Postregistration Monitoring of Pesticides is Urgently Required to Protect Ecosystems

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Abstract—*Current admission policies for pesticides follow a controlled experimental tiered risk assessment approach, giving results that are difficult to extrapolate to a real-world situation. Later analyses of compounds such as DDT and neonicotinoid pesticides clearly show that the actual chemical impacts frequently affect many more components of an ecosystem than a priori suggested by risk assessment. Therefore, to manage the actual risks for ecosystems imposed by manufactured compounds, it is proposed that current admission policies for chemicals be enriched by using postregistration monitoring. Such monitoring is essential to identify unexpected direct and indirect impacts on organisms by accounting for multiple propagation routes and exposures. Implementation of postregistration monitoring could build on existing monitoring networks. This approach would tackle the current policy impasse of compartment-based regulations versus exposure-based regulations, and, more importantly, would provide a safety lock for risk assessment across compartments and more likely ensure the protection of our natural environment. Environ Toxicol Chem 2017;36:860–865. © 2016 SETAC*

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Only a few decades ago we became aware that environmental risks are a dominant product of our industrial society, and not just an unpleasant, manageable side effect [1]. Because these risks are the product of human activity [2], it was argued that it should be possible to assess the level of associated risk [1]. Quantitative risk assessment as a science and as a basis for regulatory decision-making thus emerged [3,4]. A Society of Environmental Toxicology and Chemistry (SETAC) Pellston workshop on research priorities in environmental risk assessment was held in 1987, aiming to provide governments with tools to make reasoned choices on the permission of chemicals within a dynamic economy and innovative society that relies on risk-taking decisions. Subsequently, concepts such as sustainability and the precautionary principle have gained attention with the aim of decreasing levels of risk by preventive measures.

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Despite numerous efforts, we still have not succeeded in curtailing the risks of novel chemical applications to our natural environment; that a rethinking of our current approaches toward risk assessment is urgently required. We argue that in addition to laboratory and semifield data, assessments also need to rely on field data of postregistration monitoring and/or cross-ecosystem calculations and discuss how such monitoring can be incorporated as an essential safety lock in environmental risk assessment and management to curtail the ongoing impairment of ecosystems, including their biodiversity, their functioning, and the services they provide. Thus we can enrich current risk assessment efforts by refining the "chemical path" (the phrase used by Carson [5]).

Current "Single-Minded" Risk Assessment

The principles of prevention and risk reduction through risk assessment and risk management of compounds have been firmly established in many regulations of the European Commission. Within pesticide risk assessment, the first-tier risk levels are assessed based on single-species toxicity data derived using easy-to-culture test species that may not be the most sensitive to the chemical under focus and may not use an exposure pattern that is realistic for field conditions. Exceedance of these risk levels is considered acceptable as long as no unacceptable effects in the field are expected, based on scientific evidence derived from higher tiers. Following the guidance documents set forth by the European Food Safety Authority [6], these higher tiers typically include species sensitivity distributions and may, ideally, include microcosm and mesocosm studies as well as ecological modeling. This "single-minded" and experimentally controlled approach is largely fuelled by pragmatism and focuses on 1 single species, 1 single endpoint, or 1 single compartment. Even when more emphasis is placed on the fate and movement of a pesticide within the field, as increasingly occurs within environmental risk assessment procedures, the question remains of whether the analyses used provide accurate predictions of fate, transport, and resulting ecological risk for a multitude of species. The connectivity of the ecosystems through soil, water, or air compartments can be overlooked, and extrapolation from microcosm and mesocosm model systems can be hampered by the plethora of environmental variables that may affect the fate and toxicity of compounds over various spatial and temporal scales.

Natural Complexity and Ecosystem Connectivity

Attaining reliable estimates of the fate and effects of existing and novel chemicals on ecosystems has been notoriously challenging. Field-based approaches suffer from the notion that they are less reliable because of the typical difficulties in causally linking chemical stressors to ecosystem structure and functioning in natural environments that are highly variable in both space and time. However, despite their complexity, field studies provide the only means to capture actual environmental conditions and ecological complexity.

The need to account explicitly for ecosystem complexity was recognized more than 50 yr ago—before the development of the risk assessment framework—following Rachel Carson's 1962 revelations about DDT in *Silent Spring* [5]. The impacts of DDT were almost all off-field and affected multiple species from birds of prey to top predator fish species. Data published in 1998 on persistent organic pollutants showed us that chemicals can be distributed across the entire globe [7]. Exposure to emitted chemicals used at target sites may occur at nontreated, connected ecosystems, because multiple propagation routes potentially occur. Recently, the agricultural application of neonicotinoid insecticides has presented a highly relevant case [8] to illustrate that a quantitative cross-ecosystems perspective is essential to ensure an adequate level of ecosystem protection (see Box 1). This unexpected wider impact on the ecosystem can be seen in numerous examples, most recently including organophosphates such as diazinon and chlorpyrifos in both the European Union and United States; data on pyrethroids may soon follow. When neonicotinoids are taken as a relevant example, it is clear that existing admission procedures did not prevent the detrimental effects of these insecticides on various nontarget ecosystem components (e.g., bees [9–11], aquatic invertebrates [12–14], and birds [15,16]). Multiple studies (referred to in European Academies Science Advisory Council [17]) have shown that effects of new generations of pesticides having either unknown or specific modes of action, like the neonicotinoid insecticides, resonate beyond the boundaries of the treated fields. These studies have uncovered multitrophic propagation routes for flagship species like insectivorous birds [15], and raised awareness on the importance of accounting for multitrophic responses.

Although comprehensive field analyses are difficult to attain for each newly manufactured and introduced chemical compound, these field-based studies show the potential to complement assessments on acute, chronic, and sublethal effects obtained in controlled experimental settings [17]. We embrace the rejuvenated emphasis on field studies, because they have proved to be of great scientific importance and particularly relevant for compounds with novel modes of action that are directly (e.g., pesticides) applied in the environment.

Safeguarding Our Natural Environment

Admission procedures of chemicals, in this case pesticides, are given within the legislation documents, and all necessary data has to be submitted by industry to the authorization organization. Combining exposure and effect concentrations allows us to assess a risk quotient (Figure 1); by taking that quotient together with a safety factor depending on uncertainties and data availability, a product is currently allowed on the market. Monitoring of approved chemicals is currently not a default step following admission procedures. The reasons why monitoring lags behind are various: different actors are involved in collecting surveillance data in different compartments; these various stakeholders are unaware of new admitted chemicals; and measurements are not possible because of lack of analytical techniques and insufficient funding. The incorporation of manufactured compounds within monitoring programs is often triggered by an incident and currently relies mainly on the efforts of scientists to create societal and political awareness. This carries the risk that many existing and emerging chemical stressors remain overlooked.

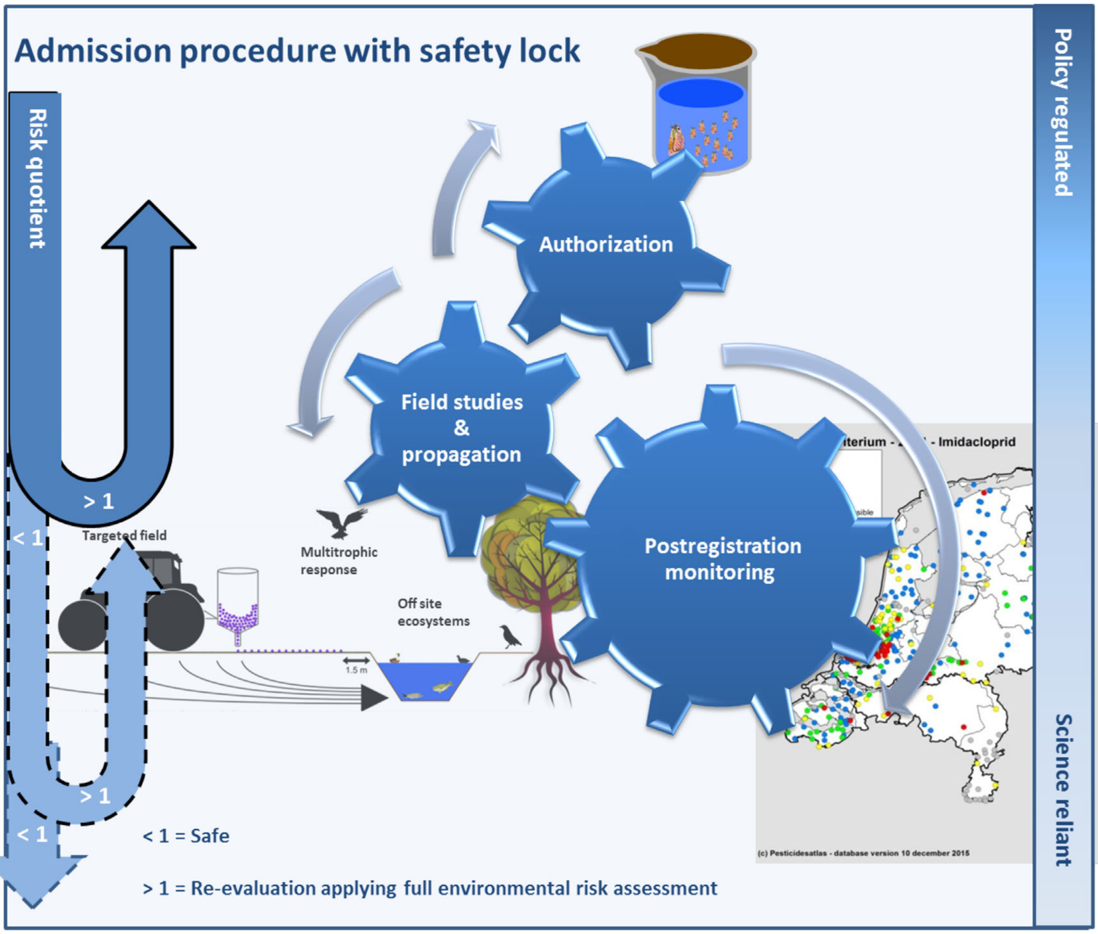

FIGURE 1: Schematic view reflecting the policy-driven admission process (dark blue arrow on the left) supplemented with the proposed postregistration monitoring and cross-ecosystem approach (light blue arrows on the left) as a safety lock to provide the necessary tools to assess and mitigate ecosystem threats. A simplified assessment based on risk quotients shows that a ratio (+ uncertainty anticipated safety factors) of < 1 results in admission and that risk quotients > 1 require re-evaluation.

To create a safety lock, we propose to enrich the admission procedure with postregistration monitoring (Figure 1, right wheel driven by authorization). Indeed, as soon as a compound is measured within a monitoring program, the pesticide residues can be compared with the relevant environmental quality criteria and their ecological effects in field settings.

To gain a better understanding of the actual environmental impact of newly produced compounds for which monitoring programs take years to develop, we propose a cross-ecosystem meta-analysis (Figure 1, left wheel driven by authorization). Such an analysis of a subset of relevant organisms and ecosystem compartments could provide a first indication of actual risks across trophic and ecosystem linkages. Based on this analysis, the risk quotients can also be calculated (for an illustration of this calculation, see Box 1).

Such a postregistration assessment (Figure 1, blue arrows), preferably based on the monitoring data of chemicals admitted or on the results of cross-ecosystem meta-analysis, can be used to calculate a second risk quotient including a safety factor to measure anticipated uncertainties. When this relative risk exceeds 1, re-evaluation of admission should be started.

Applying this type of safety lock accounts explicitly for the cascade effects that may occur in the field. It thus becomes evident that the sensitivity of different species varies strongly, and that multiple species in both targeted and connected ecosystems can be impacted [15,16]. The cross-ecosystem perspective as exemplified for the neonicotinoids case in Box 1 shows that the highest risks prevail not necessarily at the targeted field systems. The severe underestimation of impacts as observed in the present study likely may hold true for a wide range of anthropogenic (chemical) pressures.

Toward Postregistration Assessment in Policy and Management

Although the European Union (EU) policies and the Food and Agriculture Organization have promoted the idea of postregistration monitoring since 2000 [18], to date primary interest is still centered on isolated ecosystem compartments or perceptions of exposure (e.g., the Registration, Evaluation, Authorization, and Restriction of Chemicals [REACH] regulations).

An indicative cross-ecosystem meta-analysis of pesticide impacts using secondary data

We performed an indicative cross-ecosystem meta-analysis using a feasible (<30) set of peer-reviewed publications on the ecological effects of neonicotinoids (Supplemental Data I). Neonicotinoids, mostly applied as seed coatings, are partly taken up by crops. Rundlöf et al. [10] provided one of the first pieces of field evidence that seeds coated with neonicotinoids negatively affected bees. Our re-analysis indicates that bees show effects from 0.0001 μg a.i./g and upward for exposure via pollen (Figure 2), to 0.7 μg a.i./L for exposure via nectar (Figure 2). Following the example of Rundlöf et al. [10], coated seeds can be seen to result in an exposure of a total of 6 mg to 7.5 mg of neonicotinoids/m^2 of soil. This is important, as it has been reported that a level of 5 mg a.i./m^2 of soil can have significant ecological effects for various distinct terrestrial macrofaunal species (Figure 2). In contrast, the lowest critical values (chronic toxicity) for the microbial community in the field were only reported at 1 mg/kg soil (Figure 2).

Emitted chemicals used at target sites can enter nontreated ecosystems. Often this type of calculation is already part of the risk assessment. If not available in the risk assessment, exposure in connected off-site ecosystems can be considered based on generic assumptions, for example, we consider an agricultural field of 250 m × 250 m with a ditch on 2 sides having the standard 30 cm depth × 2 m width and 250 m length (details given in Supplemental Data II). Most of the applied (80–97%) neonicotinoids from coated seeds end up in the soil and porewater (Goulson et al. [16] and Sanchez-Bayo [14]), and leach into the groundwater and adjacent drainage ditches. In the most positive scenario, which uses a relatively fast degradation time (half-life = 27 d) and 10 d of leaching before reaching the adjacent ditch system, concentrations in the ditches are approximately 38.7 μg/L. In the worst-case scenario, which uses slow degradation time (half-life = 214 d) and a 1-d leaching time before reaching the adjacent ditch system, this concentration can reach levels of up to 60.4 μg/L (Supplemental Data II).

Both concentrations are well above (100–1000 times) test thresholds as reported for many distinct aquatic insects [12], for which sublethal ecological effects of neonicotinoid (in this case imidacloprid) residues detected in surface waters can already emerge when levels are just above 0.035 μg/L [35] (Figure 2).

In the case of imidacloprid, the first tier invertebrate test species *Daphnia magna* (US Environmental Protection Agency database, acute toxicity value, median effective concentration [EC50] of 85 200 μg/L) proved to be >10 000 times less sensitive compared to ecological keystone species such as mayflies (EC50 value of 1.0 μg/L for *Cloeon dipterum* [36]).

Monitoring networks that can be exploited for our proposed postregistration assessment include existing large datasets such as those collected under the European Water Framework Directive [19] and the European Soil Thematic Strategy [20]. For example, the pesticides atlas [21] currently includes concentrations of 550 different pesticides in surface waters of 700 locations sampled over the past 18 yr [22]. Others are the Reporting Obligations Database [23] on river water quality of French surface waters, databases created by the German regional water quality authorities [24] the National Water-Quality Assessment Program [25], and the Water Quality Data Portal datasets in the United States [26]. Infrastructures for ecological surveillance data also exist within all the EU Water Framework Directive programs and the many—mostly species-related—biodiversity and environmental monitoring schemes. Currently such ecological monitoring efforts are not tuned to chemical monitoring, making it difficult to link both types of datasets [12].

Through concerted efforts to systematically and rigorously combine and centralize the currently scattered monitoring efforts, a comprehensive postregistration monitoring network can be achieved. Currently, the efforts to achieve coupling of (inter)national databases is limited, and efforts are scattered. A full roadmap of "how" the postmonitoring should be established is not the purpose of our article, because this must be done following consensus. We propose that admission authorities and guiding authorities of the European Commission such as the European Food Safety Authority collaborate with commissions across the world (such as the US Environmental Protection Agency, the Organisation for Economic Co-operation and Development, and the EU Water

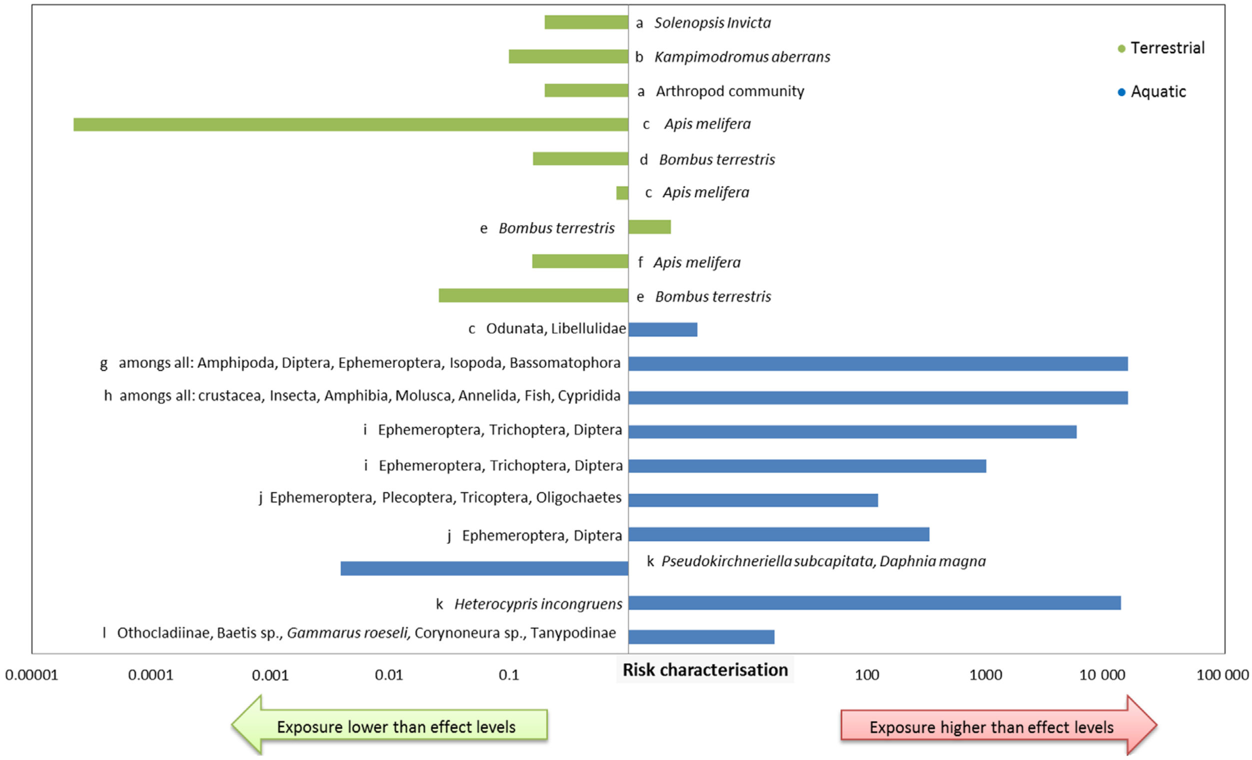

FIGURE 2: Sensitivity of species unwarranted exposed to neonicotinoids, normalized to the maximum application rate (set at 100% = 1), providing a risk characterization. The ecosystem most at risk is given the highest risk characterization. Green = terrestrial targeted site; blue = aquatic nontargeted site.

Framework Directive) to establish a working group providing guidance on how to effectively funnel monitoring data collected under different frameworks toward postregistration monitoring. Through a joint system, joint abatement strategies can be developed [27] when necessary, even though authorities are responsible for different regulatory frameworks. An obligatory postregistration monitoring can be implemented uniformly across the EU, and additional zone- or nation-specific landscape features can be incorporated by local governments.

Like admission procedures, postregistration assessment efforts may follow the established tiered approach. If only chemical field data are available, the pesticide concentrations can be compared with different environmental quality standards, indicating exceedance and hence potential to affect the ecological system [21]. One of the remaining challenges is that not all ecosystems receiving chemical emissions are represented within monitoring programs. For instance, although agricultural drainage ditches are the primary receivers of pesticide emissions, they are currently not included within EU Water Framework Directive monitoring schemes. Within the actual design, preferably both chemical fate (driven by the octanol/water partition coefficient [K_{OW}], persistence, and so on) and the effect targets (the sensitive biological groups) should be accounted for.

Combining chemical and ecological monitoring would allow us to establish statistical associations of exposures and ecological impacts [12,13]. When chemical and biological datasets with a range of modeling approaches are combined, multiple complex causality chains within natural ecosystems under stress can be evaluated [28]. In addition, the 10 recommendations provided by Brack et al. [27] to improve monitoring in risk assessment and to strengthen the process to harmonize chemical legislation (e.g., under REACH) may help in the implementation of postregistration assessment.

In practice, discernment of effects because of a particular pesticide in the presence of other stressors is challenging—but a multitude of approaches have been used to tackle such challenges, for example, through causality checks based on modeling [13] or on the use of data collected from in situ or caged assays within the field. Large-scale (landscape) modeling, accounting explicitly for both chemical fate and ecology, provides upscaling possibilities [29,30]. An example is the study by van den Brink et al. [31], who integrated multiscale and big-data approaches driven by the availability of site-specific models and data.

To identify potential ecological issues with a given pesticide, toxicological tools can be applied. Information on the chemical mode of action and adverse outcome pathways [32], for example, can help identify which types of biota are likely to be most sensitive and how such species effects might manifest under different environmental conditions. In terms of the potential risks of new chemicals, especially with an unknown mode of action for which the current risk assessment scheme fails to provide protection [33,34], indications of underestimations of actual ecological risks can be reached more quickly with implementation of the proposed post-registration monitoring.

The planned update of the EU Water Framework Directive in 2019 offers opportunities to put more emphasis on monitoring in many ways, from implementing new continuous monitoring techniques to the detection of new synthesized chemicals directly on admission. Postregistration monitoring and/or meta-analysis based on field data may thereby provide a safety lock within risk assessment by either re-evaluating the admission procedure or enforcing regulatory intervention.

Supplemental Data

The Supplemental Data are available on the Wiley Online Library at DOI: 10.1002/etc.3721.

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Data Availability

Data, associated metadata, and calculation tools are available from the corresponding author (vijver@cml.leidenuniv.nl).

REFERENCES

[1] Beck U. 1992. *Risk Society: Towards a New Modernity*. Sage, London, UK.

[2] Giddens A. 1999. Risk and responsibility. *Modern Law Review* 62:1–10.

[3] Paustenbach DJ. 1995. The practice of health risk assessment in the United States (1975–1995): How the U.S. and other countries can benefit from that experience. *Hum Ecol Risk Assess* 1:29–79.

[4] Van Leeuwen CJ, Vermeire TG. 2007. *Risk Assessment of Chemicals: An Introduction*. Springer, New York, NY, USA.

[5] Carson R. 1962. *Silent Spring*. Houghton Mifflin, Boston, MA, USA.

[6] European Food Safety Authority Panel on Plant Protection Products and Their Residues 2013. Guidance on tiered risk assessment for plant protection products for aquatic organisms in edge-of-field surface waters. *EFSA J* 11:3290–3558.

[7] Wania F, MacKay D. 1998. Tracking the distribution of persistent organic pollutants. *Environ Sci Technol* 9:390–396.

[8] Sánchez-Bayo F. 2014. The trouble with neonicotinoids. *Science* 346:806–807.

[9] Kessler SC, Tiedeken EJ, Simcock KL, Derveau S, Mitchell J, Softley S, Stout JC, Wright GA. 2015. Bees prefer foods containing neonicotinoid pesticides. *Nature* 521:74–76.

[10] Rundlöf M, Andersson GKS, Bommarco R, Fries I, Hederstrom V, Herbertsson L, Jonsson O, Klatt BK, Pedersen TR, Yourstone J, Smith HG. 2015. Seed coating with a neonicotinoid insecticide negatively affects wild bees. *Nature* 521:77–80.

[11] Woodcock BA, Isaac NJB, Bullock JM, Roy DB, Garthwaite DG, Crowe A, Pywell RF. 2016. Impacts of neonicotinoid use on long-term population changes in wild bees in England. *Nature Commun* 7:1–8.

[12] Van Dijk TC, Van Staalduinen MA, Van der Sluijs JP. 2013. Macro-invertebrate decline in surface water polluted with imidacloprid. *PLoS One* 8:e62374.

[13] Vijver MG, van den Brink PJ. 2014. Macro-invertebrate decline in surface water polluted with imidacloprid: A rebuttal and some new analyses. *PLoS One* 9:e89837.

[14] Sánchez-Bayo F, Goka K, Hayasaka D. 2016. Contamination of the aquatic environment with neonicotinoids and its implication for ecosystems. *Front Environ Sci* 4:71.

[15] Hallmann CA, Foppen RPB, Turnhout CAM *et al.* 2014. Declines in insectivorous birds are associated with high neonicotinoid concentrations. *Nature* 511:341–343.

[16] Goulson D. 2014. Pesticides linked to bird declines. *Nature* 511:295–296.

[17] European Academies Science Advisory Council. 2015. Ecosystem services, agriculture and neonicotinoids. German National Academy of Sciences Leopoldina, policy report 26. Halle, Germany.

[18] European Commission Directorate General Health and Consumer Protection. 2000. Technical material and preparations: Guidance for generating and reporting methods of analysis in support of pre- and post-registration data requirements for Annex II (part A, Section 4) and Annex III (part A, Section 5) of Directive 91/414. SANCO/3030/99 rev.4 working document. Brussels, Belgium.

[19] European Commission. 2000. Directive 2000/60/EC of the European Parliament and of the Council establishing a framework for the Community action in the field of water policy. EU WFD 2000/60/EC. Brussels, Belgium.

[20] European Commission staff working document. 2006. Document accompanying the Communication from the Commission to the Council, The European Parliament, the European Economic and Social Committee and the Committee of the Regions. Thematic strategy for soil protection—Impact assessment of the thematic strategy on soil protection {COM(2006)231 final} {SEC(2006)1165} /* SEC/2006/0620 */. Brussels, Belgium.

[21] Institute of Environmental Sciences (CML), Leiden University, Rijkswaterstaat-WVL. 2016. Pesticides atlas. [cited 2016 August18]. Available from: www.bestrijdingsmiddelenatlas.nl

[22] Vijver MG, Van 't Zelfde M, Tamis WLM, Musters KJ, Snoo GR. 2008. Spatial and temporal analysis of pesticides concentrations in surface water: Pesticides atlas. *J. Environ Sci Health B* 43:665–674.

[23] European Environment Information and Observation Network (EIONET). 2016. Reporting obligation for: River quality (EWN-1). Reporting obligations database. [cited 2016 September 22]. Available from: http://rod.eionet.europa.eu/obligations/28/deliveries

[24] Schreiner V, Szöcs E, Bhowmik AK, Vijver MG, Schäfer RB. 2016. Pesticide mixtures in streams of several European countries and the USA. *Sci Total Environ* 573:680–689.

[25] US Geological Survey 2015. National Water-Quality Assessment Program. [cited 2016 September 22]. Available from: http://water.usgs.gov/nawqa/.

[26] National Water Quality Monitoring Council. 2017. Water Quality Portal. Collaboration of United States Geological Survey (USGS), Environmental Protection Agency (EPA), National Water Quality Monitoring Council (NWQMC) [cited 2016 September 22]. Available from: https://www.waterqualitydata.us/.

[27] Brack W, Dulio V, Ågerstrand M, Allan I, Alterburger R, Brinkman M, Bunke D, Burgess RM, Cousins I, Escher BI, Hernandez FJ, Hewitt LM, Hilscherova K, Hollender J, Hollert H, Kase R, Klauer B, Limdim C, Herraez DL, Miege C, Munthe J, O'Toole S, Posthuma L, Rudel H, Schafer RB, Sengl M, Smedes F, van de Meent D. 2017. Towards the review of the European Union Water Framework management of chemical contamination in European surface water resources. *Sci Total Environ* 576:720–737.

[28] Chariton A, Sun M, Gibson J, Hose GC. 2016. Emergent technologies and analytical approaches for understanding the effects of multiple stressors in aquatic environments. *Mar Freshw Res* 67:414–428.

[29] Baird DJ, van den Brink PJ, Chariton AA, Johnston EL. 2016. New diagnostics for multiply stressed marine and freshwater ecosystems: Integrating models, ecoinformatics and big data. *Mar Freshw Res* 67:391–392.

[30] De Laender F, Morselli M, Baveco H, van den Brink PJ, Di Guardo A. 2015. Theoretically exploring direct and indirect chemical effects across ecological and exposure scenarios using mechanistic fate and effects modelling. *Environ Int* 74:181–190.

[31] van den Brink PJ, Bo Choung C, Landis W, Mayer-Pinto M, Pettigrove V, Scanes P, Smith R, Stauber JL. 2016. New approaches to the ecological risk assessment of multiple stressors. *Mar Freshw Res* 67:429–439.

[32] Ankley GT, Bennett RS, Erickson RJ, Hoff DJ, Hornung MW, Johnson RD, Mount DR, Nichols JW, Russom CL, Schmieder PK, Serrrano JA, Tietge JE, Villeneuve DL. 2010. Adverse outcome pathways: A conceptual framework to support ecotoxicology research and risk assessment. *Environ Toxicol Chem* 29:730–741.

[33] Brock TCM, Van Wijngaarden RPA. 2012. Acute toxicity tests with *Daphnia magna, Americamysis bahia, Chironomus riparius* and *Gammarus pulex* and implications of new EU requirements for the aquatic effect assessment of insecticides. *Environ Sci Pollut Res* 19:3610–3618.

[34] Van Wijngaarden RPA, Maltby L, Brock TCM. 2015. Acute tier-1 and tier-2 effect assessment approaches in the EFSA Aquatic Guidance Document: Are they sufficiently protective for insecticides? *Pest Manag Sci* 71:1059–1067.

[35] Morrissey CA, Mineau P, Devries JH, Sanchez-Bayo F, Liess M, Cavallaro MC, Liber K. 2015. Neonicotinoid contamination of global surface waters and associated risk to aquatic invertebrates: A review. *Environ Int* 74:291–303.

[36] Roessink I, Merga LB, Zweers HJ, van den Brink PJ. 2013. The neonicotinoid imidacloprid shows high chronic toxicity to mayfly nymphs. *Environ Toxicol Chem* 32:1096–1100.