



Universiteit
Leiden
The Netherlands

Low-cost environmental traceability of pesticides is essential for safety

Vijver, M.G.; Snoo, G.R. de; Visser, M.D.

Citation

Vijver, M. G., Snoo, G. R. de, & Visser, M. D. (2025). Low-cost environmental traceability of pesticides is essential for safety. *Integrated Environmental Assessment And Management*. doi:10.1093/inteam/vjaf132

Version: Corrected Publisher's Version

License: [Creative Commons CC BY-NC 4.0 license](https://creativecommons.org/licenses/by-nc/4.0/)

Downloaded from: <https://hdl.handle.net/1887/4281886>

Note: To cite this publication please use the final published version (if applicable).

Low-cost environmental traceability of pesticides is essential for safety

Martina G. Vijver^{1,*}, Geert R. de Snoo^{1,2}, and Marco D. Visser¹

¹Institute of Environmental Sciences, Leiden University, Leiden, The Netherlands

²Royal Dutch Academy of Arts and Sciences (KNAW), Amsterdam, The Netherlands

*Corresponding author: Martina G. Vijver. Email: vijver@cml.leidenuniv.nl

Abstract

We issue a call to action: in the context of safe design, all pesticides must be traceable via low-cost methods that are accessible for routine environmental monitoring by public institutions. Insights into the far-reaching impacts of pesticides depend on our ability to detect these chemicals in the environment. Once a pesticide is authorized for use, environmental monitoring serves as a critical warning system that complements risk assessments. Postregistration monitoring is recognized by different policy frameworks such as the Water Framework Directive and the European Green Deal. However, we highlight an urgent concern: despite formal requirements for detectability in registration, novel pesticides are becoming progressively undetectable in practice. We demonstrate how mandated reductions in pesticide use measured as volume can drive chemical innovations that unintentionally undermine environmental accountability and safety. For example, volume can be decreased while maintaining effectiveness by increasing the specificity or toxicity of the pesticide. This phenomenon is analogous to “analytical homeopathy,” where active ingredients remain effective even at extremely low dosages, rendering them undetectable by standard analytical chemistry. This issues a significant challenge: higher toxicity can imply lower environmental quality standards near detection limits. This leads to the troubling problem of “known unknowns,” risks posed by active ingredients whose emissions remain unquantified under current field monitoring conditions. In response to this emerging threat, we propose a foundational principle, that all synthetic pesticides should be detectable in the environment at the concentration of their active ingredients, enabling cost-effective and reliable monitoring. If neglected, then the credibility and function of monitoring as a warning system for unintended biodiversity harm is increasingly undermined, regardless of formal analytical capabilities.

Keywords: ecotoxicity, post-registration monitoring, accountability and responsibility, pesticides residues

Introduction

Driven by demand from consumers, governments, and civil society organizations, industries are under increasing pressure to adopt responsible business practices and reduce their environmental and public health impacts. In response, transparency has become a priority within industrial sectors, emphasizing adherence to Safe and Sustainable by Design principles (Van de Poel & Robaey, 2017). Reflecting this shift, the European Commission adopted a recommendation in 2022 to establish a European assessment framework for Safe and Sustainable by Design chemicals and materials, supporting the Chemical Strategy for Sustainability and the Green Deal’s zero pollution targets (e.g., Subramanian et al., 2023). Similarly, the European Food Safety Authority (EFSA) promotes openness and accountability on pesticide data. Here, we argue that with the rise of novel pesticides, pesticide detection methods that are sensitive, practical, implementable, and cost-effective are crucial, because without them, reduced emissions goals may paradoxically jeopardize human and environmental health.

Pesticides are intentionally introduced into the environment to control pests, weeds, and fungi. Ideally, pesticides achieve a >99.9% efficacy in controlling pest species with negligible

impact on nontarget organisms and within nontarget areas. Ongoing research aims to refine pesticide development to meet evolving agricultural needs and sustainability goals. This is driving technological innovation towards less pesticides per acre or crop volume, or so-called weight-based and volume-based measures. Using a basic mathematical model (see [online supplementary material](#)), it can be shown that novel chemicals can achieve mandated reductions in pesticide use in nonmutually exclusive ways (Figure 1A): the logarithm of the mandated reduction ($\log(z)$) must be matched by a linear increase in effectivity ($\mu_{\text{new}} < \mu_{\text{old}}$), a corresponding decrease in specificity ($\sigma_{\text{new}} < \sigma_{\text{old}}$), or a combination of both mean toxicity and uncertainty.

Increased effectivity and specificity, for instance, can be achieved by designing molecules that exploit unique biological vulnerabilities in target pests (Umetsu & Shirai et al., 2020) and understanding the biochemical pathways and physiological processes of the pest (Araújo et al., 2023). Reducing uncertainty as an alternative is often achieved by modifying the bioavailability of formulations. For example, granular seed-coating applications can have lower impact on nontarget areas than spray applications where drift can occur, e.g., clothianidin-coated oilseed rape (Elbert et al., 2008). Pesticide efficacy also depends on how well

Received: June 13, 2025. Revised: August 12, 2025. Accepted: September 19, 2025

© The Author(s) 2025. Published by Oxford University Press on behalf of the Society of Environmental Toxicology and Chemistry.

This is an Open Access article distributed under the terms of the Creative Commons Attribution-NonCommercial License (<https://creativecommons.org/licenses/by-nc/4.0/>), which permits non-commercial re-use, distribution, and reproduction in any medium, provided the original work is properly cited. For commercial re-use, please contact reprints@oup.com for reprints and translation rights for reprints. All other permissions can be obtained through our RightsLink service via the Permissions link on the article page on our site—for further information please contact journals.permissions@oup.com.

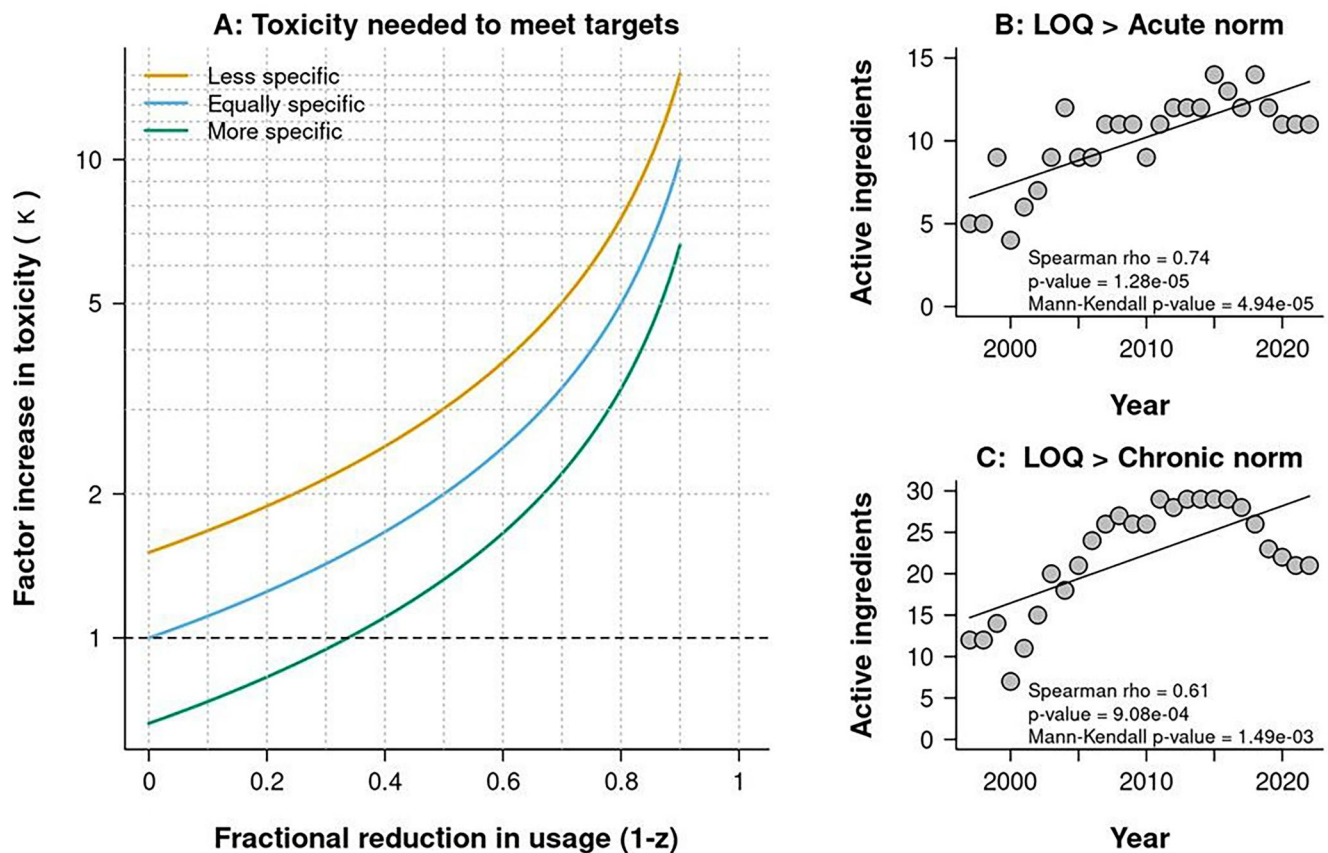


Figure 1. (A) Required toxicity of novel chemicals to achieve mandated reductions in pesticide usage, as predicted by a basic ecological risk assessment model. The mathematical model builds the hypothesis that mass-based reductions incentivize a shift towards lower required dosages in the field due to more toxic or more targeted chemicals, or by reducing uncertainty in volumes required (i.e., by spraying more precisely or reducing pesticide losses). The x-axis represents the mandated reduction in pesticide usage (1-z), indicating the fractional levels of reduction ($0.2 = 20\%$ volume or mass based reduction in total usage). The y-axis (log-scale) represents the factor increase in median toxicity (κ) of a novel chemical. Lines show the κ needed to compensate for the mandated fractional mass-based reduction (1-z). The model suggests that mass-based reduction targets can be met by optimizing a combination of toxicity or specificity of new chemicals. The three scenarios illustrated are: less targeted novel chemicals (orange line; $\sigma_0 > \sigma_e W$): median toxicity must always be larger than before ($\kappa > 1$) and increase disproportionately with the mandated reductions (z). Equally targeted novel chemicals (blue line; $\sigma_0 = \sigma_e W$): Median toxicity must increase with z ($\kappa \geq 1$). More targeted chemicals (green line; $\sigma_0 > \sigma_e W$): median toxicity can be reduced ($\kappa < 1$), and increases less rapidly with z, and median toxicity may increase ($\kappa > 1$) depending on how strict the target reduction goals are. See [online supplementary material](#) for more mathematical details. Numbers of active ingredients (a.i.) with a mean reporting threshold (i.e., LoQ) above the acute (B) and chronic (C) environmental norms per year. LOQ = limit of quantitation, which is the lowest concentration or amount of a substance that can be reliably and accurately measured by a specific analytical method. In essence, there are an increasing number of substances that are only detected at concentrations exceeding environmental protection norms. Data come from the Dutch monitoring program 1997–2022 and contain over 9.3 million measurements of substances sampled from over 6,364 days at 3,354 locations. The analysis focuses on 158 a.i. with water quality norm in the EU legislation. These so-called “untraceable substances” have increased despite the fact that the reporting threshold has dropped on average 28% per decade. Orange = Highest line, Blue = Middle line, Green = Lowest line.

the active ingredient is absorbed (e.g., nanopesticides [Kah et al., 2021]), distributed, and remains active in the target organism or environment. The formulation is critical in ensuring stability, solubility, and controlled release of the active ingredient.

Schulz et al. (2021) highlighted the limitations of weight-based measures in pesticides policy, noting a significant shift in novel chemicals over the past 25 years including impacts to vertebrates and increased impacts on insects and aquatic invertebrates. At the same time, De Snoo (2003) pointed out the psychological challenge of applying low amounts of pesticides; applicators might feel that small quantities are insufficient for effective pest control, potentially leading to overapplication. So even when lower application rates are recommended, application rates may be high due to perceived beliefs that greater pesticide application will achieve greater benefits. Thus, despite foreseen overall reductions in pesticide application, the anticipated decline in environmental impacts may not materialize, underscoring the

inherent complexity of achieving substantive reductions in pesticide-related effects.

Trace detection in monitoring

Once a pesticide is authorized, environmental monitoring serves as a crucial warning system complementing risk assessments (Vijver et al., 2017). However, this system appears increasingly compromised as novel, more potent pesticides emerge (Figure 1). A clear risk in the development of pesticides that are effective at lower dosages that is not highlighted is that we will reach the limits in our ability to detect and quantify chemicals in monitoring programs—a trend that already seems underway (Figure 1B and C). This can lead to undetected environmental damage and creates a blind spot in understanding the risks of new chemicals, despite the availability of registration-level detection methods.

Monitoring programs are, by necessity, organized to screen numerous pesticides and therefore must deal with constraints in analytical methods. All analytical methods have a detection limit, defining the smallest amount of substance that can be reliably identified. Although analytical detection limits have been optimized over recent years and allow detection within the picogram to nanogram ranges, small traces or single molecules often fall within this limit, requiring methods with extraordinary sensitivity. However, even sensitive methods can fail, because a certain amount of molecules is needed before a cumulative signal becomes strong enough to outweigh the background noise. Moreover, detecting single molecules often requires expensive instruments like specialized mass spectrometry or single-molecule fluorescence microscopy. All require precise calibration, maintenance, advanced sample preparation, and considerable technical expertise. Especially for field relevant samples, the standard protocols often selected by water managers for broad screening purposes may fall short. Logistical constraints and financial considerations limit tailored matrix-dependent extraction methods, which in practice means that the water manager can choose from among two or three different packages of standardized extraction protocols before a multiresidue is analytically measured. As a result, measuring ever lower concentrations becomes disproportionately more expensive and increasingly out of reach for routine national and regional monitoring systems. Moreover, there is an inherent lag in the adaptation of monitoring programs to newly authorized compounds, partly due to the limited scope of commercial laboratories, which do not always offer up-to-date screening options and then, only after request by regional water managers. As noted, current standard monitoring packages are not specifically designed to address the analytical challenges posed by the most novel pesticides. For instance, this is the case with nanopesticides, for which routine analytical methods have not yet been developed, as well as that both very polar and very nonpolar chemicals can be analytically challenging because they do not ionize efficiently in standard mass spectrometry setups.

Sampling surface water under field conditions involves variation in water chemistry across locations, seasons, and day-night fluctuations. Such variation in water chemistry considerably influences detection techniques and hence limits by affecting the noise level in samples, emphasizing the need for precise sampling preparation protocols tailored to the different water or sediment types sampled (Campanale et al., 2021). The Water Framework Directive, through Legislative Decree 172/2015 (amending Legislative Decree 260/2010), defines technical criteria for identifying and characterizing water bodies. Once a pesticide enters the environment, it may undergo biotic or abiotic transformation processes. Consequently, the absence of the parent compound in environmental samples does not necessarily indicate its nonoccurrence but may reflect its conversion into one or more transformation products. Transformation products can persist and exhibit less or greater toxicity than the parent compound. This complexity presents a significant challenge for regional water authorities tasked with monitoring and risk assessment.

In practical terms, all the reasons above can lead to more chemicals—despite being formally registered with validated detection methods—going undetected in field conditions. As a result, exceedances of environmental quality standards may go unnoticed, representing a concerning risk that aligns with observed trends (Figure 1B and C). Moreover, it should be noted that

even barely detectable trace amounts can accumulate over time and contribute to significant cumulative (joint) risks.

Statistical factors further complicate the detection of single molecules. Sampling highly toxic but low-concentration pesticides from natural surface waters is inherently challenging. These highly effective active ingredients, if undetected due to their low concentrations, can lead to “unknown knowns”; we understand their reactivity, but remain unaware of their occurrence until identified through monitoring. This underscores the principal role cost-effective detection methods play in environmental health.

Transparency in authorization documents the way forward in low-cost monitoring

The current authorization of pesticides does not result in zero pollution, and despite the consideration of environmental risks, we cannot ignore that pesticides are ubiquitous in the environment across virtually the entire globe (Tang et al., 2021). We have previously advocated for postregistration monitoring (Vijver et al., 2017). Balancing the needs of farmers, landowners, municipalities, citizens, and others with those of water managers, conservation nongovernmental organizations (NGOs), and governmental institutions responsible for monitoring emissions is a delicate task and requires respectful consideration of multiple desired goals. As of 2024, there are two evolving routes to enhance transparency in pesticides authorization.

Preregistration

The EFSA requires manufacturers to submit all pertinent information when filing a pesticide dossier, including substance test methods and measurement protocols. These detailed protocols can then be distributed, possibly automatically, to authorities responsible for monitoring, such as authorization agencies, water managers, and commercial measurement laboratories. This would enable the measurement of new substances from the first year of authorization. Currently, protocols are often not available after a substance has been authorized (for example, sulfoxaflor was only after three years of authorization for the first time measured and introduced within the monitoring reporting; see www.bestrijdingsmiddenatlas.nl). Currently, affordable public monitoring is not systematically enabled or prioritized despite the theoretical availability of detection protocols.

Postregistration

The Authorizations Board of Member States is mandated to conduct official controls to ensure compliance with the regulation (Article 68: Monitoring and Controls). Within six months of the end of the year, they must report to the Commission detailing the scope and outcomes of these controls. Several government agencies are involved in monitoring and enforcing pesticide use, focusing on compliance checks, enforcement in trade and distribution, safe working conditions, biocidal product use, and monitoring pesticide use in agriculture and horticulture. The broad chemical surveillances done in the Rhine catchments under the lead of International Commission for the Protection of the Rhine are potentially a good model for a monitoring program. Other excellent examples are the monitoring data on pesticides in surface waters as measured by water managers within the Netherlands made publicly accessible at www.bestrijdingsmiddenatlas.nl containing 10 M measurements covering 700 active ingredients over a period of 1997 until the present. Integrating this information into reassessments several years postregistration is now currently under consideration, as advocated by Vijver et al. (2017).

However, the effectiveness of this monitoring hinges on detecting and quantifying all chemicals at concentrations below their norms under field conditions, an outcome not guaranteed by regulatory requirements alone.

National authorization boards for plant protection products and biocides have the opportunity to set country-specific legal actions to address water-specific or ecosystem-specific needs. These boards must rely not only on modeling results but also on monitoring data to effectively protect ecosystems. Next to accounting for persistence, bioaccumulation, and toxicity (ECHA; chemicals of concern criteria adopted within the Green Deal and Authorization), it is crucial to ensure that pesticides are traceable in nature and at low costs. The latter is essential for transparency and requires cautious admission of highly effective active ingredients, as their low detection limit and high toxicity at trace levels pose significant operational challenges for those tasked with ensuring compliance and environmental safety, particularly in budget-constrained monitoring settings. Armed with cost-effective monitoring abilities, stakeholders such as drinking water companies, food producers, water managers, environmental NGOs, and governmental organizations concerned with human and environmental health will be better equipped to perform their tasks.

Accountability comes with traceability

Technological advances are leading to tailored pesticides that can meet volume-based emission goals by being more specific and effective at lower concentrations. Analytically, these novel chemicals resemble homeopathy; their active ingredients are untraceable yet still potent. More effective, hence more toxic, substances generally require stricter environmental quality standards. This means that these new chemicals designed for lower dosages create a dual challenge of increased chemical potency and reduced traceability, as their norms frequently fall below what routine environmental monitoring can reliably detect (Figure 1). This poses significant risks because detecting traces or even single molecules using standard environmental monitoring programs is extremely challenging due to the limitations of analytical methods and low probability of detection of rare molecules. This creates a pitfall: the unknown risks of unintended emissions of untraceable active ingredients.

Over the years, policymakers, risk assessors, and other relevant stakeholders have progressively vacillated between hazard-based approaches, which focus primarily on exposure, and risk-based monitoring frameworks that incorporate both exposure and effect. Taking the European Union's Water Framework Directive as an example, both approaches are mandated: (1) chemical monitoring, which aligns with policy frames such as the circular economy and zero pollution, and (2) ecological monitoring, which supports risk-based frames aimed at protecting a high proportion (95%) of aquatic species. Within the scope of ecological monitoring, the concept of effect-based monitoring has gained increasing prominence. Although a detailed discussion of the diverse methodologies encompassed within risk-based monitoring lies beyond the scope of this article, it is important to acknowledge that even with the plurality of approaches traceability is key.

Cost-effective traceability should be a preregistration criterion before any new chemical is allowed or is authorized for use and thus allowed to enter environmental systems. Ensuring this traceability is essential to monitor emissions effectively, safeguarding both human and environmental health. These

underlying principles and implications apply universally across environmental compartments—water, soil, and air—as chemicals traverse through all ecosystems. We also plead for a system ensuring all manmade pesticides come with analytical protocols before they are permitted for use. This aligns with transparency, open science, and verifiable green claims. Ultimately, it protects human and environmental health from the unintended side effects of chemical innovation, driven by mass-based reduction targets that prioritize volume reduction over detectability and accountability.

Supplementary material

Supplementary material is available online at *Integrated Environmental Assessment and Management*.

Data availability

No data were generated for this article.

Author contributions

Martina G. Vijver (Conceptualization, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Writing—original draft, Writing—review & editing), Geert R. de Snoo (Conceptualization, Writing—review & editing), and Marco D. Visser (Conceptualization, Investigation, Methodology, Software, Visualization, Writing—review & editing)

Funding

This article was funded by the European Research Council 101002123. www.bestrijdingsmiddenatlas.nl is developed within the Leiden University CML and financially supported by the Dutch Ministry of Infrastructure and water management and the impact funds of the CML Institute.

Conflicts of interest

The authors have no competing interests.

Acknowledgement

We thank the staff of the team of Dr Pol for discussions and proofreading of the manuscript and check on the facts. Dr Pol leads a team at the Board for the Authorisation of Plant Protection Products and Biocides (CTGB), the Dutch governmental body responsible for evaluating and authorizing pesticides (plant protection products) and biocides before they can be marketed and used in the Netherlands.

References

- Araújo, M. F., Castanheira, E. M. S., & Sousa, S. F. (2023). The buzz on insecticides: A review of uses, molecular structures, targets, adverse effects, and alternatives. *Molecules (Basel, Switzerland)*, 28, 3641. <https://doi.org/10.3390/molecules28083641>
- Campanale, C., Massarelli, C., Losacco, D., Bisaccia, D., Triozzi, M., & Uricchio, V. F. (2021). The monitoring of pesticides in water matrices and the analytical criticalities; a review. *TrAC Trends in Analytical Chemistry*, 144, 116423. <https://doi.org/10.1016/j.trac.2021.116423>

- De Snoo, G. R. (2003). Variation in agricultural practice and environmental care. In F. den Hond, P. Groenewegen, & N. M. van Straalen (Eds.), *Pesticides: Problems, improvements, alternatives* (pp. 100–112). Blackwell Science, Sustainable Pest Management Series.
- Elbert, A., Haas, M., Springer, B., Thielert, W., & Nauen, R. (2008). Applied aspects of neonicotinoid uses in crop protection. *Pest Management Science*, 64, 1099–1105. <https://doi.org/10.1002/ps.1616>
- Kah, M., Johnston, L. J., Kookana, R. S., Bruce, W., Haase, A., Ritz, V., Dinglasan, J., Doak, S., Garelick, H., & Gubala, V. (2021). Comprehensive framework for human health risk assessment of nanopesticides. *Nature Nanotechnology*, 16, 955–964. <https://doi.org/10.1038/s41565-021-00964-7>
- Pesticidesatlas. (2025). www.bestrijdingsmiddelenatlas.nl
- Schulz, R., Bub, S., Petschick, L. L., Stehle, S., & Wolfram, J. (2021). Applied pesticide toxicity shifts toward plants and invertebrates, even in GM crops. *Science (New York, N.Y.)*, 372, 81–84. <https://doi.org/10.1126/science.abe1148>
- Subramanian, V., Peijnenburg, W. J. G. M., Vijver, M. G., Blanco, C. F., Cucurachi, S., & Guinée, J. B. (2023). Approaches to implement safe by design in early product design through combining risk assessment and life cycle assessment. *Chemosphere* 311137080, 311, 137080. <https://doi.org/10.1016/j.chemosphere.2022.137080>
- Tang, F. H. M., Lenzen, M., McBratney, A., & Maggi, F. (2021). Risk of pesticide pollution at the global scale. *Nature Geoscience*, 14, 206–210. <https://doi.org/10.1038/s41561-021-00712-5>
- Umetsu, N., & Shirai, Y. (2020). Development of novel pesticides in the 21st century. *Journal of Pesticide Science*, 45, 54–74. <https://doi.org/10.1584/jpestics.D20-201>
- Van de Poel, I., & Robaey, Z. (2017). Safe-by-design: from safety to responsibility. *Nanoethics*, 11, 297–306. <https://doi.org/10.1007/s11569-017-0301-x>
- Vijver, M. G., Hunting, E. R., Nederstigt, T. A. P., Tamis, W. L. M., Van den Brink, P. J., & Van Bodegom, P. M. (2017). Postregistration monitoring of pesticides is urgently required to protect ecosystems. *Environmental Chemistry and Toxicology*, 3721, 860–865. <https://onlinelibrary.wiley.com/doi/10.1002/etc.3721>