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OPINION

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The ConSoil project: An integrated framework for monitoring plant protection product residues in agricultural soil

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Abstract

Plant Protection Products (PPPs) are widely used to maintain high productivity and protect crops, but can have unintended toxic effects on beneficial non-target soil organisms. To avoid unacceptable adverse effects of PPPs on soil organisms, a prospective risk assessment is carried out, which focuses on individual substances and their effects on a few individual species or groups. However, the reality of agricultural soils consists of complex networks of organisms exposed to mixtures of several PPP active substances. It is therefore essential to monitor PPP residues in soils. This paper describes the ConSoil project and its proposed framework for monitoring PPP residues in Swiss Agricultural soils which includes and integrates (1) risk-based reference values for PPP residues in soil and (2) indicators of their effects on long-term soil fertility. For risk-based reference values, a proposal has been developed to derive Soil Guideline Values (SGVs) for PPP residues and a mixture risk assessment concept is being developed. Regarding indicators, a toolbox of ecological and ecotoxicological indicators will be proposed to reflect the protection goal of long-term soil fertility in agricultural soils. For this objective, standardised and/or well-established bioindicator methods will be selected for the key soil organisms that support soil fertility. To integrate SGVs and the biomonitoring toolbox, an adapted TRIAD approach is proposed, where generic SGVs are used as a screening tool to identify monitoring sites potentially at risk and to trigger more detailed monitoring. Detailed monitoring will refine the SGVs based on site-specific characteristics and implement the bioindicator toolbox to measure the effects of PPP residues and their risk to long-term soil fertility. As a novel integrated framework, it is essential to use the data generated in detailed assessments to calibrate and refine the SGVs and bioindicator tools and improve the monitoring over time.

KEYWORDS

bioindicators, ecosystem services, functions, mixtures, pesticides, plants, risk assessment, soil fauna, soil fertility

1 | INTRODUCTION

Plant Protection Products (PPPs) are a pillar of modern agriculture, widely used to maintain high productivity and protect crops from disease and pests. However, these substances can have unintended toxic effects on beneficial non-target soil organisms (Gunstone et al., 2021), which play a critical role in soil functioning (Creamer et al., 2022). To avoid unacceptable effects of PPPs on soil organisms, a prospective risk assessment for the soil compartment is carried out in the EU (EC, 2002, 2013a, 2013b). For soil organisms, this assessment requires effect data on earthworms (sub-lethal), and microorganisms (nitrogen transformation). Additional data may be required for earthworms (field study), collembola and mites under specific circumstances of application, persistence and toxicity. Overall, the authorisation process focuses on a few single species data, which do not adequately represent the diversity and complexity of soil communities, and does not consider indirect effects along soil food webs (Ockleford et al., 2017). The only exception is the earthworm field study, but which still focuses on a single group and has been criticised for lacking specific guidance on how to summarise and interpret study results in a statistically robust manner (Brulle et al., 2022). In addition, the assessment of chemicals is tied to the particular substance for which authorisation is sought. Mixture effects of several substances applied together or present in the soil over time are not currently considered.

Environmental regulations also seek to limit the authorisation of persistent substances, such as Regulation (EC) No 1107/2009, which does not authorise substances considered to be persistent organic pollutants (POPs), persistent, bioaccumulative and toxic (PBT), and very persistent and very bioaccumulative (vPvB) (EC, 2009). Despite efforts to understand the fate of PPPs in the environment prior to authorisation, initial monitoring data have shown a higher than expected persistence of PPP residues in agricultural soil (Froger et al., 2023; Riedo et al., 2021, 2023; Silva et al., 2019). These data show that most agricultural soils contain mixtures of multiple PPP active ingredients. In terms of risk to beneficial soil organisms, the concentration and number of PPP residues in soil have been associated with a moderate to high risk for chronic (reproductive) effects on earthworms (Froger et al., 2023), correlated with a decline in mycorrhizal fungi (Riedo et al., 2021) and shown to alter the soil microbiome (Walder et al., 2022). Overall, data highlight the importance of monitoring PPP residues in soils, assessing their long-term effects and, where possible, using this information to improve their prospective risk assessment.

Highlights

- Plant Protection Products can occur as mixtures in soil with possible unintended toxic effects.
- Currently no retrospective risk assessment is generally performed for Plant Protection Products in soil.
- An integrated approach is proposed for monitoring Plant Protection Products in agricultural soil.
- Monitoring data generated must be used to refine and calibrate risk and effect assessment tools.

As a result of increasing concern with PPP, in September 2017, the Swiss Federal Council approved an action plan to halve the risks of PPPs by 2027 and promote their sustainable use in soils (Conseil Fédéral Suisse, 2017). The action plan includes the development of a monitoring programme for PPP residues in agricultural soils, which includes as specific objectives the chemical monitoring of PPP residues, the development of risk-based reference values and indicators for the effects of PPP on long-term soil fertility of agricultural soils. To address these specific objectives, a collaboration between the Swiss Soil Monitoring Network (NABO), the Ecotox Centre and EnviBioSoil was established in 2019 (Godbersen et al., 2019). NABO is responsible for the chemical monitoring of PPP residues in soil, while the Ecotox Centre and EnviBioSoil established the ConSoil project, which will develop a proposal for risk-based reference values and bioindicators for the effects of PPP residues on long-term soil fertility of agricultural soils. This paper presents progress on the two individual objectives of the ConSoil project and the proposed integrated approach for assessing risk to long-term soil fertility. The possible implementation of the risk-based reference values and indicators in a routine monitoring will only be proposed at the end of the project, once the main research questions and the implementation challenges have been assessed.

2 | PROTECTION GOAL AND CONTEXT

The main protection goal of the ConSoil project is the preservation of long-term soil fertility of agricultural soils. Excluding human and animal health aspects not covered in this monitoring, and according to the Swiss national soil strategy, a soil is considered fertile when (Swiss Federal Council, 2020):

a. The active biotic community, soil structure and composition, and soil depth are typical of its site, and its degradation capabilities have been unaffected;
b. Natural plants and plant communities, and those that have been subject to human influence, are able to grow and develop unhindered with their characteristic properties intact.

In line with this concept of soil fertility, monitoring should focus on in-soil organisms and plants that play an important role in maintaining soil fertility (Godbersen et al., 2019). More specifically, on non-target in-soil organisms and plants that play an important role in the three ecological soil functions that support soil fertility (Dell'Ambrogio et al., 2023; Swiss Federal Council, 2020):

a. Habitat function: The ability of soil to sustain organisms and to maintain the diversity of ecosystems, species and their gene pool. The habitat function also covers soil's suitability as a habitat for organisms and as a location for plants.
b. Regulating function: The ability of soil to regulate, buffer or filter water and energy cycles, as well as to transform substances.
c. Production function: The ability of soil to produce biomass, that is, food and feedstuffs, as well as wood and other fibres.

In addition to the protection goal, the monitoring should focus on PPP residues in the in-crop area of agricultural fields. The in-crop area is defined as the area where crops are grown including their different spatial organisation and variability which can be natural (e.g., cereals) or systematic, such as rows (e.g., vineyards) or trees (e.g., orchards) (EFSA PPR, 2010). Since the focus is on PPP residues, and monitoring must not target the effect of PPP during the application periods, sampling will take place at the end of the winter period (February–March) when no PPP application is expected, before the first application of the year and where only the residues will be assessed. Samples will be collected in this period for the chemical monitoring and analysed using a multi-residue method (Rösch et al., 2023). The same sampling period will be used for bioindicator methods for sites identified as potentially at risk.

3 | RISK-BASED REFERENCE VALUES

To meet the first individual objective of ConSoil project, Soil Guideline Values (SGVs) were proposed as risk-based reference values. The SGVs methodology was supported based on a review of different regulatory methodologies used to derive soil reference values (Marti-Roura et al., 2023a), among which two prospective (EC, 2002; EC—Joint Research Centre, 2003) and four retrospective methodologies (CCME, 2006; NEPC, 2011; US-EPA, 2005; van Vlaardingen & Verbruggen, 2007). From this extensive review, a methodology is proposed with specific recommendations adapted to the context and protection goals of the ConSoil project (Marti-Roura et al., 2023b). Considering the goal of protecting long-term soil fertility of agricultural soils and the focus on residue concentrations, SGVs are first intended as screening values, below which no negative effects on soil fertility are expected, and aim at capturing all potentially at-risk agricultural sites. The general stepwise procedure for deriving soil protection values which is similar across all methodologies and the basis for the derivation of SGVs, consists of data collection, data screening (evaluation and selection), data extrapolation and soil protection value determination (Fishwick, 2004). While most methodologies follow this general stepwise procedure, they may differ in the specific criteria to consider within each of the respective steps (e.g., which sources used for data collection, what criteria used for data screening, which methods used for extrapolation). For the SGVs the main recommendations and adaptations for the ConSoil project are shown in Figure 1, and the full list of recommended adaptations at each step of the derivation procedure are available in Marti-Roura et al., 2023b.

The procedure described in Figure 1 represents the derivation procedure for individual substances, but as previously highlighted, soils rather than single substances contain mixtures of different active substances. So, the derived values for individual substances must be combined to reflect the risk from multiple co-occurring substances. To better grasp the effects of mixtures, a mixture risk assessment approach using the currently available knowledge is necessary and will be developed in the ConSoil project. For this goal a review has started focused on currently used mixture models in regulatory contexts but also on novel approaches from the scientific literature. However, mixture experiments with organic substances in soil are relatively scarce and usually focus on simpler binary or ternary mixtures (Martin et al., 2021), which do not reflect the actual complexity of mixtures occurring in-crop. As such the validation of mixture modelling concepts for real world exposure scenarios is challenging.

4 | BIOINDICATORS

The second objective of the ConSoil project is to select and test bioindicators to assess the effects of PPP residues on long-term soil fertility. To achieve this objective, the first step was to identify and prioritise the soil organisms and plants (actors) that contribute to ecological soil functions and, thus, to soil fertility (Dell'Ambrogio et al., 2023). In short, because ecological soil functions are set at a very high structural level, the concept of Ecosystem Services (ES) was used, namely the Common International Classification of Ecosystem Services (CICES, 2023, www.CICES.eu), which has a hierarchical structure that allows the splitting of ecological soil functions into more specific ES classes. ES classes were then linked to soil ecological processes and attributed to individual actors using key references from the scientific literature (Creamer et al., 2022; EFSA PPR, 2014; Faber et al., 2021; Ockleford et al., 2017). A visual summary of the procedure is shown in Figure 2.

The technical report Dell'Ambrogio et al. (2023) identified and quantified the number of links between soil organisms and ecological soil functions using the ES concept. However, not all ES are equally important for soil fertility from the perspective of different stakeholders. So, in addition to the number of links between actors and soil functions (Figure 2 and in detail in Dell'Ambrogio et al., 2023) the relative importance, namely of ecosystem services, must also be considered. In this case Stakeholders, representing science, policy and land users, were asked to rate ES on a scale of 1–5 in terms of their relative importance for long-term soil fertility, considering the context and protection goal of the ConSoil project. Once stakeholder evaluation is concluded the final scoring of actors will include the degree of linkage of actors to ecological soil functions (Dell'Ambrogio et al., 2023) as well as the relative importance of ES for soil fertility (stakeholder evaluation).

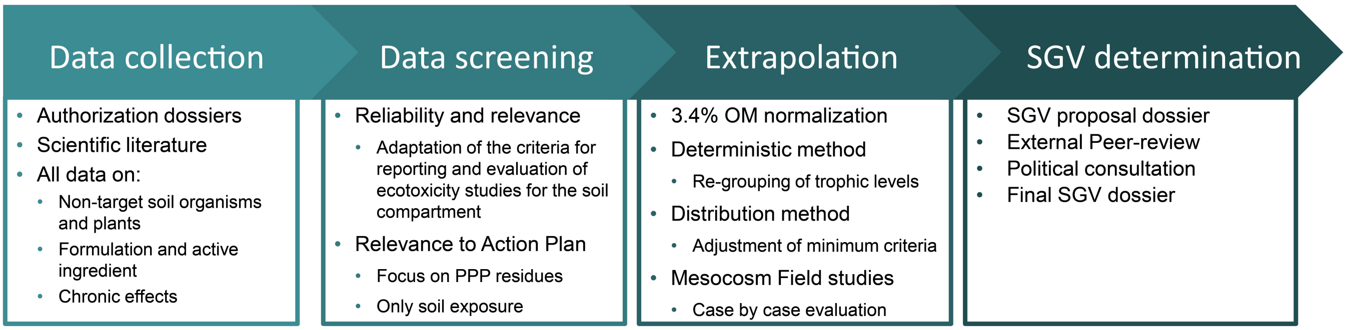

FIGURE 1 General stepwise procedure for determination of soil protection values (arrows) and main adaptations and recommendations for the specific derivation of Soil Guideline Values (SGVs) in boxes. For a complete list of specific recommendations for SGVs at each step of the derivation procedure please see Marti-Roura et al., 2023b. PPP, Plant Protection Product.

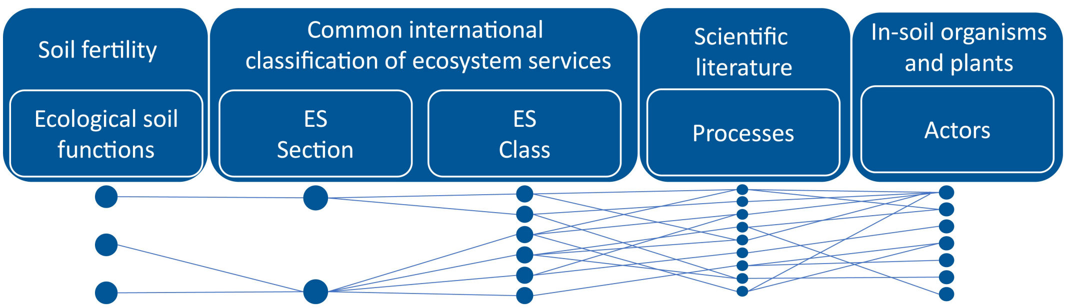

FIGURE 2 Procedure for linking in-soil organisms and plants to ecological soil functions using the ecosystem services concept and scientific publications to link processes and actors. The dots are a generic representation of the hierarchical deconstruction allowing links between high level Ecological soil function and soil actors (in-soil organisms and plants). Lines represent the links between each hierarchical level and highlights the interconnected nature of processes and actors, where one actor or process can contribute to multiple ecosystem services. ES, Ecosystem Services.

For the highest scoring actors, standardised or well-established ecological and ecotoxicological methods will be selected in consultation with national and international experts. Ecological indicators are field observations of soil organisms and plants that provide a measure of ecosystem structure and functioning, while ecotoxicological indicators are laboratory tests on organisms or species designed to measure the toxicity of field soil samples. The selected bioindicators toolbox will then be tested and refined in various pilot studies to assess its variability, sensitivity and overall feasibility.

5 | INTEGRATED FRAMEWORK

The initial objectives of proposing risk-based reference values and indicators for the effects of PPP residues must be integrated to effectively achieve the protection of long-term soil fertility. Soil is a complex medium that strongly modulates toxicity of substances and fitness of organisms (Kuperman et al., 2009), increasing the uncertainty of risk-based reference values. Bioindicators can help bridge this gap by measuring the effects on field communities (ecology) and the toxicity of field soil samples (ecotoxicology). Ecological data collected in the field provide a 'real world' view of communities and their function. However at a much higher complexity and with reduced causality since in-field communities are not only exposed to PPP residues but to multiple stressors (e.g., environmental, management) (e.g., Cortet et al., 2002). In this case, ecotoxicity testing can provide a link between toxic pressure identified in chemical monitoring and effects in the field by testing the toxic effects of field soil samples under controlled conditions.

The concept of using chemistry linked to reference values, ecology and ecotoxicology, is commonly referred to as the TRIAD approach. This approach has been used as a tool for site-specific risk assessment of contaminated sites (e.g., Niemeyer et al., 2010, 2015), has specific guidance (Jensen & Mesman, 2006) and is standardised for the soil compartment (ISO19204, 2017). Recent scientific literature has highlighted the use of the TRIAD approach for site-specific risk assessment of contaminated soils and the needed improvements for diffuse pollution (Grassi et al., 2022).

For large-scale monitoring, the TRIAD needs to be adapted (Figure 3), firstly because detailed assessment is not possible at all monitoring sites, and secondly because

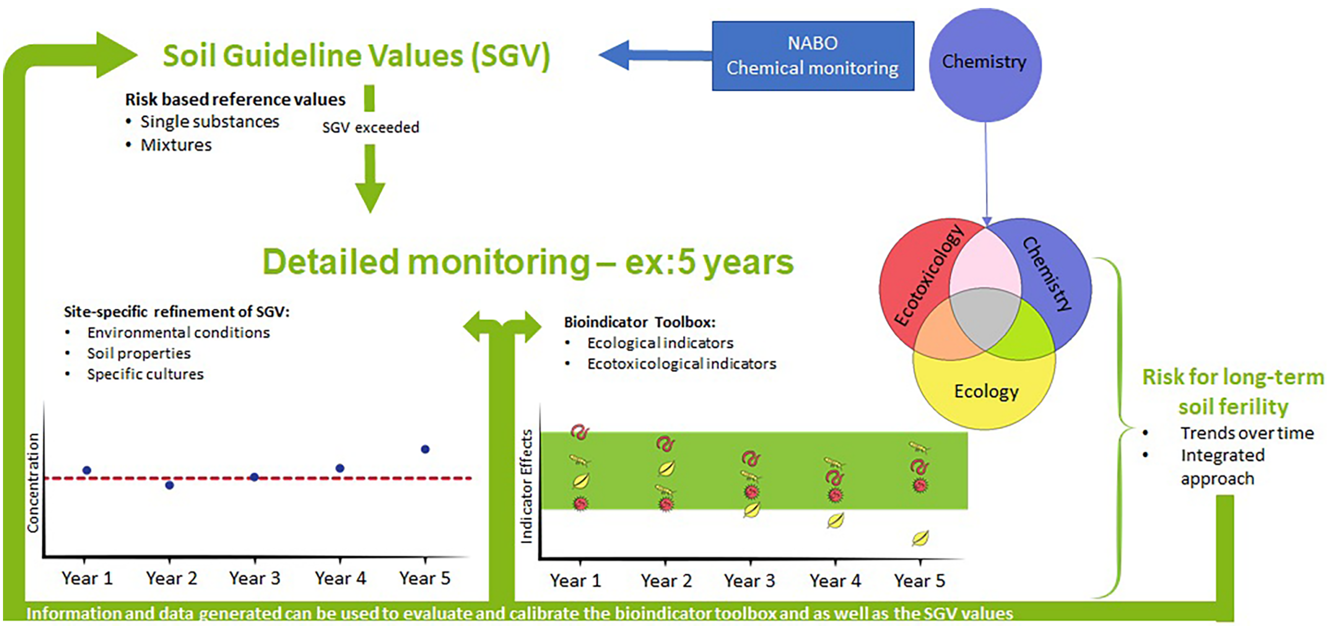

FIGURE 3 Conceptual framework for an integrated monitoring of PPP residues in soil. In the proposed framework, Soil guideline values are compared to chemical monitoring data performed by the Swiss Soil Monitoring Network (NABO) and if exceeded for single substances or integrated in a mixture risk assessment a detailed monitoring is triggered. For each site triggering detailed monitoring, chemical residue concentrations will continue to be measured but compared to refined SGV values for site-specific properties (left panel; chemical monitoring) and the bioindicator toolbox with ecological and ecotoxicological indicators will be implemented (right panel; ecological and ecotoxicological monitoring). The duration of the detailed monitoring is not fixed but currently a period of 5 years is proposed. Based on the chemical, ecological and ecotoxicological data collected in the detailed monitoring, a risk assessment for long-term soil fertility for the site is performed. It is also proposed that the data collected in detailed monitoring schemes across different sites is used to improve and calibrate the SGVs and bioindicator toolbox.

representative reference (i.e., uncontaminated) sites are unlikely to be available for each monitoring site. For the first challenge, SGVs can be used to screen potentially at-risk sites and trigger more detailed monitoring. Detailed monitoring will refine the SGVs based on site-specific characteristics and implement ecotoxicological and ecological indicators. The second adaptation of the TRIAD approach relates to the lack of reference sites, a common issue for diffuse pollution (Grassi et al., 2022). Their absence is critical because under the TRIAD approach indicators are normalised against reference site response. In this case, some adaptions are proposed to the TRIAD approach in the absence of reference sites. Firstly, normal operating ranges or effect thresholds should be established for bioindicators to measure deviations from a normal state. To achieve this goal, research on the natural variability of the indicator's biological response in the absence of contamination (e.g., testing a range of soil properties with low/no contamination) is needed. Secondly, in line with the protection goal of long-term soil fertility we propose that detailed monitoring be carried out over time (e.g., 5 years). Monitoring over time allows the interpretation of data trends rather than single observations which is particularly important for ecological indicators, where establishing a normal response might not be possible. Data trends while not measuring the level of impact against this 'normal', allow an indication of the direction and size of the effect over time. In particular, if there is a tendency for an improvement or decline of the indicators at the monitored site, which is well aligned with the long-term aspect of the protection goal.

One of the main challenges in the use of chemical, ecological and ecotoxicological tools, in environmental monitoring, regulation and management, is the lack of long-term exposure and effect data. For this reason, it is essential that the data generated from the detailed assessment feedback into the framework to enable the calibration and refinement of both the SGVs and the bioindicator toolbox. Understanding trends and effects over time is critical to link back to the protection goal of long-term fertility. To allow more consistent data generation, it is recommended that the bioindicator toolbox be fixed rather than the tiered approach recommended in current guidances (ISO 19204, 2017; Jensen & Mesman, 2006). Through this approach, the data generated in detailed assessments with a fixed toolbox could contribute to establish normal operating ranges as well as effect thresholds, particularly for ecological indicators for which this is more complex and currently not possible. Integration of monitoring data over time and calibration of these tools will not only improve the assessment of risk for long-term soil fertility through refined effect thresholds and improved bioindicator tools, but also cost-effectiveness by improving and refining SGVs and thus reducing false positive screening.

6 | CONCLUSION

In general, the comprehensive monitoring of PPP residues and their effects in the agricultural context is a challenging goal, which to our knowledge has yet to be tackled at a large and long-term scale. As such, the currently proposed integrated monitoring scheme, for the SGVs but in particular the bioindicators methods, their sampling approaches and designs need to be tested in pilot studies and refined before a final methodology can be proposed. Even then we acknowledge that long-term data on both chemistry, ecology and ecotoxicology in a monitoring context is lacking, so in addition to short-term pilot studies it is important that this framework can be refined over time as data is generated.

The ConSoil project as an ongoing long-term (9 years, 2019–2027) applied research project, has specific details regarding the final scope, size, frequency and cost for the monitoring which cannot yet be defined and are still being developed in a collaborative effort with NABO partners conducting the chemical monitoring.

Overall, what is clear is that considering the complexities of soil as a matrix (e.g., soil heterogeneity) and of PPP residue mixtures for an adequate monitoring, the integrated approach proposed is not only the best course of action but necessary to establish causality in a multi-stressor environment and to meet current national and international measures to promote sustainable soil management.

AUTHOR CONTRIBUTIONS

Mathieu Renaud: Conceptualization (equal); writing – original draft (lead); writing – review and editing (equal). **Sophie Campiche:** Conceptualization (equal); writing – original draft (supporting); writing – review and editing (equal). **Gilda Dell'Ambrogio:** Conceptualization (equal); writing – review and editing (equal). **Mireia Marti-Roura:** Conceptualization (equal); writing – review and editing (equal). **Marion Junghans:** Conceptualization (equal); writing – review and editing (equal). **Benoit J. D. Ferrari:** Conceptualization (equal); funding acquisition (equal); writing – review and editing (equal).

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CONFLICT OF INTEREST STATEMENT

The authors have no conflict of interest to declare.

DATA AVAILABILITY STATEMENT

Data sharing not applicable—no new data generated.

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