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Brief Communication

Precision farming and environmental pesticide regulation in the EU—How does it fit together?

Michael Faupel, Felix von Blanckenhagen, Johannes Lückmann, Daniel Ruf, Gisela Wiedemann, and Jan-Dieter Ludwigs
RIFCON GmbH, Hirschberg, Germany

Abstract
Precision farming technology allows pesticides to be applied precisely to the target while leaving the rest of the field untreated. In the regulation of pesticides, however, a homogeneously sprayed field is considered as the standard scenario. To this end, the current status of pesticide risk assessment from the perspective of terrestrial vertebrates, terrestrial invertebrates, and plants as well as aquatic organisms was examined with respect to the EU registration of a pesticide to be applied via precision farming techniques. We highlight which and how respective parts of the technical procedures could be adapted to account for this technology. Our results demonstrate that large parts of risk assessment procedures can be modified, reducing pesticide application and the exposure to the environment. However, further studies and definite procedures are essential to realistically apply, for example, area restriction in the currently required environmental risk assessment schemes. Precision farming has then great potential to achieve the political and public goal of reducing pesticide use, increasing environmental safety, and enhancing the needs of a sustainable agricultural practice. *Integr Environ Assess Manag* 2022;00:1–7. © SETAC

KEYWORDS: Environmental risk management, Pesticide regulation, Precision farming

INTRODUCTION
There is a major trend in opinions toward the need for reduction of pesticides, which is being heatedly debated both politically and publicly. The European Commissions' Green Deal, for example, aims to include a 50% reduction in pesticide use in European agriculture until 2030 (European Commission [EC], 2020). At the same time, current technical innovations make it possible to precisely apply pesticides spatially, meaning exclusively to where they are needed, that is, for a given target pest and not to the total field area. These precision farming options can contribute to a general pesticide reduction (Finger et al., 2019; Möhring et al., 2020) and therefore to a reduced exposure of pesticides to the environment, without compromising the efficacy necessary to withstand pest pressures on crop yield or quality. Therefore, precision farming can decrease the negative effects of agricultural production on the environment, without decreasing crop quality at the same time (Finger et al., 2019). The term precision farming (PF) means a field management system that uses site-specific information and technologies to treat the field not as a single unit, but to divide it into smaller, manageable units with specific characteristics (cf. Zakka et al., 2019). In general, the term PF can be used more broadly to include, for example, optimization of nutrient and water supply to individual plants or the possibility of managing individual fields with mixed crops. Here, however, we use the term PF in the sense of a spatially precise application of pesticides. Mulla and Khosla (2016) defined PF as doing the right practice at the right location and time, and at the right intensity. Thus, the PF technique intends the application of pesticides only on field areas of pest infestation, which can considerably reduce the overall amount applied (i.e., the total area treated). Technically, this can be achieved by using spraying devices that are able to operate on a small scale, for example, on single plants or plant rows. These can be simple, manually controlled handheld sprayers, tractor-mounted spray booms equipped with a targeted detection system for individual nozzle control, or semi- or fully autonomous drones equipped not only with sprayers but also with other optical and motion sensors, for example, for crop monitoring (Devi et al., 2022; Hafeez et al., 2022; Mogili & Deepak, 2018; Song et al., 2015). Currently, environmental requirements (among others) for the registration of pesticides and their active ingredients (a.i.) in the EU are regulated by Regulation 1107/2009 (European Commission [EC], 2009) and by a variety of technical guidance documents (e.g., European Food Safety Authority (EFSA), 2009, 2013a; Forum for Co-Ordination of Pesticide

Correspondence Michael Faupel, RIFCON GmbH, Goldbeckstrasse, Hirschberg, Germany.
Email: michael.faupel@rifcon.de
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Fate Models and Their Use (FOCUS), 2015, among several others). In practice, the application of pesticides in the field follows the product-specific use pattern, the GAP (Good Agricultural Practice) table, which defines at what time, in which crop, at what quantity, how often, and against which pest or for which indication the product can or should be applied. The GAP defines the application to be effective and allowed as the maximum for environmental safety as well as resistance prevention. For spray applications, this quantity is typically expressed as L product/ha (1 hectare [ha] corresponds to 10 000 m²) or g a.i./ha (seed treatments and granular pesticides are handled differently in the risk assessment and are therefore not considered here). The rate g a.i./ha implies that the pesticide is applied equally to the entire field. Currently, the respective risk assessment and its evaluation either scale or depend on this rate. Assuming a PF scenario where, for example, only 25% of a field is treated and 75% remains untreated, the amount of effectively applied pesticide over the field area would be reduced by a factor of 4, although in treated areas the residue level in soil or on crops would be the same as after a full field application. However, in current pesticide risk assessment schemes for calculations of environmental fate and ecotoxicology, it is crucial if 25% of a given field area in full application rate is considered or if, for example, 25% of the intended use per ha as a mean application rate is considered. Therefore, guidance is needed to cope with these new and overall pesticide-reducing application techniques within the regulatory framework to adapt regulation to such farming options already available. In fact, considering these techniques in the risk assessment and registration procedures will support publicly and politically desired pesticide reduction in the EU and worldwide. In addition, pesticides that cannot be registered because they do not pass the current risk assessments, based on the application rate being effective, but being desired by farmers for certain infestations or in terms of resistance management, may be reconsidered by connecting specific restrictions directly to PF tools, decreasing the total application area and the overall pesticide amount, and increasing nontreated areas per field and within the landscape. Therefore, PF can be a step toward exploring new registration approaches to products that must remain available to agriculture while significantly reducing exposure of the environment. However, this cannot be applied to pesticides that exceed EU-agreed cutoff criteria (e.g., endocrine disrupting properties) being independent of the area sprayed.

Giving a practical example, we consider the use of a herbicide that is applied via PF technique in single spots or on small areas of weeds present in the field, as opposed to a full-area application (see also Christensen et al., 2008; Oerke et al., 2010). Following this example, we present the current status of the risk assessment and evaluation scheme. Then, we elaborate on how a reduced treatment area affects the current risk assessment scheme regarding terrestrial vertebrates, terrestrial invertebrates, and plants as well as aquatic organisms and, where data are missing, to apply such changes appropriately. Without claiming completeness, we highlight general aspects that we propose for revision to account for a pesticide risk assessment and evaluation intended to be applied, at least optionally, with PF techniques. Further, we would like to point out that the assumptions that we discuss regarding possibilities of exposure and risk reduction need to be underpinned by experimental data comparing conventional full field with partial field or spot application.

Terrestrial vertebrates and precision farming

Background information. For terrestrial vertebrates (i.e., wildlife), acute and chronic toxicity exposure calculations are carried out based on toxicity data and dietary intake of the species in focus (EFSA, 2009). As a worst-case scenario, a first-tier approach to acute scenarios, it is assumed that the diet exhibits the maximum or the 90th percentile residue load for the specific diet item that an indicator species feeds on. For first-tier chronic assessments to cover the reproductive risk, it is assumed that the residue load is lower and decreases over time (EFSA, 2009).

Impact of PF. Following the current scheme, the reduction in pesticides through PF technique reduces the area where treated food items per field can be taken and, therefore, the respective exposure and risk to animals foraging in cropped and treated fields. That only proportions of the diet are taken from the treated area (compared with diet from untreated area) is already the most common higher tier refinement for reproductive risk assessments (the PT concept: PT is defined as the proportion of an animal's daily diet obtained in habitat treated with pesticide). As a worst-case scenario, animals are supposed to find all their food in the treated area (PT = 1). In higher tier risk assessments, it is recommended to use more realistic estimates of PT (EFSA, 2009) in addition to a.i.-specific residue decline on vertebrate diet (EFSA, 2009). Here, the respective species activity ranges (i.e., within the area treated, or not) and ecology (i.e., where, how, and on what foraging, or not) can be considered in higher tiers, which apply to all vertebrates: birds, mammals, amphibians in the terrestrial phase, or reptiles (European Food Safety Authority [EFSA], 2018) as well as for other specific taxa likely to be included in the risk assessment, for example, bats (European Food Safety Authority [EFSA], 2019b). Therefore, current refinement approaches in higher tier chronic risk assessments already consider exposure reduction for in- or off-treated areas (see also Table 1). However, specific definitions are needed in a revised guidance (currently in progress; European Food Safety Authority [EFSA], 2021), on how, when, and for which species they can be applied. For some species with small activity ranges like small herbivorous mammals, this is considered less important, but for most species to be assessed according to EFSA (2009), it might be a useful consideration. Respective data could be recorded for in-field studies, which

TABLE 1 Impact of precision farming (PF) on environmental risk assessments of pesticides in Europe

Area	Subtopic	Can PF options be considered with a factor equal to % of treated area in current risk assessment schemes?
Terrestrial vertebrates (wildlife)	Acute scenarios	In principle, yes, but the current acute risk assessment scheme does not allow area-related refinements (EFSA, 2009). However, in the revision process of EFSA (2021), the acute refinement options are discussed again.
	Reproductive scenarios	Yes, the assessment can be well adapted as the general procedure of proportions of diet taken from the treated area is already in place (the "PT concept"). How to collect and implement the data would need to be determined.
Terrestrial invertebrates and plants	Bees, partly NTA	Yes, with restrictions. For highly mobile organisms such as bees and other flying insects, a rather linear relationship between the percentage of area treated and the exposure of the organisms can be assumed. However, this needs to be confirmed by studies.
	Soil organisms, NTTP, partly NTA	No, for sessile or less mobile organisms, the distribution of treated areas is considered more crucial as the movement behavior does not equal the exposure over time and more heterogeneities can be expected. Potential for recovery after treatment effects may depend strongly on the treatment pattern.
Aquatic organisms	Groundwater assessment, drainage exposure scenario	Yes, it can be well applied to the currently used one-dimensional calculation approach to the groundwater assessment. The same applies to drainage, which is independent from distance between the treated area and the water body.
	Drift and runoff exposure scenarios	No, these scenarios depend on the distance between the treated area and the water body. In addition, it needs to be agreed how the respective catchment areas are compared with the rest of the field (e.g., equally treated or fully treated as a conservative approach).

Abbreviations: NTA, nontarget arthropods; NTTP, nontarget terrestrial plants.

would fit well into the requirements on how to conduct studies gathering data for the PT concept (see e.g., Northern Zone, 2020). For the acute scenario, PF techniques can generally be considered in risk assessment schemes, but area-related refinements are currently not allowed according to EFSA (2009) and the scenario is restricted to a one-day perspective and common field sizes (assumed to be fully treated). However, it cannot be ignored that animals utilize and forage in only one larger treated area each day. If treated areas are patchily distributed within a common field, the likelihood that animals are continuously exposed during the acute phase is much lower than in farmland areas with fully treated fields and small off-crop areas only.

Terrestrial invertebrates, plants, and precision farming

Background information: This part of the evaluation handles the risk assessment of soil organisms (Santé des Consommateurs [SANCO], 2002), bees (European Food Safety Authority [EFSA], 2013b), nontarget arthropods (NTA; covering all terrestrial arthropods except focus pollinators), and nontarget terrestrial plants (NTTP; Candolfi et al., 2001). The exposure of soil organisms focuses on in-field scenarios, considers organismal recovery, and is covered by environmental fate assessments, using predicted environmental concentrations (PECs) in the form of the PEC_{SOIL}. Its calculation follows a one-dimensional approach, that is, the application rate is converted into a concentration in soil under the treated area or spot (European Food Safety Authority [EFSA], 2017; Forum for Co-Ordination of Pesticide Fate Models and Their Use [FOCUS], 1997). Specifically for bees, acute and chronic toxicity exposure calculations for adults and larvae are carried out based on specific exposure factors, residues in food matrixes, and dietary intake.

Impact of PF. For the assessment of the soil compartment, the regular PEC_{SOIL} could be calculated in the form of a $PEC_{SOIL\text{-}TREATED}$ and a $PEC_{SOIL\text{-}UNTREATED}$, representing the situation in the field and accounting for treated and untreated areas. This is not reflected in current procedures according to FOCUS (1997) but is mentioned in an upcoming calculation method according to EFSA (2017, 2019a). In this approach, it is assumed that all spots will have received the same amount of pesticide after many years of application, which is considered for calculating background concentrations. Theoretically, it can be assumed that a heterogenic treatment over several years will result in complex soil contamination scenarios with areas of higher (several spots over several consecutive years), medium (treatment in only one or a few years), and lower (background) concentrations. However, according to EFSA

(2019a), in the year of evaluation, a specific spot is either considered treated or not treated, and the respective concentration is added to the background concentration. This method thus results in two different PEC_{SOIL} values, reflecting application patterns after PF treatment. Currently, the corresponding risk assessment for soil organisms is carried out using the highest PEC_{SOIL} value such that untreated areas in the field and their potential positive effects on surrounding populations on treated areas is not reflected (SANCO, 2002). However, using a $PEC_{SOIL\text{-}TREATED}$ and $PEC_{SOIL\text{-}UNTREATED}$ as exposure values and considering the background contamination for untreated areas appear to realistically reflect the soil organisms' exposure and therefore the corresponding risk assessment. Here, both PEC values can be used to carry out two assessments. However, if and how more or less treated areas could be considered together in the overall risk evaluation remains currently open. In corresponding higher tier field studies, this should be investigated further, especially because it is unclear how PF application patterns, compared with a full field application, affect the terrestrial (invertebrate) environment. Particularly, effects on recovery ability of populations and communities from untreated areas need to be studied, which is an important factor in higher tier risk assessments. Regarding the evaluation of bees, the theoretical oral exposure to contaminated pollen and nectar as well as the contact exposure is linearly dependent on the rate applied to the field (EFSA, 2013b). A reduction in the exposure factors seems to be reasonable, but has to be experimentally determined. For this, as stated by Lückmann et al. (2019), different application patterns need to be considered to investigate contact exposure proportions of foraging honeybees and residue levels of pollen and nectar entering the hives. Similar studies could be conducted for bumblebees and solitary bees. Attention should be paid to the specific routes of exposure (Gradish et al., 2018; Sgolastra et al., 2019). Thus, it is expected that PF application reduces the overall oral and contact exposure to bees, but there is currently no clear procedure how treated and untreated areas should be handled and whether linearity between the proportion of area applied and exposure is present for these highly mobile insects (see also Table 1). However, in the current guidance, an exposure assessment at landscape level is discussed (EFSA, 2013b), resulting in the proposal to assess exposed and non- or less-exposed bees, an aspect that can be related to PF in the future. Likewise, for NTA and NTTP risk assessments, no clear guidance is available on how unexposed or less-exposed individuals are considered because it is the overall application rate that is used in the risk assessment. However, off-field areas are currently already considered to account for plants and arthropods present in the vicinity of a field. Further, they are considered a potential source of recolonization of treatment areas. As the number and structure of untreated areas is expected to increase and change under PF practice, respectively, it is worthwhile to study how populations and communities are affected and, if so, how they may recover when PF techniques are used compared with conventional full-area spraying. Case studies could be conducted in fields with existing structures, such as orchards, where strip applications can be compared with full-area applications.

Aquatic organisms and precision farming

Background information. This part of the evaluation handles the risk assessments of aquatic organisms, and considers acute and chronic assessments for, for example, fish, algae, aquatic invertebrates, and macrophytes, depending on the pesticide under consideration (EFSA, 2013a). The respective aquatic exposure values are calculated for groundwater (PEC_{GW}) as well as surface water and sediment ($PEC_{SW\text{-}SED}$). In addition, there is also a calculation for fate in the air, but currently this is not quantitatively addressed in risk assessment procedures. The PEC_{GW} calculation follows a one-dimensional approach and considers concentrations in 1 m depth directly under the treated area (FOCUS, 2014). Thus, in current standard calculations, horizontal mixing (e.g., with untreated areas) or mixing with deeper groundwater layers is not considered. The calculation of $PEC_{SW\text{-}SED}$ values comprises drift, runoff, and drainage scenarios that account for the different entry pathways to surface water bodies that are assumed in the risk assessment to be present in the vicinity of any field. The amount of pesticide that eventually enters the water body depends on the specific catchment area of the water body and thus on the pesticide use, that is, the pest infestation, in this defined area (FOCUS, 2015).

Impact of PF. For the aquatic risk assessment, a reduction in pesticides achieved by PF can lead to a reduced entry in water bodies and can therefore reduce risk to the respective aquatic population or community but depends on the specific scenario: Regarding groundwater, the currently EU-agreed, one-dimensional calculation approach (vertical leaching) does not consider horizontally varying application rates due to spot treatment. It can be assumed that a reduction in the applied amount of pesticide leads to an equivalent reduction in the mean concentrations in groundwater because the total amount applied to a given field, and not the application pattern, is decisive due to vertical and horizontal mixing processes. Representative concentrations could therefore be simply calculated with a reduced application rate, which accounts for the share of the treated area (see also Table 1). For this approach, it would only be necessary that the GAP table specifies the maximum percentage of area that may be treated. For $PEC_{SW\text{-}SED}$ values, the situation is more complex. In particular, it depends on the application pattern (i.e., whether application takes place in the vicinity of the water body or more remotely) and on the treatment of fields in the upstream catchment, because the risk assessment considers pesticide loadings from an entire catchment. As a pragmatic approach to upstream catchments, it could be assumed that all fields in the catchment area of the water body are treated similarly. Further, different entry pathways of a pesticide into a water body need to be considered differently: Drift, runoff, and drainage inputs are calculated based on a 1 ha treated area. Erosion, however, is calculated for a 20 m-wide strip parallel to a water body. Spraying on plots close to a water body results in higher drift entries than spraying on remote plots because spray drift decreases with distance. This means that the distribution of treatments in these areas in relation to the water body is crucial. It is therefore not possible to simply introduce a correction factor accounting for the reduced area. Although it is assumed that pest infestation patterns may not depend very strongly on the presence of water bodies, it is essential to study its realistic distribution and define how to implement them in the respective $PEC_{SW\text{-}SED}$ calculation. Pesticide entries by drainage, on the contrary, are independent from the plot distance to the water body, so that reduced entries could simply be calculated proportionally to the percentage of treated area. Overall, if no further information about the distribution is available, a conservative pragmatic assumption would be to apply the application pattern in the form of a correction factor only to the drainage and groundwater scenarios. For the other scenarios, the conservative assumption would be that the treated area is directly adjacent to the water body.

DISCUSSION AND CONCLUSION

Overall, it appears to be technically possible to register a pesticide applied with PF technique that reduces the treated field area under the current legislation by considering potential PF technique effects on exposure. However, following most current technical guidance, several assumptions need to be made that do not consider the differences between a pesticide that is sprayed equally on the entire field or only on parts of it, and how these differences are exhibited. Further, using solely the mean field rate irrespective of the application pattern does not reflect ups and downs of exposure. In addition, we would like to note that, from a regulatory perspective, PF is applicable for indications where information on the pest distribution is available before the application. We have chosen here the scenario of an herbicide that is applied in single spots. However, fungicide and insecticide applications can be perceived as similar from a risk assessment point of view, irrespective of single data requirements that may differ. In practice, this would most probably require remote sensing (e.g., via drones) to investigate how much and which areas of the field need to be treated, and which pesticide can thus be used (Pretty, 2018). In addition, a registration with PF might then be linked to a specific technical device for the application. Further, it should be noted that the potentially reduced exposure from PF techniques does not necessarily translate into environmental benefits. The technology itself appears to have great potential for achieving the political goal of pesticide reduction (Finger et al. 2019; Rajmis, et al. 2022), but careful consideration needs to be given to the prospects and limitations that can be assumed after large-scale adoption of PF. On the one hand, reductions in pesticide use caused by a significant proportion of untreated area can directly relate to reduced side effects on so-called nontarget organisms. On the other hand, PF treatments could also be required more often than a full field application. This will become clearer once the technology has been widely introduced. However, because the political goal of 50% reduction is the premise, the authors are confident that PF will make an important contribution here.

Generally, even if pesticide reduction is wanted, intended, and assumed by using PF techniques, there is an overall lack of clarity on how to deal with the reduction in pesticides through these techniques. This is the result of missing comparative data and also how the different mobility of individuals (in vertebrates) and populations (in invertebrates and plants) utilize partly sprayed fields, and how respective residues are distributed. Having these data would reveal how non- or less-exposed individuals should be evaluated as a subpopulation under assessment.

However, the risk assessment for terrestrial vertebrates can probably be further adapted more easily regarding PF exposure patterns, following the PT factor concept according to EFSA (2009) and Northern Zone (2020; see Table 1). For the risk assessment of soil organisms, bees, NTAs, and NTTPs, it is first of all necessary to investigate how an area-related reduction in pesticide use, that is, the application pattern itself, affects the corresponding exposure. Specifically for animals, the mobility of the taxon (adults and preimaginal stages) in question should be considered to determine if heterogeneity of PF application plays an important role. In this sense, spatially explicit population models can also help to explore effects of PF on population levels, especially as different scenarios can be covered more quickly and compared more extensively with field studies. It can therefore improve or increase confidence in the risk assessment. The individual-based model of springtails by Meli et al. (2013), for example, can consider heterogeneities in exposure. For this, different exposure distributions can easily be linked to the landscape behind the model, and questions on recovery ability and worst-case landscapes can be determined. Regarding the aquatic environment, current groundwater calculations could cope with the overall pesticide reduction through PF techniques, although its one-dimensional approach is an unrealistic assumption. However, for surface water, a definition based on a realistic exposure pattern is needed. As a conservative approach, it could be assumed that the defined catchment area of a water body is fully treated, which would, however, not account for the PF technology at all. As soon as a more realistic scenario with treated and untreated areas is chosen, a convention is required. This is ideally based on field data because potential heterogenic pest infestation, that is, in the vicinity of water bodies, can affect the exposure, which may also finally lead to the definition of "no-spray buffer zones" as part of risk mitigation measures in pesticide authorizations.

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In conclusion, PF will change the environmental risk assessment schemes and pesticide evaluation and can fine-tune pest control and resistance management options and strategies. Precision farming can contribute significantly to sustainable agriculture and environmental protection accounting for the need to protect biodiversity as stated by the regulation 1107/2009 (EC, 2009), and it can promote the reduction in the amount of pesticides applied in accordance with the EC (2020). To this goal, potential environmental benefits and effects of PF pesticide applications on community dynamics and recovery patterns related to the registration-relevant taxon of interest (i.e., birds, mammals, arthropods, bees, and earthworms, among others) need to be investigated. Conclusions can then be drawn from the results to adapt future risk assessment schemes.

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CONFLICT OF INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

DATA AVAILABILITY STATEMENT

No raw data exist for this manuscript as it is not a full research paper. Requests for further information can be sent to corresponding author Michael Faupel (michael.faupel@rifcon.de).

REFERENCES

Candolfi, M. P., Barrett, K. L., Campbell, P. J., Forster, R., Grandy, N., Huet, M.-C., Lewis, C., Oomen, P. A., Schmuck, R., & Vogt, H. (2001). *Guidance document on regulatory testing and risk assessment procedures for plant protection production with non-target arthropods*. ESCORT 2 Workshop 21–23 March 2000. SETAC Office, Pensacola, FL.

Christensen, S., Søgaard, H. T., Kudsk, P., Nørremark, M., Lund, I., Danimi, E. S., & Jørgensen, R. (2008). Site-specific weed control technologies. *Weed Research*, *49*, 233–241.

Devi, K. G., Kumar, C. S., & Kishore, B. (2022). A survey on the design of autonomous and semi autonomous pesticide sprayer robot. *El-Cezerî Journal of Science and Engineering*, *9*(1), 371–381.

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

European Commission (EC). (2020). *Farm to Fork Strategy—for a fair, healthy and environmentally-friendly food system*. Retrieved 13 October 2021, from: https://ec.europa.eu/food/farm2fork_en

European Food Safety Authority (EFSA). (2009). Guidance document on risk assessment for birds & mammals on request from EFSA. *EFSA Journal*, *7*(12), 1438–1575.

European Food Safety Authority (EFSA). (2013a). Guidance on tiered risk assessment for plant protection products for aquatic organisms in edge-of-field surface waters. *EFSA Journal 2013*, *11*(7), 3290.

European Food Safety Authority (EFSA). (2013b). EFSA guidance document on the risk assessment of plant protection products on bees (*Apis mellifera*, *Bombus* spp. and solitary bees). *EFSA Journal 2013*, *11*(7), 3295.

European Food Safety Authority (EFSA). (2017). EFSA guidance document for predicting environmental concentrations of active substances of plant protection products and transformation products of these active substances in soil. *EFSA Journal 2017*, *15*(10), 4982.

European Food Safety Authority (EFSA). (2018). Scientific opinion on the state of the science on pesticide risk assessment for amphibians and reptiles. *EFSA Journal 2018*, *16*(2), 5125.

European Food Safety Authority (EFSA). (2019a). *Update of PERSAM software models for predicting environmental concentrations in soil in permanent crops and annual crops: User manual PERSAM 3.0.0* (EFSA Supporting Publication 2019:EN-1756).

European Food Safety Authority (EFSA). (2019b). Scientific statement on the coverage of bats by the current pesticide risk assessment for birds and mammals. *EFSA Journal 2019*, *17*(7), 5758.

European Food Safety Authority (EFSA). (2021). *Public Consultation PC-0090—Risk assessment for birds and mammals—Open 29/09/2021 to 10/11/2021*. Retrieved 13 October 2021, from: https://connect.efsa.europa.eu/RM/s/publicconsultation2/a0l1v00000E7Zev/pc0090

Finger, R., Swinton, S. M., El Benni, N., & Walter, A. (2019). Precision farming at the nexus of agricultural production and the environment. *Annual Review of Resource Economics*, *11*, 313–335.

Forum for Co-Ordination of Pesticide Fate Models and Their Use (FOCUS). (1997). *Soil persistence models and EU registration*. The final report of the work of the Soil Modelling Work Group of FOCUS.

Forum for Co-Ordination of Pesticide Fate Models and Their Use (FOCUS). (2014). *Assessing potential for movements of active substances and their metabolites to ground waters in the EU—Report of the FOCUS Ground Water Work Group, Version 3 of 10 October 2014* (EC Document Reference SANCO/13144/2010, Version 3).

Forum for Co-Ordination of Pesticide Fate Models and Their Use (FOCUS). (2015). *Generic guidance for FOCUS surface water scenarios, Version 1.4*, May 2015.

Gradish, A. E., van der Steen, J., Scott-Dupree, C. D., Cabrera, A. R., Cutler, G. C., Goulson, D., Klein, O., Lehmann, D. M., Lückmann, J., O'Neill, B., Raine, N. E., Sharma, B., & Thompson, H. (2018). Comparison of pesticide exposure in honey bees (Hymenoptera: Apidae) and bumble bees (Hymenoptera: Apidae): Implications for risk assessments. *Environmental Entomology*, *48*, 1–10.

Hafeez, A., Husain, M. A., Singh, S. P., Chauhan, A., Khan, M. T., Kumar, N., Chauhan, A., & Soni, S. K. (2022). Implementation of drone technology for farm monitoring & pesticide spraying: A review. *Information Processing in Agriculture*. https://doi.org/10.1016/j.inpa.2022.02.002

Lückmann, J., Kaiser, S., & von Blankenhagen, F. (2019). Precision farming—Consideration of reduced exposure in the pollinator risk assessment. In J. Pistorius & T. Steeger (Eds.), *Hazards of pesticides to bees—14th International Symposium of the ICP-PR Bee Protection Group, October 23–25, 2019 Bern, Switzerland–Proceedings* (Nr 465, pp. 78–82). Julius–Kühn–Archiv.

Meli, M., Auclerc, A., Palmqvist, A., Forbes, V. E., & Grimm, V. (2013). Population-level consequences of spatially heterogeneous exposure to heavy metals in soil: An individual-based model of springtails. *Ecological modelling*, *250*, 338–351.

Mogili, U. M. R., & Deepak, B. B. V. L. (2018). Review on application of drone systems in precision agriculture. *Procedia Computer Science*, *133*, 502–509.

Möhring, N., Ingold, K., Kudsk, P., Martin-Laurent, F., Niggli, U., Siegrist, M., Studer, B., Walter, A., & Finger, R. (2020). Pathways for advancing pesticide policies. *Nature Food*, *1*, 535–540.

Mulla, D., & Khosla, R. (2016). Historical evolution and recent advances in precision farming. In R. Lal & B. A. Stewart (Eds.), *Soil-specific farming: Precision agriculture* (pp. 1–36). CRC Press.

Northern Zone. (2020). *Pesticide risk assessment for birds and mammals. Selection of relevant species and development of standard scenarios for higher tier risk assessment in the Northern Zone in accordance with Regulation EC 1107/2009*. Version 2.1, December 2020. Retrieved March 15, 2022, from: https://eng.mst.dk/chemicals/pesticides/applications-for-authorisation-after-14-june-2011/cooperation-in-the-north-zone/

Oerke, E. C., Gerhards, R., Menz, G., & Sikora, R. A. (2010). *Precision crop protection—The challenge and use of heterogeneity*. Springer.

Pretty, J. (2018). Intensification for redesign and sustainable agricultural systems. *Science*, *362*, 908.

Rajmis, S., Karpinski, I., Pohl, J.-P., & Herrmann, M. (2022). Economic potential of site-specific pesticide application scenarios with direct injection and automatic application assistant in northern Germany. *Precision Agriculture*. https://doi.org/10.1007/s11119-022-09888-1

Santé des Consommateurs (SANCO). (2002). *Guidance document on terrestrial ecotoxicology under Council Directive 91/414/EEC* (SANCO/10329/2002 rev 2 final).

Sgolastra, F., Hinarejos, S., Pitts-Singer, T. L., Boyle, N. K., Joseph, T., Lückmann, J., Raine, N. E., Singh, R., Williams, N. M., & Bosch, J. (2019). Pesticide exposure assessment paradigm for solitary bees. *Environmental Entomology*, *48*, 22–35.

Song, Y., Sun, H., Li, M., & Zhang, Q. (2015). Technology application of smart spray in agriculture: A review. *Intelligent Automation & Soft Computing*, *21*(3), 319–333.

Zakka, U., Lawal, O., & Nwosu, L. C. (2019). Leveraging of agricultural entomology in precision farming for sustainable agriculture and food security. *Canadian Journal of Agriculture and Crops*, *4*, 173–187.