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To cite this version:

Garnault Maxime, Barbu Corentin, Alexix Aulagnier, Bockstaller Christian, Kudsk Per, et al.. Evaluation of two indicators according to the objectives of the Sustainable Use of pesticides Directive (SUD). A French case study. 2024. hal-04564733v2

HAL Id: hal-04564733
https://hal.science/hal-04564733v2

Preprint submitted on 3 May 2024

Evaluation of two indicators according to the objectives of the Sustainable Use of pesticides Directive (SUD). A French case study.

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Abstract

The European agricultural protests of 2023/2024 have prompted a reassessment of public policies at the EU level with the SUR put on a stand still. In France, in early 2024, the government replaced the historical monitoring indicator "NoDU'' with the European Harmonized Risk Indicator HRI1 to monitor the progress in the use of Plant Protection Products (PPP) in its National Action Plan (NAP). This study aimed to assess the relevance of these two indicators regarding the objectives outlined in the Sustainable Use of pesticides Directive (“SUD”) that defines the framework within which they operate. To this effect, we analyzed the PPPs they consider, the official calculation formulas, but also their past evolution and possible future evolutions through putative scenarios of changes in PPP use and regulation: ban or not; substitution or not; for the top 5 synthetic insecticides; all synthetic insecticides; glyphosate; mancozeb; and the top five active ingredients from HRI1 risk group 3 (candidates for substitution). French PPP sales data from 2011 to 2021 were used for past evolutions and we used the last available figures in France, 2021, for simulations.

Designed to monitor the use of PPPs by farmers, the NoDU mostly monitors achievement with regards to one aim of the SUD: to "reduce dependency on the use of pesticides" and promote "the use of Integrated Pest Management". Its value does not change with the mere substitution of a product by another, even if the second is deemed less toxic. This limits its ability to assess the "risks and impacts of pesticide use on human health and the environment", the first aim of the directive. The HRI1

indicator is not supposed to strictly quantify the use of PPP and was found to inadequately reflect significant changes in PPP use, but also in the induced risk: 1) changes of use without a ban on a substance are limited and as such, past correlation of HRI1 with the QAI of the fourth group (banned PPPs) is very high (0.90); 2) the impact of variations of low-dose active ingredients is minimal, independently of their toxicity/ecotoxicity, even in the case of a ban. Thus, the putative withdrawal of all insecticides sold, even without substitution by other PPPs, would reduce HRI1 by only 4 in percentage points (from 67.1 % to 63.1 %), while NoDU would drop by 16 percentage points (from 94.5% to 78.5%), thus better reflecting both the paradigm shift in PPP use for farmers and the large diminution of the risk induced for the environment. On the opposite end, banning only glyphosate, a high dose active ingredient, even with full substitution with another herbicide, would bring the HRI1 down to 43.8% of its value in 2011-2013 and sells of glyphosate in 2021 would represent 47.8% of the HRI1 before the ban, when it is only 4.3% of the use of PPPs as measured by the NoDU. Finally, 2022 ban of mancozeb, even if fully substituted by other PPPs, might be enough to bring the HRI1 very near to the 50% target of the Ecophyto plan (56.9%), while the NoDU would remain at 94.5% of its average value in 2011-2013.

Our results strongly suggest that HRI1 fails to adequately monitor the objectives of the SUD. We accordingly recommend that the European Commission reconsider the design of Harmonized Risk Indicators. NAP monitoring indicators at national and European level should encompass three primary features. First, the indicators should be founded on robust scientific and technical evidence. Second, they should consider toxicity and ecotoxicity profiles of PPPs. Last, they should be computable for each member state and

allow comparisons in absolute values between member states to account for “the risk or use reduction" targets already achieved prior to the application of this Directive.

Keywords: Directive 2009/128/CE; National Action Plan; pesticide risk indicators; Harmonized Risk Indicator 1 (HRI1); Number of Unit Doses (NoDU); toxicity; ecotoxicity

Introduction

Early 2024 was marked by farmer protests across the European Union (EU). They voiced their opposition to several issues such as rising production costs, declining incomes, competition between European countries due to free-trade agreements, and constraining environmental regulations. In Germany and France, farmers blocked the roads in January 2024, notably with regards to the abolition of lower taxes on off-road diesel. Farmers also protested against the Green Deal (Filipović et al., 2022), elements of the European policy to mitigate climate change and environmental degradation. The agricultural package of the European Green Deal includes measures for a sustainable use of key natural resources and therefore increases environmental requirements, for example, in terms of reducing the use of plant protection products (PPPs; Bourget, 2024). Actions for the reduction of the use of PPPs have been set gradually, initially at the EU level. In 1991, common approval procedures for PPPs were introduced. In 2002, the European Parliament and Council established the Sixth Community Environment Action Programme (European Parliament and Council, 2002). The Directive of the European Parliament and of the Council of 21 October 2009 (2009/128/CE Directive, also called SUD for Sustainable Use of pesticide Directive) was established to enable a framework for Community action to achieve the sustainable use of PPP (European Parliament and Council, 2009). This text obliged Member States to set up National Action Plans (NAPs) and quantitative targets for PPP risk reduction. It mentioned the need for harmonized risk indicators at the European level, while leaving it up to Member States to define national indicators for monitoring the impact of their NAP to "reduce risks and impacts of pesticide use on human health and the environment and to encourage the development and introduction of integrated pest management and of alternative approaches or techniques in order to reduce dependency on the use of pesticides” (Article 4.1).

In the period between the passing of the SUD and the Commission Directive (EU) 2019/782 (European Commission, 2022), several Member States have continued using existing or developed new national indicators, notably to meet the requirement of Article 4 of the SUD: “The National Action Plans shall also include indicators to monitor the use of PPPs containing active substance of particular concern, especially if alternatives are available”. This is why a variety of indicators exist among Member States of the European Union. Some of them chose to focus on the use of PPP such as the French Number of unit dose used (NoDU, MASA 2017) other indicators focus on the risk induced by PPP like the Danish Pesticide Load indicator (PLI, MEFD 2017). In the meantime, the Annex 4 where the Harmonized Risk Indicators (HRI) were to be defined was left blank in the original document (European Parliament and Council, 2009; p28). It was only 10 years later that the European Commission promulgated the annex as the Directive (UE) 2019/782, which proposes the Harmonized Risk Indicators (HRI) 1 and 2, without reference to the development process of these indicators. The genesis of these indicators was a collaborative process of the European Commission and is poorly documented. We only know about discussions between Member States by the answer of the commission to the European Court of Auditors (ECA 2020 : European Court of Auditors, 2020, Sustainable use of plant protection products: limited progress in measuring and reducing risks). We will here focus on the first indicator, as the second (HRI2) is only based on the number of derogations of non-approved PPPs and is expected to be temporary. HRI1 is “based on the quantities of active substances placed on the market in plant protection products under Regulation (EC) No 1107/2009” and the respective annexes of the Regulation (EC) No 540/2011. Compared to the national previously described indicators, HRI1 is based on simple calculation with artificially assigned weights to each group of active substances. It does not take into account farming practices or exposition and it gives an aggregated final value. However, it is supposed to serve as a benchmark for all EU Member States.

In addition to technical considerations, it should be noticed that indicators can also be seen as the embodiment of political choices. In the case of environmental indicators, their selection can be the result of an interplay between those who want to highlight environmental issues and those who oppose it (Bouleau, 2009; Bouleau et al., 2017). Therefore, it is not surprising that the publication of HRI1 has been the subject to criticism. On the one hand, HRI1 has been criticized in several scientific publications (Bub, 2023; Street, 2023; Vekemans and Marchand, 2024), as well as in press releases from official organizations such as the German Environment Agency (Stallmann, 2023). Other non-governmental organizations (Burtscher-Schaden, H., 2020; PAN Europe, 2021; Foodwatch, 2022) have also criticized this indicator. On the other hand, some organizations connected to farming or farming chemical industries found the HRI1 indicator to be more appropriate to assess the implementation of the Farm to Fork strategy (European Union, 2020) than some of the indicators used by Member States (CropLife Europe, 2022). The publication of this indicator has especially interfered with debates at a national level and with tensions regarding NAPs. In France, for instance, two indicators were calculated annually at national level since the launch of the French National Action Plan named Ecophyto: the QAI (Quantity of Active Ingredients sold); and the NoDU (Number of Unit Doses) standardizing QAIs by reference doses, called “unit doses” (Hossard et al., 2017). Until February 2024, the NoDU was the main monitoring indicator for Ecophyto. It was designed to quantify the use of PPP treatment in French agriculture. As such, it only considered the agricultural portion of PPP national sales, a restriction from the “pesticides that are plant protection products” as stated in the 2009 Directive (Article 2.1). The use of the NoDU indicator has been criticized by PPP producers and some farmer organizations since the launch of the French NAP. Following the recent agricultural revolt, and in the context of the implementation of a new version of Ecophyto plan, the French government decided on February 21 2024, to replace the French NoDU indicator by the European indicator HRI1 to monitor the effect of the future plan (Struna, 2024).

Hereafter, we assess the relevance of both HRI1 and NoDU with regards to the two main objectives of the Directive 2009/128/EC (European Parliament and Council, 2009) which states that it “establishes a framework to achieve a sustainable use of pesticides by”: (*i*) “reducing the risks and impacts of pesticide use on human health and the environment and” (*ii*) “promoting the use of integrated pest management and of alternative approaches or techniques such as non-chemical alternatives to pesticides” (Article 1, “Subject Matter”).

Therefore, we analyzed the response of both indicators through putative scenarios of changes in PPP use and regulation, using available databases on PPP sales in France. The scenarios considered depict major changes in PPP use in France that should significantly impact risks on human health and the environment (whose reduction is the first main objective of the Directive 2009/128/EC). In addition, some of the scenarios considered substitution of PPPs by different PPPs, while other scenarios did not consider substitutions of PPP, assuming a widespread implementation of IPM solutions (second main objective of the Directive 2009/128/EC). The results obtained provide a basis for a general methodological reflection on the main features required for monitoring indicators of NAPs for pesticide reduction.

Materials and Methods

Data on sales of Plant Protection Products

Sales from 2011 to 2021 were obtained from the national database on sales of PPP (“*BNVD*”), which is accessible online *via* the “*BNVD-Traçabilité*” tool (OFB, 2023a). First, identification codes of PPPs marketed abroad were transformed into their French reference identification codes, in order to retrieve exhaustive information further needed on PPPs. This was achieved using the French reference database on PPPs (E-Phy, Anses, 2024). Then, we selected, within the BNVD database, only the products truly classified as PPPs in the E-Phy database. In addition, we removed rows with the “SA non phyto” label (standing for “non plant protection active ingredient”).

Sale data, expressed in kilograms of active ingredients sold during each calendar year, were subsequently named QAI (Quantity of Active Ingredients). QAIs are simply calculated by multiplying the PPP sold quantities by the concentration of each active ingredient within PPPs (Equation 1).

Equation 1.

$$QAI_{y,i} = \sum_{p}\left[Quantity_{y,p} * Concentration_{i,p}\right]$$

$Quantity_{y,p}$ refers to the sold quantity of the plant protection product p during year y and $Concentration_{i,p}$ corresponds to the concentration of the active ingredient i in the plant protection product p.

NoDU indicator calculation

NoDU covers a wide range of PPPs but excludes some “segments” officially defined by the Statistical Services of the French Ministry in charge of agriculture: biocontrol products; products with non-agricultural uses only (*e.g.* public gardens, railways and sport fields); and seed treatments. Biocontrol refers to PPPs containing macro- or microorganisms, semiochemicals (*e.g.* natural pheromones, kairomones), or some mineral substances, such as sulfur or oils (the complete list of these substances are defined in article L. 253-6 of the French Rural and Maritime Fishing Code).

In order to calculate an indicator that is consistent with the officially published NoDU values (MASA, 2022), we considered only the agricultural use segments available in the French data visualization tool of PPP sales (SDES, 2023). We therefore selected products belonging to the “UA” segment (PPP with agricultural uses only), the “UAZNA” segment (PPP with both agricultural and non-agricultural uses) and the “AUT” segment (PPP with multiple uses), thus removing biocontrol, seed treatments and non-agricultural uses.

When the information on the use segment was missing for a PPP, we assumed that it was used for agricultural purposes. This choice was supported by high correlation between calculated values and official NoDU figures (Figure S1).

The calculation of the NoDU is based on the use of reference doses called “Unit Dose” (UD). UDs are usually defined for each active ingredient and for each use segment, but the data source that we used provided reference doses only for the “UA” segment (OFB, 2024). Nevertheless, most active ingredients sold in PPP belonging to the “UAZNA” and “AUT” use segments were also present in the “UA” segment. Thus, we used the UD from the “UA” segment independently of the segment of the considered product. Only 5 active ingredients (representing 0.061 % of the total QAI from 2011 to 2021) were not considered in the NoDU calculation due to lack of UD. The UD calculation is detailed in Supplementary Material 1 and Hossard et al. (2017).

The NoDU of a given year y is calculated as the sum of the ratios between the QAI of year y and the UD for each active ingredient i (Equation 2). The NoDU indicator can be interpreted as the virtual cumulated areas having received a Unit Dose (UD) of active ingredient over a calendar year.

In addition, the NoDU calculation can be applied, within the group of substances selected for the general NoDU, to only to the Carcinogenic, Mutagenic and Reprotoxic chemicals (called “CMR” with two categories: CMR1, chemicals that have been identified as having the potential to cause cancer, genetic mutations, or harm to reproduction; CMR2: chemicals that are suspected to cause cancer, genetic mutations, or harm to reproduction; Regulation (EC) No 1272/2008).

Equation 2.

$$NoDU_y = \sum_i \frac{QAI_{y,i}}{UD_i}$$

With this approach, the Pearson correlation between the calculated values of NoDU and the officially published values was 0.996 (Figure S1). The average difference (absolute value) over the years between the official and calculated NoDU values was only 1.08 %.

HRI1 indicator calculation

The European indicator HRI1 is based on all PPP sales at the national level. European regulation no. 1107/2009 classifies active ingredients into four groups: (*i*) low-risk, (*ii*) approved, (*iii*) approved but candidate for substitution and (*iv*) not approved. Each of these groups is considered to represent a given risk, which is why their QAI are weighted differently in the calculation of the indicator, respectively by 1, 8, 16 and 64 (Equation 3, Directive 2009/128). The obtained values are then standardized by their 2011-2013 average and multiplied by 100 %.

Equation 3.

$$HRI1_y = \frac{\sum_g \left[Coefficient_g * \sum_{i \in I_g} QAI_{y,i} \right]}{\left(\sum_{y=2011}^{2013} \sum_g \left[Coefficient_g * \sum_{i \in I_g} QAI_{y,i} \right] \right) / 3} * 100$$

I_g corresponds to the set of active ingredients belonging to the risk group g.

The list of active ingredients of each group is published by Eurostat (Eurostat, 2023). To ensure that all active ingredients within the BNVD are associated with the correct group of risk, we performed data joins using *estat* codes rather than the common names of active ingredients. As previously, this information was available *via* the "BNVD-Traçabilité"' online tool (OFB, 2023b).

This method led to a Pearson correlation of 0.982 between the calculated values of HRI1 and the officially published values (Figure S2). The average absolute difference between the official and calculated HRI1 values was only 2.59 %.

Short description of the national dataset on sales of Plant Protection Products

A total of 436 active ingredients was considered to calculate the HRI1 indicator (Table 1), from which 314 belong to the second group of risk (*i.e.* approved active ingredients). On the other hand, the NoDU was calculated considering a notably lower number of active ingredients (295; Table 1). This is because the NoDU indicator focuses on non-biocontrol agricultural uses, contrary to the HRI1 that encompasses all sales of PPPs.

Table 1. Number of active ingredients considered for HRI1 and NoDU calculations, between 2011 and 2021 in France, according to their risk group and function. Risk groups 1 to 4 contain respectively: low-risk active ingredients, approved active ingredients, approved active ingredients which are candidate for substitution, not approved active ingredients

Indicator	**Risk group**	**Count**				
		Fungicides	Herbicides	Insecticides	Others	Total
HRI1	1	6	0	0	1	7
	2	97	85	55	77	314
	3	27	18	10	6	61
	4	14	21	9	10	54
	all	144	124	74	94	436

NoDU	all	98	113	46	38	295

Table 2. Quantity of Active Ingredients (QAI) considered for HRI1 and NoDU calculations, in 2021 in France, according to their risk group and function. Risk groups 1 to 4 contain respectively: low-risk active ingredients, approved active ingredients, approved active ingredients which are candidate for substitution, not approved active ingredients

Indicator	**Risk group**	**Quantity of Active Ingredient (10^6 kg) in 2021**				
		Fungicides	Herbicides	Insecticides	Others	Total
HRI1	1	0.01	0	0	0.15	0.16
	2	24.8	22.9	2.18	7.53	57.4
	3	3.72	5.70	0.16	0.01	9.59
	4	0.01	< 0.01	0.02	0.02	0.05
	all	28.54	28.6	2.36	7.71	67.2
NoDU	all	11.4	27.8	1.03	2.91	43.1

Therefore, in 2021, the total QAI used to calculate the HRI1 indicator was 67.2 10^6 kg, while the QAI used to calculate the NoDU indicator was only 43.1 10^6 kg (Table 2). Active ingredients that explain most of the difference between the QAI for NoDU and the QAI for HRI1 in 2021 were: kaolin among insecticides (1.1x10^6 kg, *i.e.* 79.6 % of the difference within insecticides), sulfur among fungicides (15.1x10^6 kg, *i.e.* 87.9 % of the difference within fungicides), pelargonic acid among herbicides (0.7x10^6 kg, *i.e.* 86.1 % of the difference within herbicides), and mineral oils among other uses (4.3x10^6 kg, *i.e.* 90.4 % of the difference within the “others” function category). If we set the QAI of those four active ingredients to 0 in 2021, the QAI to calculate HRI1 is much closer to the one used to calculate NoDU: 46 10^6 kg (not shown).

Overall, the “raw” QAI values are mainly composed (66 %) by active substances registered at reference doses greater than or equal to 1.0 kg.ha^{-1} (Figure S4). While, standardized QAI by reference doses (e.g. NoDU) value is mainly composed by active substances registered at reference doses of less than 1.0 kg.ha^{-1} (83 %).

Impact of weighting coefficients within the HRI1 indicator

First, we analyzed the impact of weighting coefficients within the HRI1 indicator by comparing QAIs with the global HRI1 indicator, per HRI1 risk group, between 2011 and 2021 in France. The Pearson correlation coefficients between QAI and HRI1 for each risk group were then calculated.

Generic scenarios

We simulated the values of QAI, NoDU and HRI1 in 2021 (last year of studied time range) under several putative scenarios to illustrate how their values might be affected by sales and changes in regulation. In order to be consistent with HRI1, NoDU values were expressed relatively to its average value between 2011 and 2013.

Banning a substance implies that the HRI1 is calculated again for all years since 2011 with the substance being moved from its initial group to the group 4. This makes the use of this substance having suddenly a much different weight in the variations of the HRI1, both in the past, when the substance was not actually banned, and in the future where "emergency authorizations" can (European Commission 2023a) and do allow for some use of the products (PAN Europe 2023, European Commission 2024).

To measure this new weight of the banned substance in the HRI1, we present HRI1 values for our simulation year (2021), only accounting for the considered changes in regulation, hence with no change in PPP use (*2021 ban*). We also show the current values for both indicators in 2021 with no changes in PPP sales or regulation (*reference* scenario). This second value allows us to see the change in absolute value of HRI1 before and after regulation change.

We then considered four scenarios of PPP sales cessation in 2021 (*i.e.* QAI of 2021 was set to 0), named with short tags describing regulatory and/or technical changes.

First, scenarios in which sales of one or several active ingredient(s) ceased due to a withdrawal from the market, were tagged "*ban*". If not, they were tagged "*noban*". For "*ban*" tagged scenarios, the considered active ingredient(s) is(are) transferred into the HRI1 group 4 (*i.e.* QAIs were retrospectively weighted with a coefficient equal to 64 in the HRI1 calculation). On the contrary, for "*noban*" tagged scenarios, the considered active ingredient(s) remain(s) in the same HRI1 group (*i.e.* QAIs were weighted the same way as in the *reference* scenario in the HRI1 calculation).

Second, scenarios where sales cessation was compensated by another active ingredient with equivalent QAI and UD (1:1 scenario) were tagged "*sub*". If not, they were tagged "*nosub*". Note that for the "sub" tagged scenarios, NoDU values will not change, by construction. For, these scenarios, we assumed that the substitute active ingredient belonged to HRI1 group 2 (*i.e.* its 2021 QAI was weighted with a coefficient equal to 8 in

HRI1 calculation). For “nosub” tagged scenarios, we assumed that IPM strategies were implemented to compensate for PPP non-uses.

In all, we thus considered two reference values for 2021: “*reference*”, and “*2021 ban*”; and four generic scenarios : *“ban&sub”; “ban&nosub”; “noban&sub”* and *“noban&nosub”*.

Specific scenarios

The generic scenarios described above were implemented for specific sets of active ingredients in order to assess the relevance of the HRI1 and NoDU indicators with regard to the two main objectives of Directive 2009/128/CE. Two sets of specific active ingredients were considered: those registered with low application rates; and those which were sold in high quantities during the standardization period (2011-2013) of the considered indicators (2011-2013).

Insecticides were good candidates for scenarios for active ingredients registered at low application rates, as they are often registered at much lower application rates than herbicides and fungicides (Figure S3), reflecting their high efficiency and toxicity *sensu lato*. Therefore, we designed scenarios in which we set to 0.0 kg the sales of the five synthetic insecticides with highest QAI in France in 2021. These active ingredients were: phosmet, cypermethrin, lambda-cyalothrin, pyrimicarb and tau-fluvalinate. In addition, we also considered extreme scenarios in which sales of all synthetic insecticides (46 in total) would cease in 2021 in order to maximize the impact on indicators.

For the second specific set of active ingredients, we considered: (*i*) glyphosate which is the most sold active ingredient in France in terms of QAI, regardless of the year; and (*ii*) mancozeb which is the second most sold active ingredient in terms of QAI in France, after glyphosate, during the 2011-2013 period. Both, though they are not in group 3 (candidates for substitution) but in group 2 (approved active ingredients), have seen their authorization being questioned at the same time as HRI indicators were designed and published. The renewal of the glyphosate authorization was the subject of a heated debate until its renewal for ten years in November 2023 (Regulation (EU) 2023/2660). On the contrary, the approval of mancozeb expired in February 2022 (Regulation (EU) 2020/2087). In order to consider other likely scenarios, we simulated the cessation of sales of the five most sold active ingredients (with highest QAI) from HRI1 risk group 3 (candidates for substitution) in France between 2011 and 2013. These active ingredients were: metam sodium, aclonifen, pendimethalin, copper sulfate and prochloraz.

In summary, generic scenarios were declined into two groups of specific scenarios (in 2021) for: (*i*) active ingredients registered at low application rates (the five most sold synthetic insecticides in 2021; all synthetic insecticides); (*ii*) active ingredients which were sold in high quantities during the 2011-2013 standardization period of the indicators : glyphosate; mancozeb; the five most sold active ingredients from HRI1 risk group 3. These scenarios were named respectively: “Top 5 insecticides”; “All insecticides”; “Glyphosate” ; “Mancozeb”; and “Top 5 HRI1 risk group 3” scenarios.

In all, 21 scenarios (4 generic scenarios times 5 specific scenarios, plus 1 reference scenario) were considered. For the sake of readability, only figures illustrating the most significant results will be presented in the “Results” section. In all, the considered scenarios led to the calculation of 42 distinct values of QAI, NoDU, and HRI1 that are presented in a summary table to complement the presented graphs.

Software and packages

Analyses were conducted using the 4.3.2 version of the *R software* (R Core Team, 2023). Data were read using the *data.table* and *readxl* packages (Barrett et al., 2023; Wickham & Bryan, 2023). Data handling was achieved using the *data.table* and *tidyverse* packages (Barrett et al., 2023; Wickham et al., 2019). Plots were produced using the *ggplot2* and *ggrepel* packages (Slowikowski, 2024; Wickham, 2016).

Results

Historical values of the HRI1 and NoDU indicators

Over the 2011-2021 decade, the relative QAI percentages of the four HRI1 risk groups considered to calculate HRI1 values were 0.1 %, 79.4 %, 14 % and 6.52 %, respectively for risk groups 1 to 4. These percentages are very different from their contributions to the HRI1 indicator final values, in which they represented 0.008 %, 49.8 %, 17.5 % and 32.7 % respectively, as a result of the contrasted weighting of each group (respectively 1, 8, 16 and 64; Figure 1). The QAI accounted for by the NoDU are about 30% inferior to those accounted for by the HRI1 (Table2, Figure 1), 80% of the difference corresponding to four substances authorized in organic farming (see Methods). Most of the variability in the NoDU is explained by the variations of the substances registered in the group 2 of the HRI1 even though variations in group 3 are sizable. According to the French NAP, the NoDU is complemented by the NoDU applied only to CMR (carcinogenic, mutagenic or reprotoxic substances) which shows a very important drop of use of these highly toxic PPP over the last years (Figure S6). When applied only to Carcinogenic, Mutagenic and Reprotoxic chemicals (called "CMR" with two categories: CMR1, chemicals that have been identified as having the potential to cause cancer, genetic mutations, or harm to reproduction; CMR2: chemicals that are suspected to cause cancer, genetic mutations, or harm to reproduction; Regulation (EC) No 1272/2008), the figure is totally different. The “CMR1 NoDU'' showed a drastic drop from 9.7 10^{10} ha in 2009 to 1.2 10^{10} ha in 2020, corresponding to a 88 % decrease (see Figure S6), before approaching 0 % in 2022 (MASA, 2023). The NoDU of CMRs as a whole decreased by 40 % between 2009 and 2020 (data not shown).

Dangerous substances, defined as pertaining to group 4, imply only small changes to the NoDU, as expected from an indicator monitoring the use of pesticides when banned PPPs are in practice substituted with others.

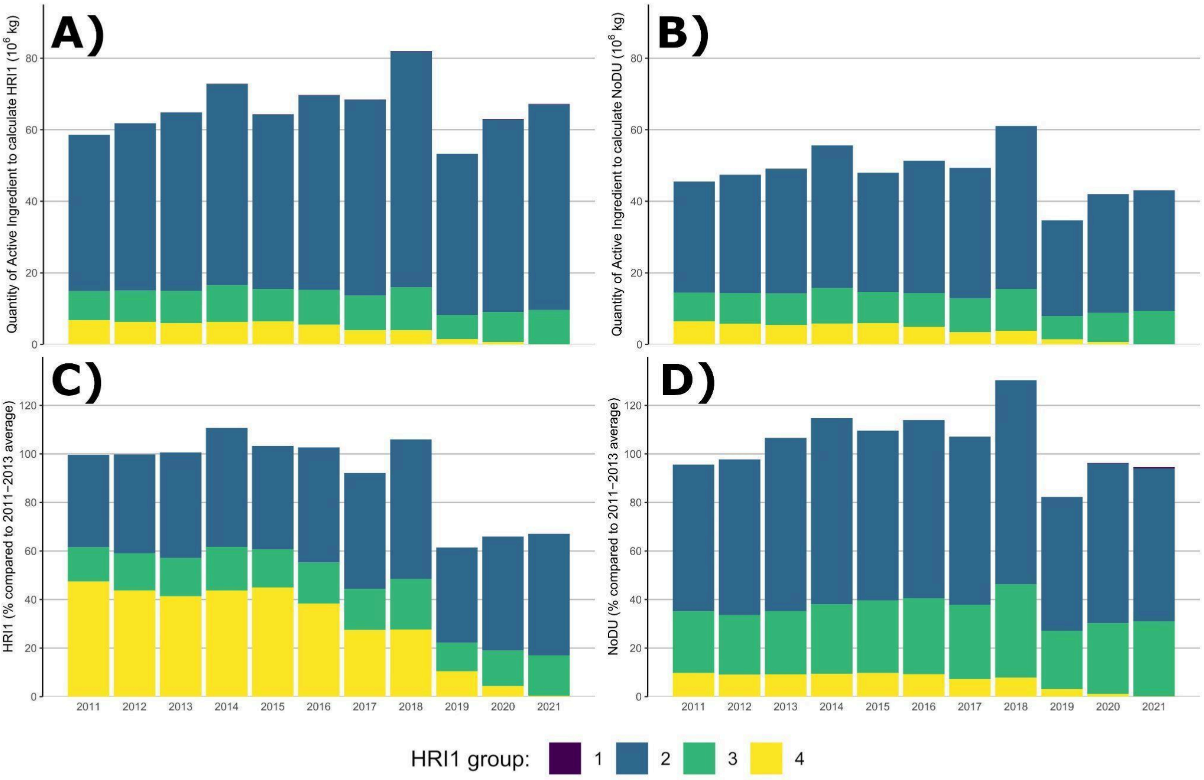

Figure 1. Quantity of Active Ingredients used to compute HRI1 (A) and NoDU (B) and resulting HRI1 (C) and NoDU (D) detailed per HRI1 risk group, between 2011 and 2021 in France.

On the contrary, due to the weighting of the risk group 4 by a factor of 64 in the HRI1 calculation, this fourth group almost single-handedly explained the global evolution of HRI1. Indeed, QAI of group 4 and HRI1 were highly correlated (Pearson r = 0.904; p-value < 0.01; Table 3). Despite this group includes 123 substances as of 2021, only two substances, chlorothalonil and isoproturon, represented roughly half of the QAI within HRI1 risk group 4 (48.3 %). Therefore, simulating the non-withdrawal of these two active ingredients (by keeping them into HRI1 risk group 3), would have a strong effect on HRI1 indicator which would be equal to 77 % in 2021 (data not shown), i.e. 10 % absolute index points (or 14.8 %) higher than the current 2021 value. As a result, a third of the current observed reduction of HRI1 between 2011-2013 and 2021, is attributable to the withdrawal (transfer from HRI1 risk group 3 to HRI1 risk group 4) of just these two active ingredients.

Table 3. Pearson correlation coefficients between the Quantity of Active Ingredient (QAI) and the Harmonized Risk Indicator 1 (HRI1) for each risk group. Significance thresholds are: (.) 10 %, (*) 5 %, (**) 2.5 %, (***) 1 %.

HRI1 group of risk	Correlation between QAI of each group and HRI1	Correlation p-value
1	-0.593	0.0546 (.)
2	0.150	0.660
3	0.571	0.0668 (.)
4	0.904	0.000134 (***)

Active ingredients registered at low application rates: Top five insecticides scenarios and all insecticides scenarios

The five most sold synthetic insecticides in 2021 (*i.e.* with highest QAIs) in France were phosmet, cypermethrin, lambda-cyhalothrin, pirimicarb and tau-fluvalinate. In 2021, they represented 76 % and 36 % of insecticide QAI used to calculate NoDU and HRI1 respectively. Two of them (lambda-cyhalothrin and pirimicarb) belong to the HRI1 group 3, which means that they are candidates for substitution.

When simulating the cessation of sales of these five active ingredients in 2021, the total HRI1 value was only slightly affected, whether active ingredients were withdrawn or not, with only - 1.83 and - 0.84 absolute index points (expressed in % of the 2011-2013 average) respectively (Figure 2). Relatively to the *reference* value of HRI1 (the current value as of 2021 legislation), this corresponds to a relative decrease of -2.73 % considering withdrawal, and -1.25 % without. By contrast, the cessation of sales of these five insecticides was more apparent with the NoDU indicator, as its value decreased by 9.9 absolute index points (expressed in % of the 2011-2013 average) (Figure 2), *i.e.* a relative decrease of -10.46 % compared with the *reference* value for NoDU. Since, by construction, NoDU does not consider regulatory status of active ingredients, the simulated reduction was the same whether or not the active ingredients were withdrawn.

If all synthetic insecticides were to be withdrawn, even without any substitution, the HRI1 indicator would equal 63.1 %, *i.e.* only 3.98 absolute index points less (or -5.93 %) than its current 2021 value, while the NoDU would drop by 16 points or 17% of its 2021 value (Table 4).

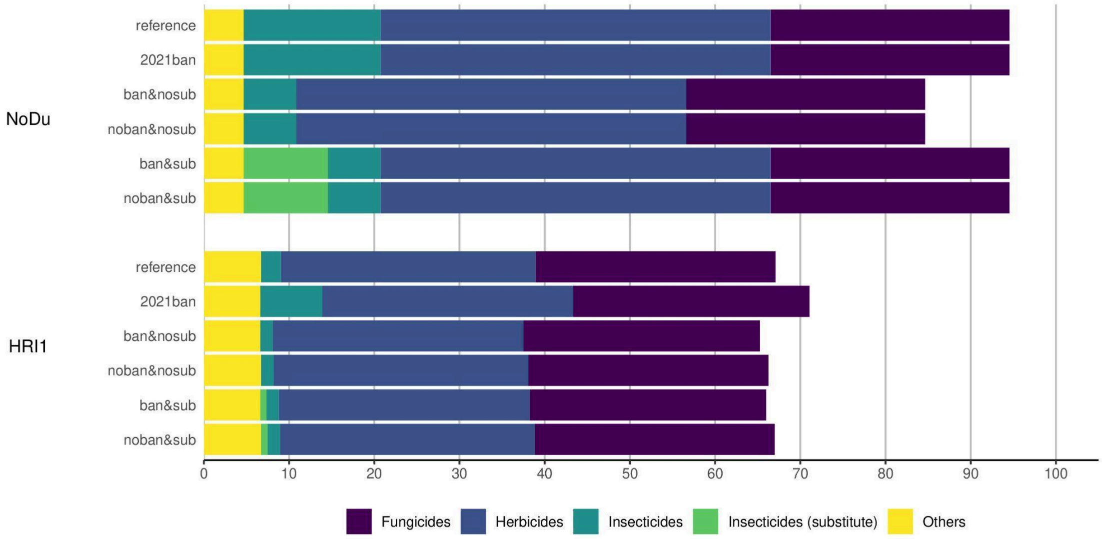

Figure 2. Number of Unit Doses (NoDU) and Harmonized Risk Indicator 1 (HRI1) values for 2021, according to different scenarios of cessation of sales of main synthetic insecticides. Involved active ingredients were those with the highest QAI in 2021 among synthetic insecticides: phosmet, cypermethrin, lambda-cyhalothrin, pirimicarb and tau-fluvalinate. Values were indexed on the 2011-2013 average of each indicator. The "reference" corresponds to the current 2021 values of the indexed indicators. The "2021 ban" corresponds to the 2021 values when the ingredients are banned. The "ban" tagged scenarios indicates that the cessation of sales is due to a withdrawal of the considered active ingredients (that are moved to the HRI1 risk group 4), otherwise the scenarios are tagged "noban" (active ingredients remain in their current HRI1 risk group).

The “nosub” tag indicates that the cessation of sales is not compensated by the sales of equivalent active ingredients.

In Figure 2, the *reference* value highlighted that all insecticides represented a very small proportion of HRI1 total value (3.5%) compared to NoDU (17%) in 2021.

Table 4. Values of QAI, HRI1 and NoDU under the different scenarios.

“reference (cur. 2021)” corresponds to the current 2021 values of indexed indicators, i.e. without any cessation of sales for all scenarios. “2021 if ban” corresponds to the same Quantities of Active Ingredients, except that the considered QAI are shifted to the risk group 4. The “ban” tag used to label scenarios corresponds to the cessation of sales due to a withdrawal of the considered active ingredients (assigned to the HRI1 risk group 4), otherwise the scenarios were tagged “noban” (active ingredients remained in their original HRI1 risk group). The “sub” tag used to label scenarios indicates that the cessation of sales was supposed to be compensated by the sales of equivalent active ingredients (same QAI and UD) from the HRI1 risk group 2. Otherwise the scenarios were tagged “nosub”.

	Set of active ingredients affected by scenarios									
Scenario	Top five synthetic insecticides		All synthetic insecticides		Glyphosate		Mancozeb		Top five AIs from HRI1 risk group 3	
	NoDU	HRI1	NoDU	HRI1	NoDU	HRI1	NoDU	HRI1	NoDU	HRI1
reference (cur. 2021)	94.5	67.1	94.5	67.1	94.5	67.1	94.5	67.1	94.5	67.1
2021 if ban	94.5	71.1	94.5	70.7	94.5	75.3	94.5	60.3	94.5	69.9
noban&nosub	84.7	66.2	78.5	65.8	90.2	60.2	94.1	66.5	91.8	60.4
ban&nosub	84.7	65.3	78.5	63.1	90.2	39.3	94.1	56.4	91.8	48.3
noban&sub	94.5	67.0	94.5	66.8	94.5	67.1	94.5	67.1	94.5	63.7
ban&sub	94.5	66	94.5	64.1	94.5	43.8	94.5	56.9	94.5	51

Active ingredients sold in high quantities during the 2011-2013 standardization period: glyphosate; mancozeb; and Top five HRI1 risk group 3 scenarios

In 2021, glyphosate represented 18.3 % of the QAI used to calculate NoDU, 11.8 % of the QAI used to calculate HRI1, 4.6 % and 10.3 % of NoDU and HRI1 indicators respectively.

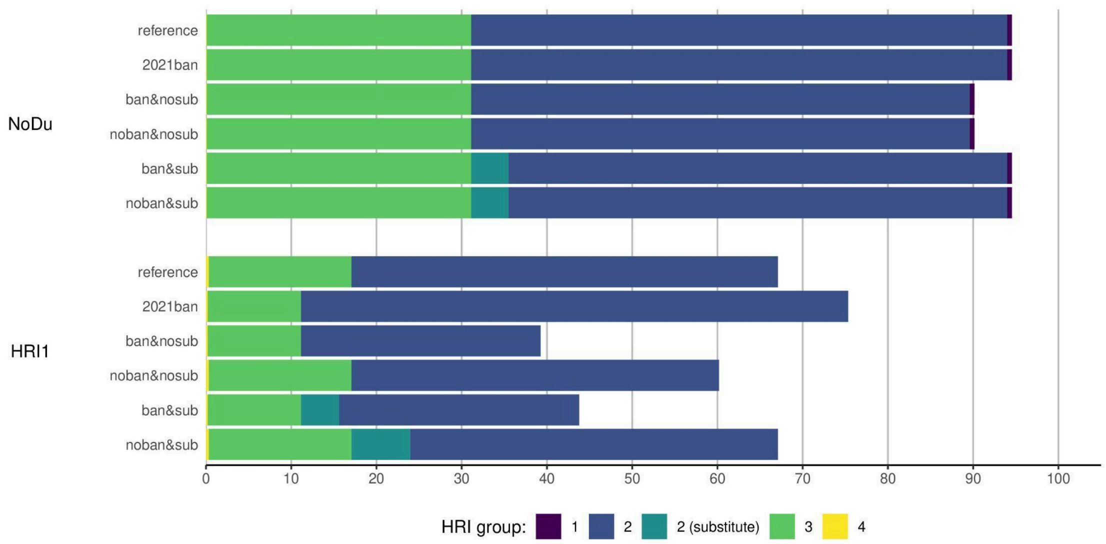

Figure 3. Number of Unit Doses (NoDU) and Harmonized Risk Indicator 1 (HRI1) values for 2021 according to different scenarios of cessation of sales of glyphosate. Values were indexed on the 2011-2013 average of each indicator. The “reference” and “2021 ban” scenario correspond to the 2021 values of each indicator respectively currently and if the glyphosate is banned. The “ban” tagged scenarios indicates that the cessation of sales is due to a withdrawal of glyphosate (moved to the HRI1 risk group 4), otherwise the scenarios are tagged “noban” (glyphosate remained in the HRI1 risk group 2). The “sub” tagged scenarios indicates that the cessation of sales is compensated by the sales of equivalent active ingredient (same QAI and UD) from the HRI1 risk group 2, otherwise the scenarios are tagged “nosub”.

When glyphosate sales were set to 0.0 kg without any substitution, NoDU was reduced by 4.39 % absolute index points (Figure 3). In scenarios with substitution by another equivalent active ingredient of the HRI1 risk group 2, the NoDU value remained the same, by construction.

The HRI1 indicator was very sensitive to a ban of glyphosate (Figure 3). Indeed, even if glyphosate was substituted, the HRI1 indicator would fall below the 50 % threshold of reduction relative to the 2011-2013 average value. If, in addition, glyphosate sales were not substituted this value drop to 39.3 (absolute index) or 41 % below the its current value (Figure 3). Suddenly, the glyphosate would correspond to 47.8% of the HRI value in 2021 before the ban, though it represents only 4.3% of the NoDU (Table 2, 2021 if ban - ban &nosub).

The withdrawal of mancozeb, the second most sold active ingredient in France after glyphosate between 2011-2013 (in terms of QAI) and banned since 2022 (Regulation (EU) 2020/2087), is less impactful on HRI1, but could still allow the HRI1 to approach the 50% symbolic reduction threshold as it would equal 56.9 % if mancozeb is replaced, and 56.4 % without substitution (Figure S5).

Similarly, the symbolic threshold of 50 % can also be approached by the withdrawal of the five active ingredients with the highest QAI sold between 2011 and 2013 that belong to the HRI1 risk group 3 : metam-sodium, aclonifen, pendimethalin, copper sulfate and prochloraz (Figure 4). Indeed, HRI1 would be reduced by 16.1 and 18.8 points (-24 % and -28 % relative reduction) compared to the *reference* scenario value, respectively with and without substitution of the considered active ingredient set.

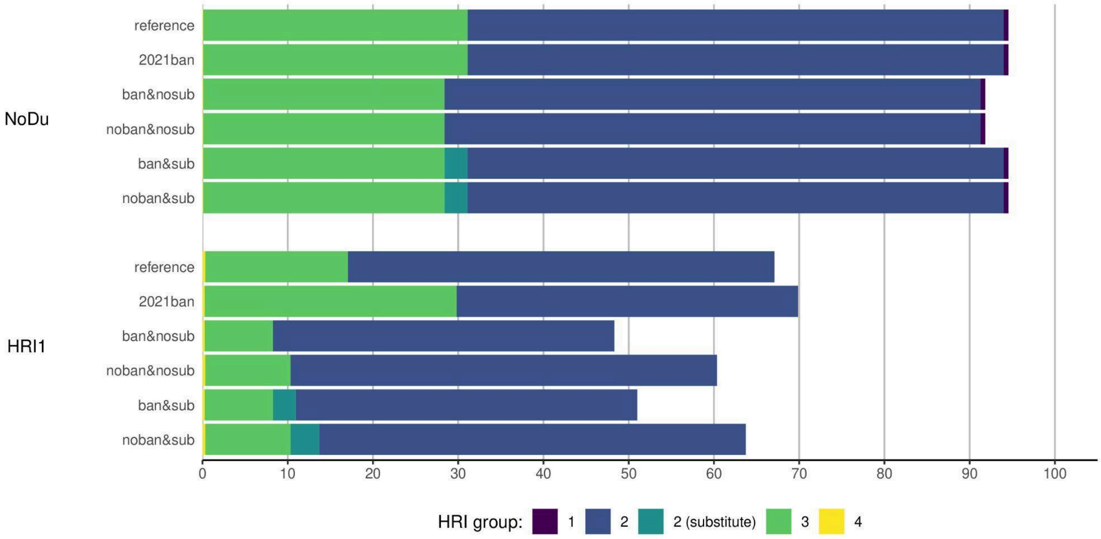

Figure 4. Number of Unit Doses (NoDU) and Harmonized Risk Indicator 1 (HRI1) under different scenarios of cessation of sales of main active ingredients from the HRI1 risk group 3. Involved active ingredients were those belonging to the HRI1 risk group 3, with the highest QAI between 2011 and 2013: metam-sodium, aclonifen, pendimethalin, copper sulfate and prochloraz. Values were indexed on the 2011-2013 average of each indicator. The “*reference*” and “2021 ban” scenarios correspond to the 2021 values respectively currently or if a ban is passed . The “ban” tag used to label scenarios corresponds to the cessation of sales due to a withdrawal of the considered active ingredients (assigned to the HRI1 risk group 4), otherwise the scenarios were tagged “noban” (active ingredients remained in their original HRI1 risk group). The “sub” tag used to label scenarios indicates that the cessation of sales was supposed to be compensated by the sales of equivalent active ingredients (same QAI and UD) from the HRI1 risk group 2. Otherwise the scenarios were tagged “nosub”.

Discussion

Highlights

Sensitivity of HRI1 and NoDU

This study revealed that HRI1 was more reactive than NoDU to the cessation of sales of active ingredients sold in high quantities and high registered doses: “glyphosate”; “mancozeb”; and “Top five HRI1 risk group 3” scenarios (Figures 3, and 4; Table 4). On the contrary, HRI1 was less reactive than NoDU to the cessation of sales of active ingredients with low registered doses: “Top five insecticides” and “All insecticides” scenarios (Figure 2; Table 4). The HRI1 value fell sharply with the withdrawal of glyphosate (from 67.1 % in average for 2011-2013 to 43.8 % in 2021). One can question whether the withdrawal of glyphosate, a group 2 active ingredient, hypothetically replaced by herbicides with identical registered doses, may really lead to a 23 % reduction in risks associated with pesticide use. On the other hand, HRI1 was not able to depict some major changes in PPP use, such as the cessation of the five most sold synthetic insecticides, or even all insecticides sold in 2021 with no withdrawal and no substitution (Figure2) although it certainly contributes to the reduction of ‘toxic risks’ and may represent a real change for biodiversity and pollination and a complete paradigm shift for EU agriculture. For those cases, risk models based on the toxicity of active substances have clear advantages.

An easy to reach 50% reduction target

The value of HRI1 of 43.8% reached with the withdrawal of glyphosate, even if replaced by herbicides with identical registered doses and QAI, is also striking in itself, as it is already below the 50 % reduction target to be reached by 2025 according to the French

NAP (French Ministry of Agriculture, 2022) and recently confirmed for the end of the decade (Girard Claudon, 2024). This symbolic target reduction was also put forward in the regulation proposed in June 2022 on the sustainable use of plant protection products (European Commission, 2022), as part of the European Green Deal (Filipović et al, 2022), and eventually not adopted by European Parliament on November 22nd, 2023 (European Parliament, 2023). Removing the five most sold PPP candidates for substitution (risk group 3) would also bring to the brink of this symbolic threshold.

Maybe more striking is the fact that the 50% reduction target could already be reached in France without us knowing about it (and additional efforts). Given that 1) the mancozeb was totally banned starting in 2022 (Regulation EU 2020/2087); and 2) the HRI1 value of 2021 is as low as 56.9% when accounting for this ban, the French NAP would suddenly be on much better tracks to reach the 50% diminution target by 2025, or at least by the end of the decade with the HRI1 being the reference compared to the NoDU, still at 94.5% of its average value in 2011-2013. Unfortunately, for some reason, the official sales figures for 2022 have remained unavailable though the official 2022 NoDU has been released for 9 months at the day of first publication (MASA, 2023), preventing us from computing the exact 2022 value of HRI1. Incidentally and despite its non renewal since 2022, the Mancozeb is also not officially listed in group 4 as of today (Eurostat, 2023).

The 50% symbolic reduction threshold at the level of the EU might very well be reached with the HRI1 just as easily as in France given the similar HRI1 values in 2021 for France (67.1%) and the EU (62%, European Commision, 2023c).

Conceptual adequation of HRI and NoDU with the objectives of the SUD

Monitoring of the PPP use reduction

For each active ingredient, the formula of the NoDU accounts for a unit dose, corresponding to a full dose treatment in the fields. This makes it a proxy of the dependency on PPPs (Hossard et al. 2017), and, conversely an indicator of IPM adoption in PPP-based crop protection practices, although IPM is a somewhat polysemic concept (Deguine et al., 2021; Tello et al., 2023). As such, it directly monitors progress towards the second objective of the SUD: "to encourage the development and introduction of integrated pest management and of alternative approaches or techniques in order to reduce dependency on the use of pesticides" (Article 4.1; European Parliament and Council, 2009). A reduction in PPP use implies higher Efficiency, Substitution with practices other than the use of chemicals, or the Redesign of the considered cropping system (Hill and McRae, 1995). Nevertheless, it does not account for the use of non agricultural PPPs (biocides) though they are part of the objective of the SUD. It also does not account for seed treatments, a major chemical protection practice which has been shown to have significant environmental impacts, particularly for neonicotinoid products (Lamichhane et al, 2020). Contrary to the NoDU indicator, the HRI1 indicator does not account for the commonly used doses of a product. This would not prevent its use as a proxy of pesticide use to assess the progress in the second objective of the SUD if the efficiencies by unit of mass were comparable between products within a given risk group. Nevertheless, as already noted by the German Environment Agency, active ingredients can be efficient at doses different by up to four orders of magnitude (Knillmann et al, 2023) and commonly one to two orders of magnitude. We found similar results with the database on PPP sales in France, with differences in UD of two to three orders of magnitude for fungicides, herbicides, and insecticides, and up to five orders of magnitude for the “others” function (Figure S3). The HRI1 indicator cannot represent the evolution of PPP use or the dependency to PPP, and we see in the simulations that indeed, when a substance is banned, its substitution or not by another substance has relatively limited impact on the reduction of the HRI1 indicator, compared to the impact of the ban (Figures 2, 3; Table 4).

Monitoring the risk induced by PPPs

As for assessing the first objective of the SUD: “reducing the risks and impacts of pesticide use on human health and the environment”, it is inherently more complex, as the toxicity of PPP can be widely different depending on their properties and the taxonomic group considered. As a matter of fact, in the USA from 1992 to 2016, the total applied toxicity (TAT) evolution diverged for aerian vertebrates (TAT divided by 9 for mammals and birds) and invertebrates (TAT more than doubled for aquatic invertebrate and insect pollinators), as a result of the replacement of organophosphorus and carbamates by pyrethroid and neonicotinoids (Schulz et al. 2021). Neither the HRI1 nor the NoDU address this complexity of the risk relative to different taxa.

If the NoDU does not explicitly account for the risk, the HRI1 structure, with only four groups of risks, might not be relevant to discriminate against the diversity in toxicity and ecotoxicity among the 436 active ingredients considered. Indeed, 314 active ingredients (*i.e.* 72 %) are in the risk group 2 accounting for 79% over 2011-2013 and 85 % in 2021 of the total mass of substances contributing to HRI1 (Table 2).

Besides, the weighting coefficients associated with the HRI1 risk groups have huge impacts on HRI1 values according to our simulations. In particular, the 64 coefficient of group 4 induced that most of the variations of HRI1 were explained by past variations in sales of the products banned at the time of computation. As already noted by the German Environment Agency “This strong weighting is not scientifically justified and therefore misleading” (Stallmann, 2023).

Given the weight of political discussions in the renewal of the authorization, as exemplified in the renewal process of glyphosate (European Commision, 2023b), giving such a weight to administrative, or even political decisions might not allow to adequately monitor toxicity, as also noted by the German Environmental agency (Knillmann et al, 2023). This is also all the less adequate if, as currently promised by the French Government, there will be “no withdrawal without a solution” (Jacquot, 2024) and hence very toxic substances can remain authorized if they are deemed necessary. As for the quantification of the risk, HRI1 implicitly considers the risk to be proportional to the mass of active substances within each risk group. But, it is well known that the mass of active ingredients do not correlate well with PPPs induced risks (Reus et al. 2002). Here, summing masses of active substances within a given risk group does not make sense since these substances have different toxicological and ecotoxicological profiles. This assertion is supported by the wide range of magnitude orders observed for registered rates of active ingredients within HRI1 group risks (5, 7, 5 orders of magnitude for risk group 2; 3; and 4 respectively; group 1 having only one officially registered rate since it mostly involves micro-organisms, data not shown).

Though the aim of the NoDU indicator is not to quantify the risk associated with PPP use, it might be seen as embedding the concept of risk through the use of Unit Doses (the mass of an active ingredient is divided by a reference dose). Of course, even for a similar Unit Dose, PPPs can display a range of impacts on human health and biodiversity, depending on their modes of action (Sharma et al., 2019). Therefore, NoDU is not usually considered a good indicator of potential impacts on human health and biodiversity. Nevertheless, PPPs are inherently toxic for their target and used in order to be efficient. Their typical use doses are hence a quantification of their toxicity and the NoDU calculation accounts for it. On the contrary, the HRI1 completely ignores this piece of information while molecules with extremely different toxicities and use dose can be in the same group (Strassemeyer et al., 2023). For example, typical insecticide applications can range from 0.010 kg.ha^{-1} for some pyrethroids or neonicotinoids to 5.0 kg.ha^{-1} (Schultz et al, 2021; Figure S3). Therefore, it is questionable whether HRI1 should be used to monitor changes in the risk associated with PPPs when such disparities can be found within a group. A corollary is that replacing old molecules by new molecules (lower weight) would tend to decrease HRI1 independently of the toxicity of the molecules and it has been a fairly constant trend in PPP history that the weight of new molecules tends to decrease for a similar efficacy (Schutz et al. 2021, Bub et al. 2023).

Finally, according to the French NAP before the change in indicator, the NoDU is also published along with the CMR NoDU, allowing a view specifically on the use of these particularly dangerous molecules. As a result, the NoDU, especially when associated with the CMR NoDU (Figure S6) might, in fact, be a better indicator of the risk relative to the applied PPPs than HRI1 despite the absence of risk classes. For example, the current collapse of insect populations in Europe (Habel et al., 2019) putting directly at risk terrestrial and freshwater ecosystems (Goulson, 2019) could be a reason to prioritize the environmental risk for insects, a risk that the HRI1 strikingly cannot capture according to our simulations. This finding is similar to that of Bub et al. (2023) when comparing HRI1 to the German NAP indicator: “[the HRI1 shows] striking conceptual shortcomings for the quantification of environmental risks compared to the previously used SYNOPS risk indicators”.

PPP perimeter of the indicators and aims of the SUD

In addition, the set of substances encompassed within HRI1 explicitly conflicts with the objectives of the SUD to foster non-chemical PPP. The HRI1 indicator includes micro-organisms (European Commission, 2022), in contradiction to the objective to foster non-chemical alternative approaches, including biological control, of the SUD (Article 3.8). MoreoverIn addition, we have shown that sulfur (Group 2 or 3), mineral oils (Group 2), pelargonic acid (Group 2) and kaolin (Group 2) accounted for over 30% of the mass of PPP considered by HRI1 (in 2021). The chemical status of these generally old and “heavy” substances can be debated and they are not necessarily danger-free. However, they are very well known and heavily used in organic agriculture, which is deeply dependent on “non-chemical alternative approaches'' to PPP, an explicit objective of the SUD. Thus, state members with significant shifts toward organic agriculture could even see their HRI1 values increase due to the high registered rates of the mentioned products (Burtscher-Schaden, 2022), despite the increased biodiversity of organically farmed fields (Gong et al., 2022) and likely benefits for consumers's health (Mie et al, 2017).

Possible comparisons in time and between member states

The monitoring of the risk and the use of PPP is also supposed to be harmonized among member states, as per the very name of the indicators in the Directive, and the indicators should be calculable at the European level. The NoDU in this respect is lacking by the fact that the UD are defined on the basis of French authorization values. Nevertheless, keeping the idea of dividing the mass of substance by a typical application rate, such values could be defined at the European level. The harmonized calculation of HRI1 over Europe allows us to compare trends between member states. Nevertheless, its standardization by the average value in 2011-2013 prevents any comparison between member states in absolute value, a characteristic also preventing HRI to be used in NAP and account for “the risk or use reduction targets achieved already prior to the application of this Directive”, as stated by the Article 4.1.

Risks inherents to the use of the HRI1 to set political targets

Finally, our analysis suggests that according to HRI1, the NAP PPP reduction targets could be met by substituting old substances, with high active doses, even of low toxicity with more recent equivalent molecules. This could be a dangerous incentive to European political instances, if only to do some Green Washing. This risk might be increased by the fact that old substances such as glyphosate are not any more protected by patents and hence much less profitable than putative new substances that could be used as substitutes, an incentive for agro-chemical firms to lobby for a continuous renewal of substances. Because the HRI1 indicator is highly sensitive to withdrawals of PPP, it might be tempting to consider it as an indicator of public policies and compliance with regards to PPP regulations. Indeed, HRI1 would very strongly single out countries that would deliver authorizations for substances not approved at the European level given the 64 coefficient of group 4 (not approved), but only if the usual application doses are high and independently of their toxicity. Alternatively, approving very light (active at low doses) but more toxic substances that could replace old and heavy substances, even without forbidding them, could be tempting to greenwash European PPP use. The HRI1 is hence dangerous as its calculation could encourage green washing interdiction of low toxicity products to be replaced by equally or more toxic products but increasing incomes of agro-chemical industries at the expense of farmers, consumers and ecosystems.

Conclusion on the relevance of HRI1 and NoDU in light of the objectives of the SUD

Overall in the light of our simulation results, our conceptual analysis, in agreement with other published scientific articles and technical administrative notes criticizing in particular the chosen weights between the risk groups and the fact that it does not take into account the usual application doses of PPPs (Bub et al. 2023, Street et al. 2022, ECA 2020, Stallmann 2023 & Knillmann et al. 2023), HRI 1 seems to present such flaws, both conceptually and in practice that it cannot pretend to adequately monitor the risk for humans health and the environment relative to the use of PPPs or the efforts to promote the use of integrated pest management and decrease farmers' dependency on the use of PPPs. HRI1 hence completely misses the objectives set by the 2009 Directive though it might be seen as a more detailed HRI2. In addition, it prevents comparisons between member states in absolute value and could be an incentive for deleterious political choices in terms of PPP authorizations. In comparison, the NoDU properly monitors the more restricted objective of quantifying the use of PPPs and has some practical shortcomings despite its conceptual relevance.

Limitations

In this work, we focused on readily and publicly available data from France, to illustrate the practical extent of the conceptual limitations of two existing PPP use and risk indicators. Our argumentation would undoubtedly gain in strength if conducted with other member states' data. Precise and substance specific estimations could vary, but we showed that the general strengths and flaws are directly generated by conceptual choices in the calculation and set of substances chosen. Similarly, the general toxicity views presented here could, in a future work, be enriched by a more detailed evaluation of toxicity substance by substance, using for example the TAT approach (Schutz et al. 2021), or the Pesticide Load approach (Kudsk et al, 2018). Finally, though we focused here on two NAP indicators, several other indicators exist in other member states and their performances could be similarly evaluated in the light of the SUD. This would probably help narrow down the principles to follow to improve the current European level indicator.

Toward better indicators

Indicators reflect a policy

The discussion on indicators and more generally on the PPPs policies of the EU has been the subject of debate, both at the National and European levels, as NAP are evaluated and renewed and discussions on the SUR continue (Struna, 2024). In this context and observing the discrepancy between the objectives of the SUD and how HRI1 works, it is important to keep in mind that indicators are instruments (Lascoumes & Le Galès, 2005), which perform as "materialized theories" (Bachelard, 1934). Neither perfectly neutral nor purely technical objects, they are the result of collective choices, and therefore embody a certain vision of public problems, as well as the solutions implemented to deal with them. The definition of a measure is as much a political operation as a technical one. A sudden change of indicator marks a shift in the definition of the political objective of the French NAP and cannot be considered as a merely technical detail. Our analysis shows that the recent definition of HRI1 singularly mismatches the initial political vision of the SUD for an harmonized risk indicator. At the French level, the political implications of the indicator shift from NoDU to HRI1 are blatant when considering the 50% reduction target currently aimed at (France) or discussed (SUR). The revision of the quantitative goal when changing the indicator has not been considered publicly, unlike it was for example done when replacing Treatment Frequency Index by Pesticide Load for official monitoring of the Danish NAP (Danish Environmental Protection Agency, 2024). The calculation and scope of HRI1 implies abandoning the principles of the Directive it is supposed to embody (reducing risk by promoting non-chemical control). It also implies that the targets currently set or under discussion at both national and European level will be reached in the short term (if not already reached), which could mean the end of efforts to reduce the risk induced by PPPs.

However, the will of the people of the EU is supposed to be expressed by the European parliament in the SUD. Like other stakeholders (Stallmann, 2023), we hence recommend that the European Commission reconsider the design of Harmonized Risk Indicator at European level to improve its compliance with the guidelines of the SUD that called for it.

Improving indicators, a difficult task

As already mentioned, assessing human health and environmental toxicity is complex in essence. For example, variations of biodiversity depend on which qualitative and quantitative losses are considered in environmental assessments and how gains are generated to ensure equivalence (Bezombes et al., 2019) so that multiple indicators may not necessarily converge (Bockstaller et al., 2009). Indeed, a species or a group of species is a good indicator of an environmental contamination and impact but are not necessarily good biodiversity indicators (Duelli and Obrist, 2003). The Commission of the European Communities (2000) defines 'agri-environmental indicators' as a "generic term designating a range of indicators aiming at giving synthesized information on complex interactions between agriculture and environment. The Organisation for Economic Co-operation and Development (OECD) has developed agri-environmental indicators in 13 different areas notably biodiversity, wildlife habitats, landscape, farm management, pesticide use, nutrient use, water use, soil quality, greenhouse gas, socio-cultural issues, farm financial resources; (OECD, 1999, 2001). A recent review on indicators for sustainable agriculture shows, in a systematic literature search, 40 indicators from 77 papers for environmental assessment (Bathaei et al, 2023).

In front on this complexity, NAP have chosen different paths

The indicators used by European countries to monitor their NAPs can be differentiated by the assumptions and formalisms considered, the time and space scales taken into account, the needed parameters and data, and the types of results. We identified six risk indicators among the ten EU countries with the highest quantities of plant protection products per area of cropland in 2021 (The Netherlands, Ireland, Belgium, Italy, Portugal, Spain, Austria, Germany, Slovenia, France; FAOSTAT, 2024). They have contrasting features. Some indicators are derived from models: EIP (Reus and Leendertse, 2000), POCER (Vercruysse and Steurbaut, 2002), SYNOPS (Strassemeyer and Gutsche 2010), PL (Kudsk et al., 2018), while others are based on simple calculations as scores: OECD indicators (Balmer 2002); NoDU (MASA, 2017; Hossard et al., 2017). Moreover, some indicators take into account farming practices in addition to the PPP application amounts (POCER, SYNOPS, OECD indicators), while others do not (EIP, NoDU, PL). At last, some indicators give a result that can be aggregated into a single value (POCER, NoDU, PL), while others are in the form of a panel of sub-indicators (EIP, OECD indicators, SYNOPS).

Closing recommendations for an improved EU Harmonized Risk Indicator

Like other stakeholders (e.g. Stallmann, 2023), we recommend reconsidering the design of Harmonized Risk Indicator at European level. First, they should be founded on robust scientific and technical evidence that they follow the political aims (Bouleau, 2009; Bouleau et al., 2017) given by the SUD. To account for the complexity of these aims, we recommend using companion indicators to monitor pesticide use at a national level. Following the objectives of the SUD, these indicators should depict the risks for human health and biodiversity, as well as contamination levels of soil (Silva et al. 2018), water (Pierlot et al. 2017), atmosphere compartments (Mamy et al., 2021) and crop loss avoided. Second, new harmonized risk indicators should consider toxicity and ecotoxicity profiles of PPPs (Uthes et al. 2019) or the exposure of target organisms

(Pierlot et al. 2017). Last, they should be computable for each member state. In any case, changes in indicators for NAP aiming at PPP reduction should be made concurrently with a reflection on changes of quantitative reduction objectives (e.g. Danish Environmental Protection Agency, 2024).

Acknowledgements

The authors thank Jean-Luc Volatier (Anses) and Laurence Payrastre (INRAE) for their valuable inputs to the reflections conducted by the Scientific and Technical Committee of Ecophyto, the French National Action Plan for pesticide reduction. They also thank Antoine Camus (OFB) for his technical support for handling data on PPP sales, and Clément Chevaleyre (INRAE) for his help in scripting the results. The authors are also grateful to the ministerial staff in charge of the Ecophyto National Action Plan for useful interactions. This work was partly funded by Ecophyto, the French National Action plan, through the funding of its Scientific and Technical Committee.

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Supplementary Materials

Supplementary Material 1

Though we do not calculate UDs here, we provide hereafter their official mode of calculation. UDs are defined as the weighted mean of the maximal registered dose (quantity applied per hectare) per crop, where the weighting corresponds to the relative Utilized Agricultural Area (UAA) of each crop (Equation S1).

Equation S1.

$$UD_i = \frac{\sum_c UAA_c * max_{i,c}(RD_{i,c,u})}{UAA_{total}}$$

Equation S2.

$$RD_{i,c,u} = \left\{RD_{i,c,u} * Concentration_{i,p}\right\}$$

UAA_c stands for the area cultivated with crop c and $max_{i,c}(RD_{i,c,u})$ corresponds to the maximal registered dose for active ingredient i on crop c from all the various authorized uses u. As no real approved doses really exists for active ingredients, they are defined (Equation S2) as the multiplication of $RD_{p,c,u}$ (registered doses for product p, on crop c for usage u) and $Concentration_{i,p}$ (concentration of active ingredient i in product p).

Supplementary Material 2

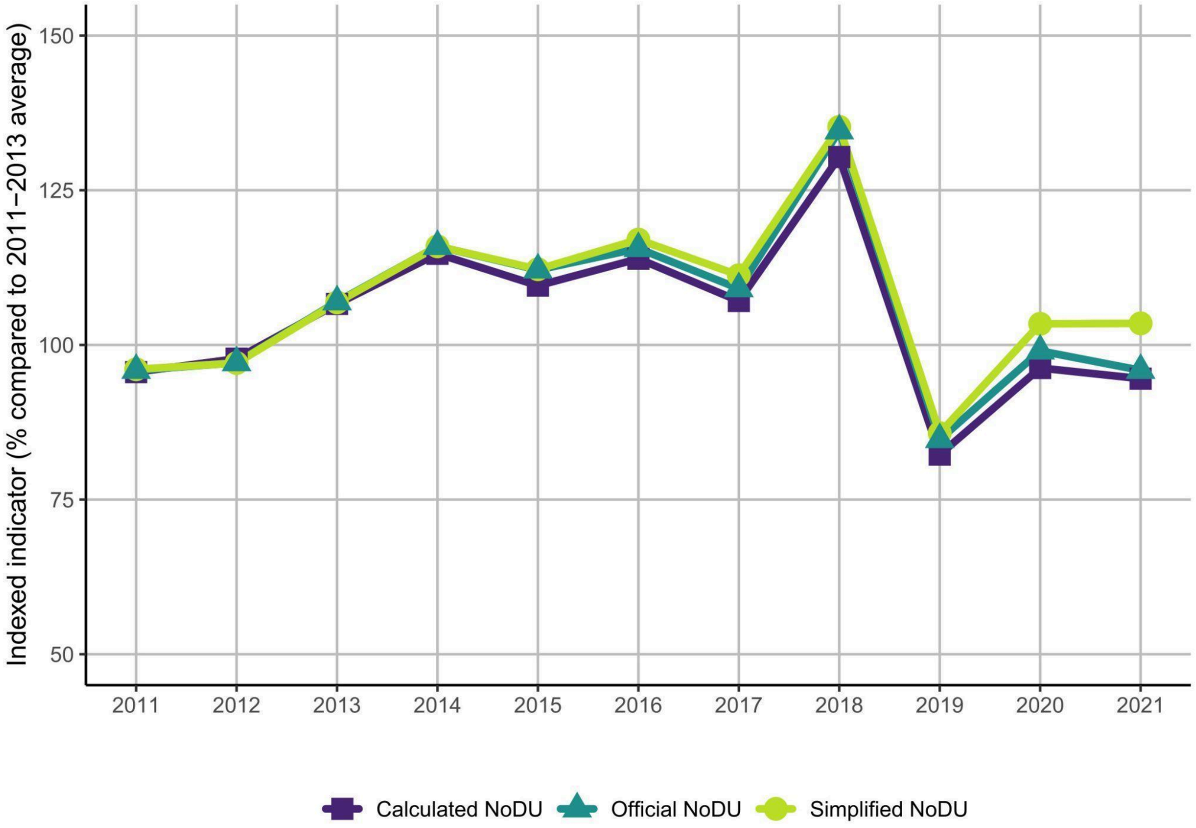

Figure S1. Evolution of indexed official, calculated and simplified NoDU indicators from 2011 to 2021. The indexation corresponds to the division of each annual value by the average value for 2011-2023.

The wider difference between simplified NoDU and the other two indicators in 2021 is likely to be attributed to new active ingredients that year, for which no official reference doses (DU) have been officially published. In contrast, the simplified NoDU relies on simplified DUs, which are calculated for every active ingredient actually present in the sales data.

Supplementary Material 3

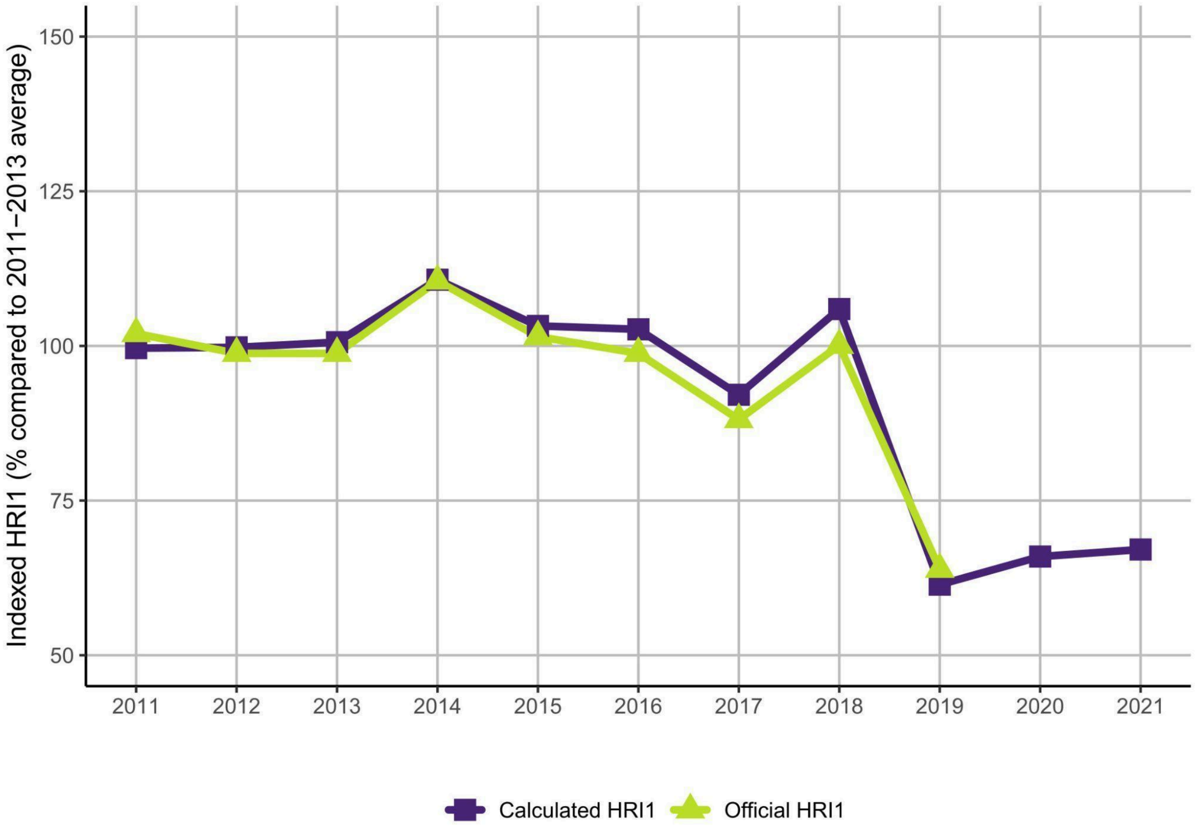

Figure S2. Evolution of indexed official and calculated HRI1 indicators from 2011 to 2021. The indexation corresponds to the division of each annual value by the average value for 2011-2023. No official data were published for 2020 and 2021 in France.

Supplementary Material 4

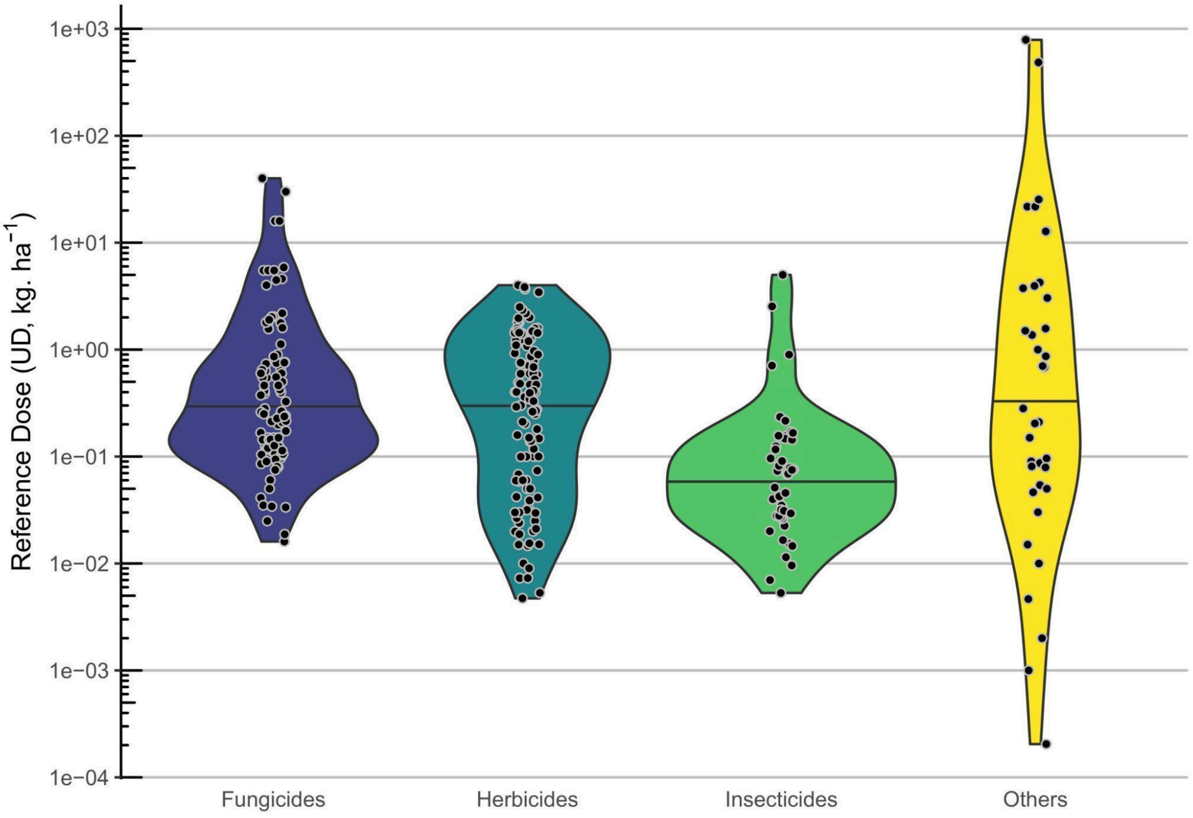

Figure S3. Reference doses (UDs, Supplementary Material 1) for each active ingredient considered for the Number of Unit Dose (NoDU) indicator calculation, according to their function. The y-axis is in log scale.

Supplementary Material 5

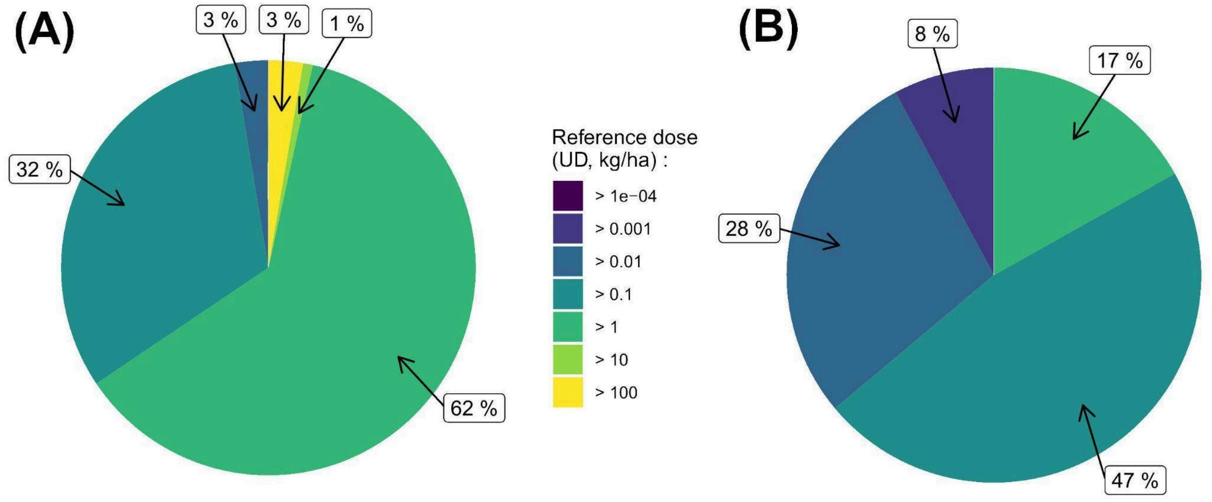

Figure S4. Distribution of the Quantity of Active Ingredients (QAI, left) and Number of Unit Doses (NoDU, right) according to the reference dose of each active substance.

Supplementary Material 6

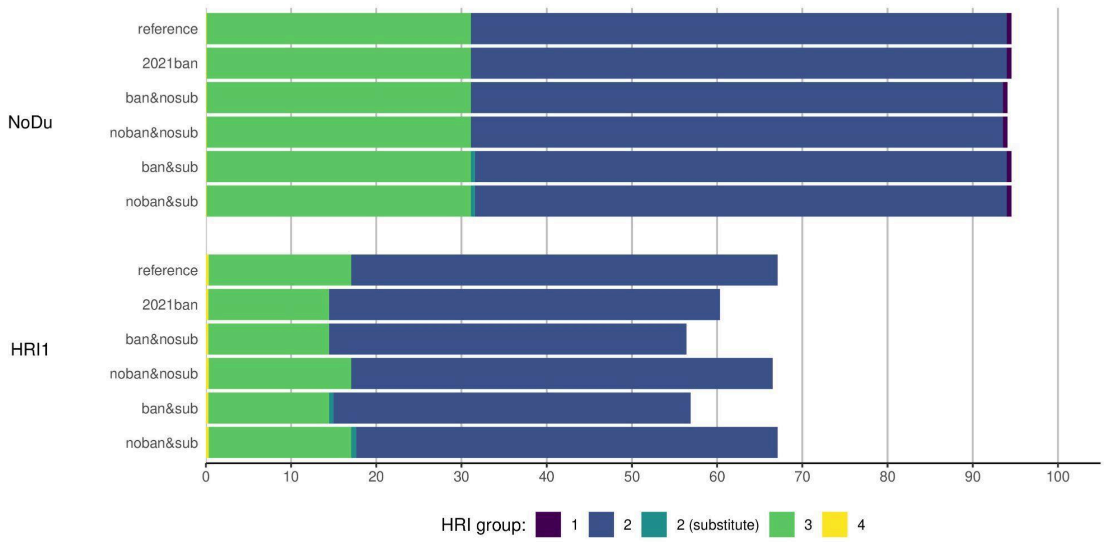

Figure S5. Number of Unit Doses (NoDU) and Harmonized Risk Indicator 1 (HRI1) under different scenarios of cessation of use of mancozeb. Values are indexed on the 2011-2013 average of each indicator. The “reference” scenario corresponds to the current 2021 values of indexed indicators. The “2021 ban” scenario corresponds to the value of 2021 if the mancozeb was later banned. The “noban&nosub” scenario corresponds to the simulation of the cessation of sales of mancozeb, without withdrawal or substitution. The “ban&nosub” scenario corresponds to the simulation of the stop to sales of mancozeb, due to a withdrawal (mancozeb is assigned to the HRI1 risk group 4) but without substitution by an equivalent active ingredient. The “noban&sub” scenario corresponds to the simulation of cessation of sales of mancozeb, without withdrawal but with substitution by an equivalent active ingredient (from HRI1 risk group 2). The “ban&sub” scenario corresponds to the simulation of the cessation of sales of mancozeb, due to a withdrawal (mancozeb is assigned to the HRI1 risk group 4) combined with the substitution by an equivalent active ingredient (from HRI1 risk group 2).

Supplementary Material 7

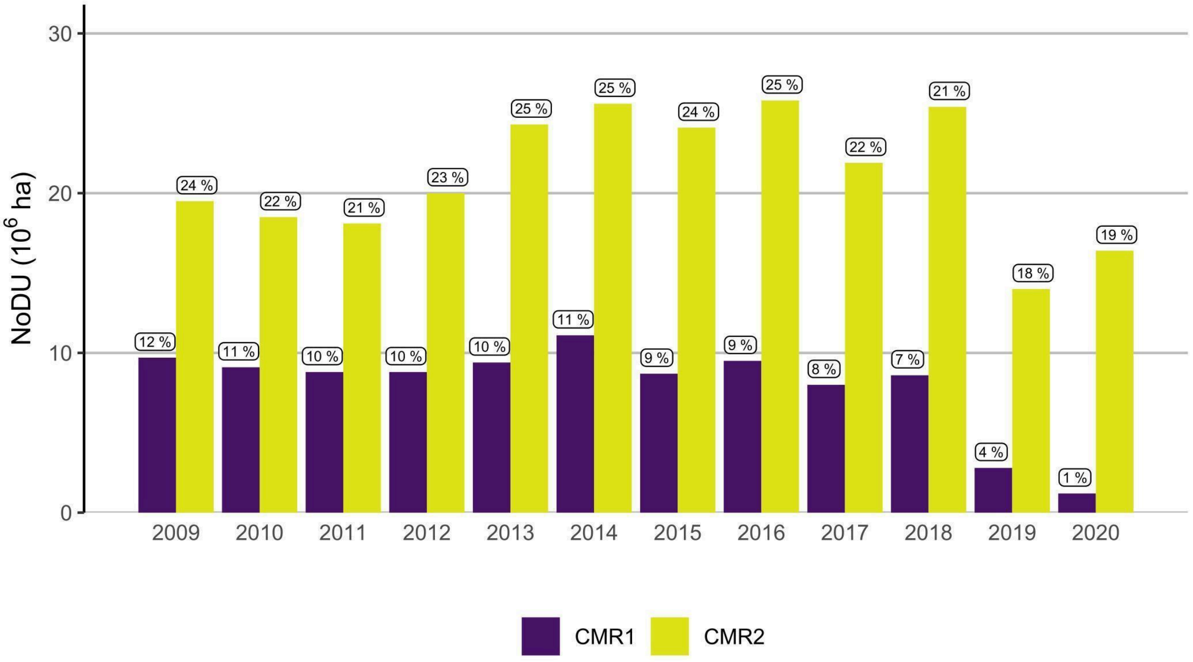

Figure S6. Evolution of specific NoDU for Carcinogenic, Mutagenic and Reprotoxic active ingredients (CMR1: proven or presumed potential; CMR2: suspected potential). Adapted from: Ministère de l'Agriculture et de la Souveraineté Alimentaire, Service de la Statistique et de la Prospective; based on the BNVD database (MASA, 2022).