applied in the EC regulations on neonics in 2013 because according to them the impact assessment procedure was not properly conducted [41,51]. However, this argument was dismissed in the EUs court decision on the industry court case appeals against the EC's partial ban on neonics. The General Court of the European Union found that the EC had been sufficiently informed about different impacts (positive and negative, economic and otherwise) of the partial ban [50, para 460].

There are also diverging opinions on whether bans on specific insecticides are helpful to protect pollinators while what is needed is for agriculture to transition to Agro Ecology and Integrated Pest Management (IPM) [52]. Precautionary regulation of neonics should not divert attention from regulating interconnected and broader issues in industrial agriculture that affect pollinator abundance and diversity [48•,53]. Additionally, even if the bans of some neonics to some degree have inspired (or forced) farmers to engage in more pollinator-friendly practices [44,55,56], it is clearly a problem that the three neonics banned may be replaced by other harmful insecticides (regrettable substitution) that are not sufficiently assessed for their risks on insects, due to insufficient and inconsistent regulatory processes [42,43••,54•]. Newer systemic insecticides such as flupyradifurone and sulfoxaflor with the same mode of action have not been restricted even while independent research found evidence of risk for bees well before they entered the market [54•].

The second strand of literature in which the PP is mentioned in relation to pollinator conservation comprises studies on **pollinator import or trade**. In recent decades, the international trade in honeybees and bumblebees has increased to meet increasing demand for pollination services. Such commercial trade not only threatens local biodiversity but may also spread parasites which contribute to pollinator decline [57]. Compared to the articles on neonics, these studies focus more on protecting pollinator diversity (in terms of protecting the genetic diversity of local and/or endangered species) than on pollinator abundance; for example, they highlight the diversity of honeybee species and the ecological and socioeconomic implications of the longstanding lack of scientific knowledge on the lesser-known honeybee species [58]. There are fewer studies on this topic, and those we found tend to be standalone articles focusing on different countries or regions; some focus on honeybee trade while others focus on bumblebee trade. Regarding **commercial honeybee** trade, the PP is mentioned as relevant in attempts to control introduced honeybees escaping and becoming feral in Australia in the 1990s [59,60]. In Denmark, the nature conservancy authorities applied the PP to prohibit the import of any species of bee other than the subspecies *Apis mellifera mellifera* (Læsø brown bee) into the Baltic island of Laesö in order to protect this endemic bee species [24••, p. 187]. The European Court of Justice supported the prohibition and thereby confirmed that members state can restrict imports of animals the purpose of maintaining local biodiversity [24••,61]. In a paper on the importance of conserving the diversity of honeybees such as the wild honeybees in Asia, it is advised to use the PP to control the importing and apiculture of *Apis mellifera* [58]. Another concern is the burgeoning international **trade in bumblebees** for agricultural pollination [62], which has led to *Bombus terrestris* becoming an invasive species in some parts of the world and has increased the risk of pathogens spreading to native wild bee populations [63]. The PP is mentioned in articles promoting the regulation of commercial bumblebee trade in order to conserve local bumblebee species in Australia [64], Asia [65] and Latin America [66•]. In the honeybee and bumblebee trade articles mentioning the PP, the PP is discussed less than in the papers reporting studies on neonics. They also focus less on controversy, perhaps because the apiculture and pollinator industry is smaller and less powerful than the pesticide industry. However, as pollinators decline, the commercial breeding and trading of managed bees (honeybees and bumblebees) is growing and thus more controversies about the ecological impacts are likely in future. Further, although the articles reviewed often focus on cases in specific areas of the world, the more recent articles call specifically for more international coordinated PP policies on species trade and import [58,66•].

It should be noted that the two topics discussed above are found in separate strands of literature and that the only point of contact we found was in the notion advanced by Vogt that *policy response to introduced species could learn from experiences with policy for neonicotinoid use* [48•, p. 203]. She contends that trade should not be seen in isolation, because *introducing managed species can compromise pollinator health directly or in combination with neonicotinoid use*. Synergistic effects between neonic exposure and honeybee pathogens have indeed been widely reported [32,37,38•]. Thus, when acknowledging complexity (and thereby, implicitly, scientific uncertainty) in research assessments, it is wise to take a precautionary approach.

The need for a broader application of the PP in pollinator stewardship

Within the literature in our sample, there is a difference between a precautionary approach to pollinator conservation in the way described by, for example, Hawksworth and Samways [28,29], and the PP as a legal principle applied in the regulation of specific threats. As a general approach, the PP is mentioned as a fundament and a starting point that underpins efforts to protect insect abundance and diversity, while as a legal principle the application of the PP has targeted specific causes of pollinator decline. Compared to the myriad of threats that cause pollinator decline such as urbanisation, intensification of agriculture, the large-scale use of agrochemicals, deforestation, spreading of pathogens, climate change and invasive species [1•,4,10•,11]; we found that the PP as a legal and regulative principle was only mentioned explicitly in empirical studies on two of these threats. These specific parts of the problems of present-day agriculture, environmental pollution and invasive alien species are indeed referred to in the list of policies for pollinator conservation proposed by Dicks *et al.* [12]. However, regulations are often late, narrow, fragmented and flawed, often have loopholes, and are often rendered ineffective by regrettable substitution.

The complexity of interlinked causes and drivers of pollinator decline ask for an integrated and globally coordinated approach to yield fundamental solutions that avoid the problems of fragmented regulation, loopholes and regrettable substitution. Pollinator decline cannot be solved by tackling a single driver in isolation from the other factors. Instead, the approach must be integrated, simultaneously addressing the key drivers in order to counteract pollinator decline and establish a balance that ensures ecosystem integrity and food security for the future. The approach could take the form of an international treaty for global pollinator stewardship and pollinator ecosystem restoration [1•]. In such a treaty, the PP should be central and strong. The treaty should set ambitious targets for the conservation and restoration of pollinator habitats, considering their core importance for ecosystem resilience and human food security, while also acknowledging their intrinsic value. As mentioned earlier, Samsays [29] argues that the PP should be a starting point for conservation planning because it can justify the protection of a broad range of species of which we know that we know very little about their role in ecosystems (so called 'known unknowns').

The land use and landscape changes that led to the habitat destruction and depletion of floral and nesting resources need to be reversed and compensated by the reintroduction and conservation of micro-habitats for pollinators [1•]. This requires ecosystem restoration and development and promotion of pollinator friendly agricultural practices and landscape management. Reduction of emissions of active nitrogen and ecosystem restoration practices that counteract nitrogen accumulation in soils of nature areas can increase floral biodiversity.

A holistic precautionary policy strategy should further include a global phase-out of the prophylactic use of ecotoxic agrochemicals such as neonics, whose global use is still increasing despite the partial EU ban. One way of achieving this is through existing international law: by including neonics in the Stockholm Convention on Persistent Organic Pollutants, the same mechanism by which other problematic pesticides have been phased out globally [24••, p. 191]. Based on its long half-life times in woody plants, soil, sediment and water, it's high ecotoxicity at field-realistic levels of pollution, its long range environmental transport in water and global food-streams, and its unprecedented damage to the planet's entomofauna, we urge that these substances should be included in category A (elimination) of the Stockholm Convention. In the shorter term, precautionary policies could start by prioritising the immediate implementation of the readily available no-regret options that are useful regardless of which of the diverging scientific interpretations of the incomplete knowledge is correct. The road map by Harvey *et al.* [14••] provides a good overview of such precautionary solutions. A holistic policy strategy for pollinator conservation and restoration where these solutions could fit in is outlined by Van der Sluijs and Vaage [1•].

Conclusion

The research front on precautionary pollinator conservation is fragmented. Studies on insect or pollinator conservation in the tradition of biodiversity conservation research sometimes mention the PP, but only briefly: the PP seem to be perceived as a general approach, mentioned in the context of our limited knowledge (scientific uncertainty) on insect species and biodiversity [22,27]. Often unrelated to that tradition, two strands of literature discuss how the PP has been (or should have been) evoked in the regulation of products (pesticides) and of practices (international pollinator trade) that contribute to pollinator decline. Thus, the PP can be seen as both a guiding approach for protecting insect/pollinator diversity and abundance, and a principle applied to regulate specific products and practices that contribute to pollinator decline.

In relation to the calls for increased attention to human and policy dimensions of pollinator conservation [13•,16•], we find that some of the studies reviewed provide some relevant lessons on the challenges of implementing pollinator conservation policies. First, the studies show there are inconsistencies in how, where and when the PP has been applied. It is clear that applying the

PP is not simple: the procedure may be prolonged, resulting in delayed, fragmented, narrow and flawed regulations [42,43••]. In relation to the argument that 'we know enough about pollinator decline to act now' [30,31], this is not very encouraging. It is widely recognised in the literature on the PP in biodiversity conservation that implementing the PP in law and policy may give varied results [27]. This is also illustrated, for example, in the case of PP policies on bumblebees in Australia [64]. It has been found that the political context matters. The decisions to invoke the PP or the interpretations of the PP sometimes depend on political constellations [18••], and precautionary approaches may be impacted by national and historically developed social/political relations [46•,47]. The fact that PP measures have been applied in some areas and regions and not in others, whereas trade (e.g. in pollinator species or pesticides) is international, adds to the urgency of the recent calls for international agreements targeting pollinator/insect decline [1•,2,14••].

Secondly, several of the studies highlight the challenges of invoking policies in a context of **scientific uncertainty and controversy** and abundance of corporate capture of regulatory science. The studies on regulating neonics are especially illustrative, as they pay particular attention to socio-political aspects when encountering scientific uncertainty. Basically, they show how scientific uncertainty may lead to great ambiguity and diverging interpretations of the knowledge and science available, often fuelled by merchants of doubt strategies of corporate actors. When stakes are high and economic interests are involved, proposed PP regulations are particularly likely to meet with resistance from powerful stakeholders because the regulations may interfere with economic interests, competitiveness and economic growth [26,27]. In addition to our own research on controversies around applying the PP to ban neonics in the EU [21], three other studies [18••,45•,46•] show how different stakeholders interpretations of science and scientific uncertainty may impact the regulation of products that harm bees. The focus on scientific uncertainty in risk management and policy implementation can be related back to certain points made in environmental law and pollinator policy literature, finding that although scientists such as biologists are familiar with scientific uncertainty, they may not be aware of how such uncertainty is perceived by bureaucrats, political actors and stakeholders. As de Sadeleer notes [23, p. 4], an inherent problem when implementing the PP as a legal principle in environmental law is that legal rules are intended to provide predictability, and lawyers tend to seek certainty rather than uncertainty. Hall and Steiner [13•] also note that it is challenging for bureaucratic thinking on insects to incorporate the complexity of possible factors in ecosystems in the way biologists do.

Indeed, the societal challenges posed by pollinator decline display all the characteristics of a post-normal science problem [8,9••]. Tackling such challenges requires a transdisciplinary approach [67] in which entomologists join with social scientists, legal scholars, legislators and policymakers to to form an extended peer community that jointly addresses the human dimensions of pollinator decline, conservation and restoration. Funding bodies should start prioritising such transdisciplinary research. Regarding the use of expertise in policy advise, a key lesson is that under post-normal conditions, the actionable knowledge base should be pluralised and diversified to include the widest possible range of high quality, potentially actionable knowledges and sources of relevant wisdom, without expecting science to speak with one voice [68,9••]. Further, one should anticipate controversies because inherent uncertainty, complexity and plurality of evidence can and will be interpreted and framed differently by different stakeholders (often intentionally, driven by vested interests). This adds a political dimension of interpreting or framing scientific uncertainty to Hall and Martins [16•] 'human dimensions' of pollinator conservation. This dimension may play a significant a role in risk assessments and risk management dynamics, and when moving from precautionary policy intentions to its actual implementation in often fragmented and narrow regulations with multiple loopholes. We need to understand these political dimensions in order to better be able to make the required move forward towards a more holistic pollinator conservation and restoration policy based on a stronger, broader and more timely application of the PP. This is needed both to address the global environmental risk of pollinator decline and the wider problem of global insect decline.

A limitation in our review is that our sample mainly exists of articles that explicitly mention the PP in relation to pollinator/insect conservation. Further lessons may be drawn from a wider range of studies, and empirical cases, on the implementation of pollinator conservation policies in different parts of the world, which could be important to review, analyse and compare in future studies and meta-studies.

Funding

This work benefitted from the RECIPES project. This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 824665.

Conflict of interest statement

Nothing declared.

Acknowledgement

We are grateful to Joy Burrough-Boenisch for linguistic and stylistic improvements.

References and recommended reading

Papers of particular interest, published within the period of review, have been highlighted as:

- • of special interest
- •• of outstanding interest

1. Van der Sluijs JP, Vaage NS: **Pollinators and global food**
• **security: the need for holistic global stewardship**. *Food Ethics* 2016, **1**:75-91 http://dx.doi.org/10.1007/s41055-016-0003-z

Topical review of the present pollinator crisis and how it threatens global and local food security. An integrated approach that simultaneously addresses the key drivers is needed. This includes the creation and restoration of floral and nesting resources, a global phase-out of the prophylactic use of neonicotinoids and fipronil, the improvement of test protocols for authorising agrochemicals, and the restoration and maintenance of independence in regulatory science. The authors argue that an international treaty for global pollinator stewardship and pollinator ecosystem restoration should be initiated in order to systemically counteract the current crisis.

2. Van der Sluijs JP: **Insect decline, an emerging global environmental risk**. *Curr Opin Environ Sustain* 2020, **46**:39-42.

3. Wagner DL: **Insect declines in the Anthropocene**. *Annu Rev Entomol* 2020, **65**:457-480.

4. IPBES: **The assessment report on pollinators, pollination and food production**. *Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services*. 2017. Bonn.

5. Rhodes CJ: **Are insect species imperilled? Critical factors and prevailing evidence for a potential global loss of the entomofauna: a current commentary**. *Sci Prog* 2019, **102**:181-196.

6. Zattara EE, Aizen MA: **Worldwide occurrence records reflect a**
• **global decline in bee species richness**. *One Earth* 2020, **4**:114-123 http://dx.doi.org/10.1016/j.oneear.2020.12.005

The 2017 IPBES Assessment Report on Pollinators, Pollination and Food Production [4] reported a lack of data to support conclusions on the global extent of bee decline, despite the many local and few regional reports pointing out that this decline could indeed reflect a global phenomenon. By analysing historical data from the Global Biodiversity Information Facility (GBIF), this study assessed the global extent of bee decline. The number of bee species found each year in the GBIF data has declined since the 1990s. Approximately 25% fewer species were found between 2006 and 2015 than before 1990. The number of bee records in this database has increased by around 55% since 2000, so the decline cannot be attributed to a lack of observations. Results underline the urgency for swift global actions to avoid further pollinator decline.

7. Nieto A, Roberts SPM, Kemp J, Rasmont P, Kuhlmann M, Criado MG, Biesmeijer JC, Bogusch P, Dathe H, De la Rúa P *et al.*: *European Red List of Bees*. Luxembourg: Publication Office of the European Union; 2014 https://ec.europa.eu/environment/nature/conservation/species/redlist/downloads/European_bees.pdf.

8. Funtowicz SO, Ravetz JR: **Science for the post-normal age**. *Commonplace* 2020 http://dx.doi.org/10.21428/6ffd8432.8a99dd09.

9. Renn O, Baghramian M, Capaccioli M, de Rijcke S, Drotner K,
•• Dubertret L, Irwin A, Luty T, Makarow M, Moberg C *et al.*: **Making sense of science for policy under conditions of complexity and uncertainty**. *Evidence Review Report No. 6*. SAPEA, Science Advice for Policy by European Academies; 2019 https://www.sapea.info/wp-content/uploads/MASOS-ERR-online.pdf

Must-read for everyone involved in science for policy. The world's most pressing problems are also incredibly complex. Scientific knowledge around these areas can often be uncertain or contested. Science provides meaning to the discussion around critical topics within society. Science advice supports effective policymaking by providing the best available knowledge, which can then be used to understand a specific problem, generate and evaluate policy options and monitor results of policy implementation. This approach works best when guided by co-creation of knowledge and policy options. Science advice is always affected by values, conventions and preferences. Rather than highlighting the role of the 'objective' knowledge provider, the science–policy nexus is better served when both sides are transparent about what values and goals they apply and how knowledge claims are selected, processed and interpreted. This creates more trust and confidence in institutions and in the processes for science advice.

10. Sánchez-Bayo F, Wyckhuys KA: **Worldwide decline of the**
• **entomofauna: a review of its drivers**. *Biol Conserv* 2019, **232**:8-27

A synthesis of 73 recent studies on insect decline and proclaimed drivers. Over 40% of insect species are threatened with extinction. The taxa most affected are Lepidoptera, Hymenoptera and Coleoptera (dung beetles). Four aquatic taxa are imperilled and have already lost a large proportion of species. The main driver of the declines is habitat loss by conversion to intensive agriculture. Additional key causes are agro-chemical pollutants, invasive species and climate change.

11. Wagner DL, Grames EM, Forister ML, Berenbaum MR, Stopak D: **Insect decline in the Anthropocene: death by a thousand cuts**. *Proc Natl Acad Sci U S A* 2021, **118**:1-10.

12. Dicks LV, Viana B, Bommarco R, Brosi B, Arizmendi C, Cunningham SA, Galetto L, Hill R, Lopes V, Pires C *et al.*: **Ten policies for pollinators. What governments can do to safeguard pollination services**. *Science* 2016, **354**:14-15.

13. Hall DM, Steiner R: **Insect pollinator conservation policy**
• **innovations at subnational levels: lessons for lawmakers**. *Environ Sci Policy* 2019, **93**:118-128

This paper provides useful empirical insights into pollinator-relevant policies within the US. An analysis of 110 pollinator-relevant laws reveals that in contrast to policies proposed by biologists, the policies show a very bureaucratic way of thinking. Another finding is that legislators are becoming more aware of behaviours and technologies that pose risks to pollinators, but that more comprehensive policies are needed. This empirical account anticipates viable international policy and informs its design.

14. Harvey JA, Heinen R, Armbrecht I, Basset Y, Baxter-Gilbert JH,
•• Bezemer TM, Böhm M, Bommarco R, Borges PAV, Cardoso P *et al.*: **International scientists formulate a roadmap for insect conservation and recovery**. *Nat Ecol Evol* 2020, **4**:174-176

Over 70 scientists from different countries propose a global 'roadmap' for insect conservation and recovery that contains short-term, medium-term and long-term actions. The comprehensive list of short-term measures that must be taken to slow down insect declines include phasing out synthetic pesticides and fertilisers, reducing the import of ecologically harmful products and regulating the introduction of alien species. It is also emphasised that we know enough about key causes of insect decline to be able formulate 'no-regret' solutions that will benefit society and biodiversity.

15. Samways MJ, Barton PS, Birkhofer K, Chichorro F, Deacon C, Fartmann T, Fukushima CS, Gaigher R, Habel JC, Hallmann CA *et al.*: **Solutions for humanity on how to conserve insects**. *Biol Conserv* 2020, **242**:108427.

16. Hall DM, Martins DJ: **Human dimensions of insect pollinator**
• **conservation**. *Curr Opin Insect Sci* 2020, **38**:107-114

Research on human dimensions of insect declines is growing but more research is urgently needed. Even with only a rudimentary understanding of insect pollinator diversity and pollination, the public are ready to save bees. Experts must respond to any inaccuracies that accompany the public's enthusiasm and seize opportunities for research and science communication that improves conservation efforts. Entomologists need to team up with social researchers to increase the amount and improve the impact of socio-cultural research on pollinator conservation.

17. UNESCO: *The Precautionary Principle*. World Commission on the Ethics of Scientific Knowledge and Technology (COMEST); 2005 https://unesdoc.unesco.org/ark:/48223/pf0000139578_eng.

18. Maxim L, van der Sluijs JP: **Seed dressing systemic insecticides**
•• **and honeybees**. *Late Lessons from Early Warnings: Science, Precaution, Innovation*. European Environment Agency (EEA); 2013:401-438 https://www.eea.europa.eu/publications/late-lessons-2/late-lessons-chapters/late-lessons-ii-chapter-16/view

Describes the social process behind applying the PP when banning Gaucho® (containing the neonic imidacloprid) in France in the 1990s, and how stakeholders framed science to influence policy (strategic and selective use of science and scientific uncertainty). It thereby highlights the role of social interpretation in a context of scientific uncertainty. Facing strongly diverging risk assessments and scientific controversy, key lessons include: the knowledge base used to inform decision making should be based on all available scientific knowledge; to improve robustness in knowledge claims, uncertainty, dissent and criticism should be openly included and discussed in the analysis, synthesis and assessments delivered by expert panels; regulatory risk assessments should make better use of information from non-scientific sources (e.g. local knowledge from beekeepers); there is a need to clarify values, stakes and vested interests that play a role in research and in the political and socioeconomic context within which the research is embedded.

19. Maxim L, van der Sluijs JP: **Uncertainty: cause or effect of stakeholders' debates? Analysis of a case study: the risk for honeybees of the insecticide Gaucho®**. *Sci Total Environ* 2007, **376**:1-17.

20. Vos E, De Smedt K: *Taking Stock as a Basis for the Effect of the Precautionary Principle Since 2000. Deliverable D1 of the H2020 Project (Grant Agreement No 824665) REconciling sCience, Innovation and Precaution through the Engagement of Stakeholders (RECIPES)*. Maastricht: Maastricht University; 2020 https://recipes-project.eu/sites/default/files/2021-01/Report_Taking%20stock%20as%20a%20basis%20for%20the%20effect%20of%20the%20precautionary%20principle%20since%202000_Final.pdf.

21. Drivdal L, van der Sluijs JP: **Neonicotinoids**. *Case Study Report No 4 of WP 1 of the H2020 Project (Grant Agreement No 824665) REconciling sCience, Innovation and Precaution through the Engagement of Stakeholders (RECIPES)*. 2021 https://recipes-project.eu/sites/default/files/2021-03/D2_3_Neonics_Review.pdf.

22. Cooney R: **The precautionary principle in biodiversity conservation and natural resource management: an issues paper for policy-makers, researchers and practitioners**. *IUCN Policy and Global Change Series*. Cambridge: Gland; 2004, 2.

23. de Sadeleer N: **The precautionary principle as a device for greater environmental protection: lessons from EC courts**. *Rev Eur Community Int Environ Law* 2009, **18**:3-10.

24. •• De Sadeleer N: **Environmental law principles**. *From Political Slogans to Legal Rules*. Oxford University Press; 2020

This second edition provides in-depth insights into environmental law and its essential principles (polluter pays, prevention, and the Precautionary Principle). It documents and critically reviews case law around the three principles, providing a comprehensive overview of case law around the PP. The book also outlines the legal treatment of scientific expertise and explores the stakes, obstacles and potential solutions that could reduce the tensions between the different ways in which law and science deal with uncertainty and complexity. These insights are important for understanding and effectively tackling the key challenges of implementing precautionary environmental policies and regulations from a legal perspective.

25. Vogel D: *The Politics of Precaution: Regulating Health, Safety, and Environmental Risks in Europe and the United States*. Princeton University Press; 2012.

26. Read R, O'Riordan T: **The precautionary principle under fire**. *Environment* 2017, **59**:4-15.

27. Cooney R, Dickson B: *Biodiversity and the Precautionary Principle: Risk, Uncertainty and Practice in Conservation and Sustainable Use*. London: Earthscan; 2005.

28. Hawksworth DL: **Biodiversity and conservation of insects and other invertebrates**. *Biodivers Conserv* 2011, **20**:2863-2866.

29. Samways MJ: *Insect Conservation: A Global Synthesis*. Wallingford: CABI; 2020.

30. Forister ML, Pelton EM, Black SH: **Declines in insect abundance and diversity: we know enough to act now**. *Conserv Sci Pract* 2019, **1**:1-8.

31. Drossart M, Gérard M: **Beyond the decline of wild bees: optimizing conservation measures and bringing together the actors**. *Insects* 2020, **11**:1-23.

32. Van der Sluijs JP, Simon-Delso N, Goulson D, Maxim L, Bonmatin JM, Belzunces J-M: **Neonicotinoids, bee disorders and the sustainability of pollinator services**. *Curr Opin Environ Sustain* 2013, **5**:293-305.

33. Goulson D, Thompson J, Croombs A: **Rapid rise in toxic load for bees revealed by analysis of pesticide use in Great Britain**. *PeerJ* 2018, **6**:e5255.

34. • DiBartolomeis M, Kegley S, Mineau P, Radford R, Klein K: **An assessment of acute insecticide toxicity loading (AITL) of chemical pesticides used on agricultural land in the United States**. *PLoS One* 2019, **14**:e0220029

To investigate the relative importance of different agrochemicals to insect decline, this paper quantifies the changes by calculating the Acute Insecticide Toxicity Loading (AITL) on US agricultural land and surrounding areas from 1992 to 2014. The AITL takes account of the total mass of insecticides used in the US, their acute toxicity to insects (honeybee contact and oral LD50 are used as reference values) and the environmental persistence of the pesticides. The types of synthetic insecticides applied to agricultural land shifted dramatically from predominantly organophosphorus and *N*-methyl carbamate pesticides to a mix dominated by neonicotinoids and pyrethroids. Though generally applied to US agricultural land at lower rates per acre, neonicotoids are much more toxic to insects and generally persist longer in the environment. The 48-fold increase in AITL from 1992 to 2014 found for oral toxicity is primarily due to neonicotinoids: they accounted for 61% (via contact toxicity) to 99% (via oral toxicity) of the total toxicity loading of all insecticides in 2014. Using methodology such as the AITL screening analysis early in the registration process of new pesticides or in approving new agricultural uses would provide useful metrics with which to predict catastrophic harm to the environment resulting from the application of chemical pesticides on agricultural land.

35. Douglas MR, Sponsler DB, Lonsdorf EV, Grozinger CM: **County-level analysis reveals a rapidly shifting landscape of insecticide hazard to honey bees (*Apis mellifera*) on US farmland**. *Sci Rep* 2020, **10**:1-11.

36. Van der Sluijs JP, Amaral-Rogers V, Belzunces LP, Bijleveld Van Lexmond MF, Bonmatin JM, Chagnon M, Downs CA, Furlan L, Gibbons DW, Giorio C *et al.*: **Conclusions of the worldwide integrated assessment on the risks of neonicotinoids and fipronil to biodiversity and ecosystem functioning**. *Environ Sci Pollut Res* 2015, **22**:148-154.

37. Pisa L, Amaral-Rogers V, Belzunces LP, Bonmatin J-M, Downs C, Goulson D, Kreutzweiser D, Krupke C, Liess M, McField M *et al.*: **Effects of neonicotinoids and fipronil on non-target invertebrates**. *Environ Sci Pollut Res* 2015, **22**:68-102.

38. • Pisa L, Goulson D, Yang EC, Gibbons D, Sánchez-Bayo F, Mitchell E, Aebi A, van der Sluijs J, MacQuarrie CJK, Giorio C *et al.*: **An update of the Worldwide Integrated Assessment (WIA) on systemic insecticides. Part 2: impacts on organisms and ecosystems**. *Environ Sci Pollut Res* 2021, **28**:11749-11797 http://dx.doi.org/10.1007/s11356-017-0341-3

This synthesis has an excellent infografic on the state of knowledge on impacts of neonic insecticides on biodiversity and ecosystem services. The high toxicity of these systemic insecticides to invertebrates has been confirmed and expanded to include more species and compounds. Most of the recent research has focused on bees and the sublethal and ecological impacts these insecticides have on pollinators. Toxic effects on other invertebrate taxa also extended to predatory and parasitoid natural enemies, aquatic arthropods and soil organisms. The impact on marine and coastal ecosystems is still largely uncharted. Sublethal effects on fish, reptiles, frogs, birds and mammals are also reported, improving the understanding of the mechanisms of toxicity of these insecticides in vertebrates and their deleterious impacts on the growth, reproduction and neurobehavior of most of the species tested.

39. Bonmatin JM, Giorio C, Sánchez-Bayo F, Bijleveld van Lexmond M: **An update of the Worldwide Integrated Assessment (WIA) on systemic insecticides**. *Environ Sci Pollut Res* 2021, **28**:11709-11715 http://dx.doi.org/10.1007/s11356-021-12853-6.

40. McGrath PF: **Politics meets science: the case of neonicotinoid insecticides in Europe**. *SAPIENS* 2014, **7**.

41. Alemanno A: **The science, law and policy of neonicotinoids and bees: a new test case for the precautionary principle**. *Eur J Risk Regul* 2013, **4**:191-207.

42. Storck V, Karpouzas DG, Martin-Laurent F: **Towards a better pesticide policy for the European Union**. *Sci Total Environ* 2017, **575**:1027-1033.

43. •• Sgolastra F, Medrzycki P, Bortolotti L, Maini S, Porrini C, Simon-Delso N, Bosch J: **Bees and pesticide regulation: lessons from the neonicotinoid experience**. *Biol Conserv* 2020, **241** http://dx.doi.org/10.1016/j.biocon.2019.108356

Reviews risk assessment procedures for assessing neonics and finds that regulatory systems were unsatisfactory and slow to react. The risk assessment protocols at the time neonicotinoids were authorised were inadequate to detect some of the risks associated with neonicotinoid properties. Improving the risk assessment procedures by including cooccurrence of multiple compounds, sublethal and long-term effects on different bee species would benefit pollinator conservation. It is also stressed that regulatory studies used in risk assessments should be publicly available, and that pesticide regulation should not be discontinued once a product has been authorised.

44. Sgolastra F, Porrini C, Maini S, Bortolotti L, Medrzycki P, Mutinelli F, Lodesani M: **Healthy honey bees and sustainable maize production: why not?** *Bull Insectol* 2017, **70**:156-160.

45. • Patterson A, McLean C: **The precautionary principle at work: the case of neonicotinoids and the health of bees**. *Sci Public Policy* 2019, **46**:441-449

Describes the UK government's changing policy response to neonicotinoids; from a sound-science approach to a precautionary approach (but a weak version). Outlining the politics around taking a stance on a ban of neonics, the authors find that in this case, adherence to the PP may reflect the risk conceptions of politicians involved rather than a consistent government stance on the Precautionary Principle.

46. • Suryanarayanan S, Kleinman DL: **Be (e) coming experts: the controversy over insecticides in the honey bee colony collapse disorder**. *Soc Stud Sci* 2013, **43**:215-240

This paper explores the politics of expertise in the controversy on neonics and bee disorders in the US. The analysis shows how a set of research norms and practices from agricultural entomology came to dominate the investigation of the links between pesticides and honeybee health, and how the epistemological dominance of these norms and practices served to marginalise the knowledge claims and policy positions of beekeepers, thus helping to justify the US Environmental Protection Agency's decisions to keep these chemicals on the market. The beekeepers' precautionary epistemology focuses on complexity and multi-causality and errs on the side of false-positive conclusions, but the dominant practices of bee scientists are characterised by a causally driven, single-factorial epistemic approach focusing only on the directly visible lethal effects of insecticides on honeybees, which increases the likelihood of drawing false-negative conclusions about risks. EPA regulators adopted these non-precautionary epistemic norms. This reflects a historic shift in US regulatory risk assessments from being broadly precautionary to non-precautionary, which was precipitated by a highly fragmented and adversarial political context in which policymaking on chemicals became a key ground for battles between pro-regulatory and deregulatory forces.

47. Suryanarayanan S, Kleinman DL: **Beekeepers' collective resistance and the politics of pesticide regulation in France and the United States**. *Fields of Knowledge: Science, Politics and Publics in the Neoliberal Age*. Emerald Group Publishing Limited; 2014.

48. • Vogt MAB: **Toward functional pollinator abundance and diversity: comparing policy response for neonicotinoid use to demonstrate a need for cautious and well-planned policy**. *Biol Conserv* 2017, **215**:196-212

Underlines the interconnectedness between the use of systemic insecticides and the commercial import of managed bees, both of which may increase with the expansion of crops dependent on commercial pollinators. The outcome may be greater reliance on insecticides containing neonicotinoids and managed pollinator colonies; both can compromise pollinator conservation. The need for more studies on the interconnectedness of the threats to pollinator abundance and diversity is highlighted. The relevance of the PP is mentioned and it is argued that the bans on neonics illustrate that precautionary policy is possible for pollinator conservation even when there is controversy between stakeholders.

49. Saltelli A, Dankel D, Di Fiore M, Holland N, Pigeon M: **Science, the endless frontier of regulatory capture**. *SSRN Paper*. 2021 http://dx.doi.org/10.2139/ssrn.3795058.

50. Judgment of the General Court (First Chamber, Extended Composition) of 17 May 2018. Bayer CropScience AG and Others v European Commission. Plant protection products — Active substances clothianidin, thiamethoxam and imidacloprid — Review of approval — Article 21 of Regulation (EC) No 1107/2009 — Prohibition of the use and sale of seeds treated with plant protection products containing the active substances in question — Article 49(2) of Regulation No 1107/2009 — Precautionary principle — Proportionality — Right to be heard — Non-contractual liability. Cases T-429/13 and T-451/13 https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A62013TJ0429.

51. Bozzini E, Stokes E: **Court upholds restrictions on neonicotinoids–a precautionary approach to evidence**. *Eur J Risk Regul* 2018, **9**:585-593.

52. Wyckhuys K, Sánchez-Bayo F, Aebi A, van Lexmond MB, Bonmatin JM, Goulson D, Mitchell E: **Stay true to integrated pest management**. *Science* 2021, **371**:133.

53. Ellis RA, Weis T, Suryanarayanan S, Beilin K: **From a free gift of nature to a precarious commodity: bees, pollination services, and industrial agriculture**. *J Agrar Change* 2020, **20**:437-459.

54. • Siviter H, Muth F: **Do novel insecticides pose a threat to beneficial insects?** *Proc R Soc B* 2020, **287**:20201265

This study on the case of regrettable substitution of the three banned neonics by the novel insecticides sulfoxaflor and flupyradifurone (that have the same mode of action as neonicotinoids) provides important suggestions on how to improve the regulatory process in order to stop the continuing cycle of insecticides being licenced for use without a full understanding of their potential impact on beneficial insects: (1) make assessments of sublethal effects on wild bees mandatory; (2) assess the potential impact of the novel insecticides on non-bee beneficial insects, this is currently missing despite the known key role of non-bee beneficial insects (including pollinators such as hoverflies) in ecosystems and agriculture; (3) assess the interaction of agrochemicals and other anthropogenic stressors.

55. Furlan L, Pozzebon A, Duso C, Simon-Delso N, Sánchez-Bayo F, Marchand PA, Codato F, Bijleveld van Lexmond M, Bonmatin JM: **An update of the Worldwide Integrated Assessment (WIA) on systemic insecticides. Part 3: alternatives to systemic insecticides**. *Environ Sci Pollut Res* 2021, **28**:11798-11820 http://dx.doi.org/10.1007/s11356-017-1052-5.

56. Veres A, Wyckhuys KAG, Kiss J, Tóth F, Burgio G, Pons X, Avilla C, Vidal S, Razinger J, Bazok R *et al.*: **An update of the Worldwide Integrated Assessment (WIA) on systemic pesticides. Part 4: alternatives in major cropping systems**. *Environ Sci Pollut Res* 2020, **27**:29867-29899.

57. Goulson D, Nicholls E, Botías C, Rotheray EL: **Bee declines driven by combined stress from parasites, pesticides, and lack of flowers**. *Science* 2015, **347** http://dx.doi.org/10.1126/science.1255957.

58. Matias DMS, Borgemeister C, von Wehrden H: **Thinking beyond Western commercial honeybee hives: towards improved conservation of honey bee diversity**. *Biodivers Conserv* 2017, **26**:3499-3504.

59. Oldroyd BP: **Controlling feral honey bee, *Apis mellifera* L. (Hymenoptera: Apidae), populations in Australia: methodologies and costs**. *Aust J Entomol* 1998, **37**:97-100.

60. Pyke GH: **The introduced Honeybee *Apis mellifera* and the precautionary principle: reducing the conflict**. *Aust Zool* 1999, **31**:181-186.

61. Judgment of the Court (Fifth Chamber) of 3 December 1998. Criminal proceedings against Ditlev Bluhme. Reference for a preliminary ruling: Kriminalretten i Frederikshavn — Denmark. Free movement of goods — Prohibition of quantitative restrictions and measures having equivalent effect between Member States — Derogations — Protection of the health and life of animals — Bees of the subspecies *Apis mellifera* mellifera (Læso brown bee). - Case C-67/97. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A61997CJ0067.

62. Goulson D: **Impacts of non-native bumblebees in Western Europe and North America**. *Appl Entomol Zool* 2010, **45**:7-12.

63. Graystock P, Yates K, Evison SE, Darvill B, Goulson D, Hughes WO: **The Trojan hives: pollinator pathogens, imported and distributed in bumblebee colonies**. *J Appl Ecol* 2013, **50**:1207-1215.

64. Moore CA, Gross C: **Great big hairy bees! Regulating the European bumblebee, *Bombus terrestris* L. what does it say about the precautionary principle?** *Int J Rural Law Policy* 2012:1-19 http://dx.doi.org/10.5130/ijrlp.i1.2012.2627.

65. Williams PH, An J, Brown MJF, Carolan JC, Goulson D, Huang J, Ito M: **Cryptic bumblebee species: consequences for conservation and the trade in greenhouse pollinators**. *PLoS One* 2012, **7**:1-8.

66. • Aizen MA, Smith-Ramírez C, Morales CL, Vieli L, Sáez A, Barahona-Segovia RM, Arbetman MP, Montalva J, Garibaldi LA, Inouye DW *et al.*: **Coordinated species importation policies are**

needed to reduce serious invasions globally: the case of alien bumblebees in South America. *J Appl Ecol* 2019, **56**:100-106
Highlights the urgent need for international efforts to regulate managed pollinator trade by providing a clear example of why precautionary regulations on a country-by-country basis is not sufficient. The case from Latin America illustrates how damaging invasions of imported bumblebees move across boarders: from Chile, which allowed imports, to Argentina, which restricted them.

67. OECD: **Addressing societal challenges using transdisciplinary research**. *OECD Science, Technology and Industry Policy Papers*. Paris: OECD Publishing; 2020 http://dx.doi.org/10.1787/0ca0ca45-en. 80 p.

68. Waltner-Toews D, Biggeri A, De Marchi B, Funtowicz S, Giampietro M, O'Connor M, Ravetz JR, Saltelli A, van der Sluijs JP: **Post-normal pandemics: why CoViD-19 requires a new approach to science**. *Recenti Prog Med* 2020, **111** http://dx.doi.org/10.1701/3347.33181 (In Italian. English version of this paper: https://archive.discoversociety.org/2020/03/27/post-normal-pandemics-why-covid-19-requires-a-new-approach-to-science/).