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Development of a spatial risk indicator for monitoring residential pesticide exposure in agricultural areas

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The global increase in pesticide use has raised concerns about its impact on biodiversity, ecosystems, and human health, in particular of people living near agricultural areas. This study explores the assessment of pesticide exposure and risks to residents at a high spatial granularity using plant protection product data. Our objective was to develop an indicator to monitor pesticide risk levels faced by residents in France by integrating spatial datasets and exposure assessment methodologies. Using spatialized pesticide sales data based on crop authorizations, we mapped potential pesticide loads at the parcel level. This map, combined with population distribution data, allowed us to develop an indicator for monitoring residential pesticide exposures. Our findings indicate that, on average, 13% of people in France may be exposed to various levels of pesticides due to their proximity to treated crops. This indicator demonstrates the usefulness of granular pesticide sales data in monitoring exposure and can support risk reduction strategies, helping to identify regions where efforts towards sustainable farming should concentrate.

Keywords Risk assessment, Spatialisation, Plant protection products, European Union

Pesticides are fundamental for controlling pests that threaten crop yields, yet their widespread use can negatively impact ecosystems and human health. Despite the critical role of pesticides in boosting agricultural productivity four-fold in the last 60 years[1], the potential harm to biodiversity[2–5] and the health of people, especially those living near farms[6], has prompted the European Commission (EC) to establish targets for reducing pesticide use and risk through strategies like Farm to Fork, Biodiversity Strategies, and Zero Pollution Ambition[7–9]. The European Union (EU) has maintained a steady annual pesticide sale of approximately 350 thousand tonnes from 2011 to 2022[10–12]. Integrated pest management and the creation of pesticide-free zones are recognised methods to minimise pesticide exposure to nearby residents. However, current monitoring of pesticide risks in the EU relies on Harmonised Risk Indicators (HRIs), which use national pesticide sales data but lack the capability to accurately assess risks to humans and ecosystems, particularly for those living adjacent to agricultural lands[13,14]. There is no existing indicator that comprehensively monitors pesticide exposure for these residents, nor is there detailed information on the proximity of crops to residential areas or the percentage of the affected population. Effective risk monitoring would require detailed datasets on pesticide applications, including timing and location, as well as data on the surrounding environmental landscape and the residential population distribution. Such datasets are scarce due to the lack of harmonised, high-resolution data on pesticide use on crops among EU Member States[15,16]. Although Eurostat provides harmonised sales data, it does so at a broad chemical group level, which is insufficient for precise risk assessment. Efforts to develop fine-scale pesticide use maps have been made, yet they are not widespread or standardised across EU countries[17–21]. The forthcoming Statistics on Agricultural Input and Output Regulation (SAIO)[22] will partially fix the data scarcity from 2026, when professional users will be mandated to record pesticide use electronically, thereby improving data availability for monitoring and risk reduction. To overcome these challenges, we propose the development of a new indicator to

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monitor pesticide risk to residents living near agricultural fields. Our approach models the spatial application of pesticides in France, leveraging the country's more granular Plant Protection Product (PPP) sales data. This data enables the creation of more accurate pesticide use maps, which form the foundation for our proposed resident exposure risk indicator. Our work aims to enhance understanding of pesticide risks for communities situated close to farming activities.

Results

Spatial indicator for residential pesticide exposure and risks

Mapping the active substances potential use at parcel level

By consolidating and standardizing the quantities of all Active Substances (ASs), we created 388 maps (one for each AS), depicting potential pesticide loads at the parcel level in France, which comprises 9.5 million parcels. As an example, Fig. 1 displays a detailed map illustrating the potential application of the herbicide Fluroxypyr near the city of Orléans. Fluroxypyr is authorised for post-emergence use throughout the EU, specifically targeting broadleaf weeds and woody brush. It finds application in diverse settings, including cereal fields (e.g., wheat and maize), orchards, and vineyards.

Fine scale resident pesticide exposure risk

After mapping out potential pesticide use, we produced a risk map measuring the combined exposure experienced by generic individuals living near agricultural fields. Here we are exploring the possible risk in these areas not yet considering if there are people living in that area. This potential combined risk of all the ASs to Adults within 10-m from agricultural areas is shown in Fig. 2. The map depicts the sum of the ratio between European Food Safety Authority (EFSA) modelled exposure and the toxicological endpoint Acceptable Operator Exposure Level (AOEL). The risk calculation serves as an indicator of potential concern levels rather than providing exact risk values, as its primary purpose is to facilitate comparison of risks between different crops and regions rather than conducting an exact risk evaluation.

Risk indicator applied to population

We then identified regions potentially affected by risk to the actual population by incorporating population maps. The results can be presented in two formats: a raster format with a pixel size of 200 × 200 m and a vector layer delineated at the postcode level on the map (averaged values over postcode areas) as presented in Fig. 3. The postcode results provide a more comprehensive overview than the finer administrative division of municipalities in France. For the combined pesticide exposure assessment map, we performed a reclassification based on its quantile value distribution in conjunction with the Population distribution map. e.g. the higher the modelled exposure and risk near the field in combination with a higher number of people living in the relevant area, the higher the indicator value. We classified the indicator into five distinct classes ranging from low risk (class 1) to moderate and potentially elevated risk (class 5). The Supplementary Figure 6 presented the four different exposure routes for adults and children respectively, showing that entry into the fields is a dominant route followed by vapour, while dermal/systemic and spray drift exposure are contributing less. To ascertain the

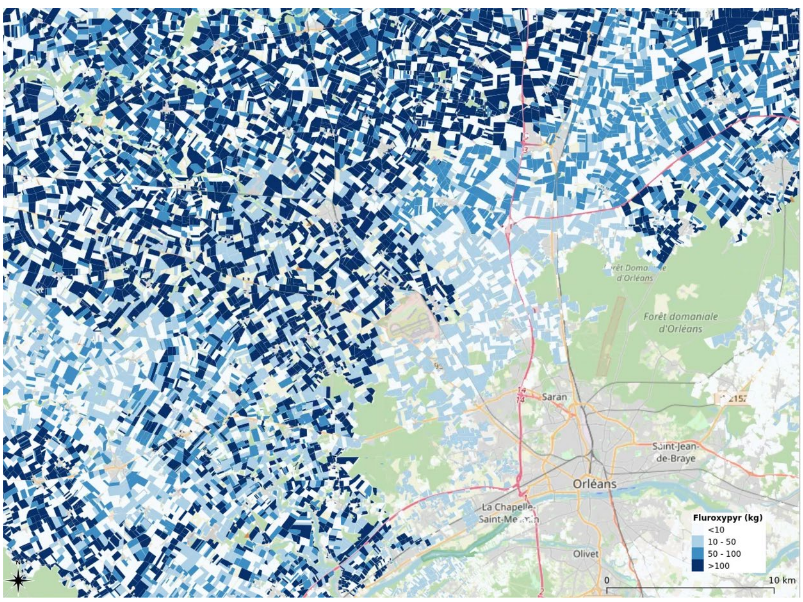

Fig. 1. A highlight of the north-west Orléans agricultural area, where a potential application of the Active Substance (AS) Fluroxypyr is estimated based on sales. The colour scale represents the potential applied amount in kg distributed among an area, which is the areas belonging from per sum of the same crop type and areas within the same postcode. *Created by F. Galimberti using QGIS 3.28 Firenze*[23].

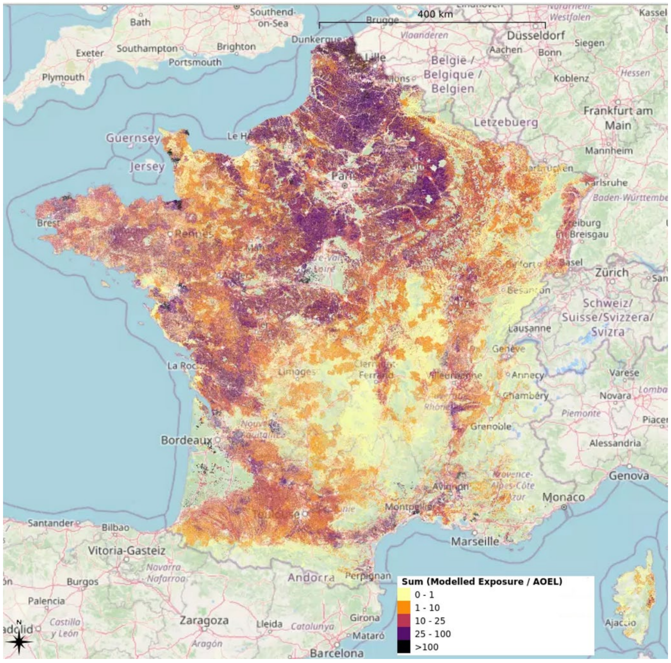

Fig. 2. Potential combined risk of all the ASs, for adults living within 10 m from agricultural areas. The colour scale depicts these worst-case risk levels calculated as sum of risk quotients of the modelled exposure divided by the reference values AOEL. *Created by F. Galimberti using QGIS 3.28 Firenze*[23].

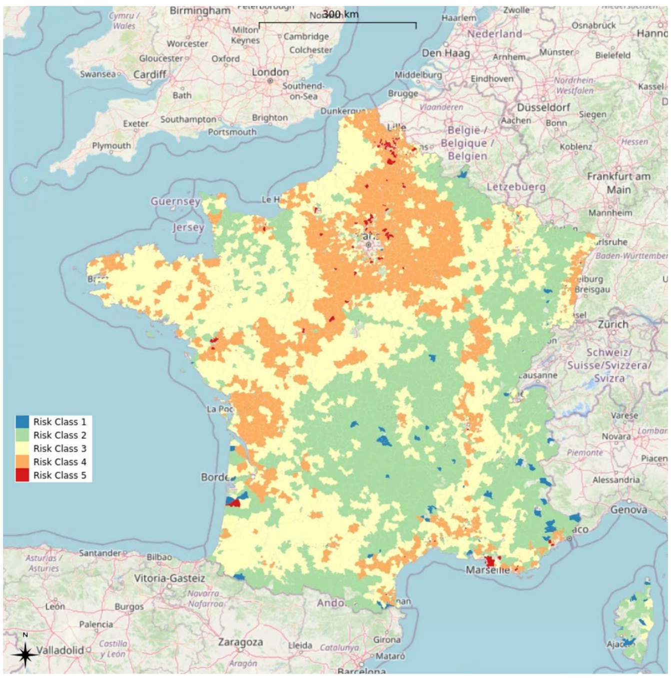

Fig. 3. Pesticide risk indicator (PRI): integration of combined pesticide risk with French population distribution map at postcode level. *Created by F. Galimberti using QGIS 3.28 Firenze*[23].

proportion of France's population potentially exposed to pesticides, we conducted an analysis at the postcode level. The map in Fig. 4 shows the proportion of adult population exposed to pesticides per postcode.

The same approach and analysis were performed for children. In Supplementary material (Children assessment), the combined exposure risk for children is reported (Supplementary Figure 12), along with the combined exposure risk for single routes of exposure (Supplementary Figure 13), the Pesticide Risk Indicator

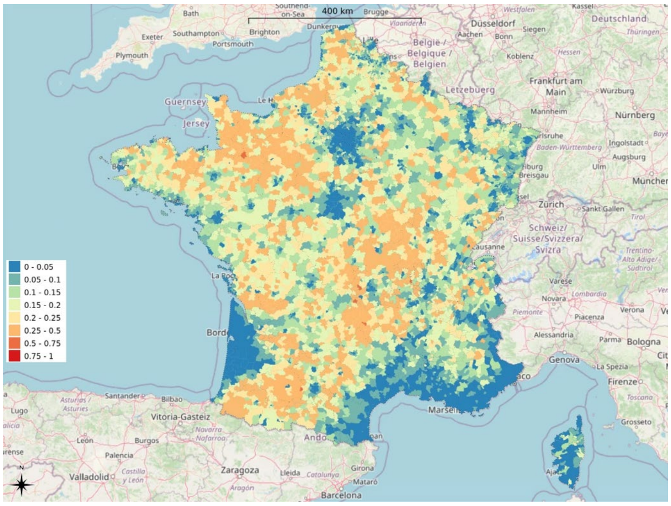

Fig. 4. Exposure of the adult population to pesticides versus the total population at the postcode level. *Created by F. Galimberti using QGIS 3.28 Firenze*[23].

(Supplementary Figure 14) and the percentage of children exposed to pesticide by postcode (Supplementary Figure 15).

Discussion

The spatialisation of AS quantities and PPP usage on crops was a critical initial step in understanding how farmers applied the products they purchased in their respective regions. However, the sales data inherently came with a significant level of uncertainty. Some purchased products might be stockpiled for future use. Postcode information was also anonymized when it could potentially identify a small number of farmers, a privacy measure. Additionally, a product authorised for multiple uses might be used exclusively on one crop, contrary to our assumptions. All reported pesticide sales within an administrative postcode are entirely utilized within the boundaries of that specific postcode, as we did in our work. This assumption, however, has a weakness. For instance, if a farm possesses fields spanning across three different administrative postcodes, and its main office is located in a fourth postcode, all pesticides acquired by that farm will be attributed to the fourth postcode. In reality, this postcode might not have received any pesticide treatment, yielding possible anomalies in the results. The paper from Martin et al.[18] partially solved this issue with non-anonymised Registre Parcellaire Graphique (RPG) data, however, these data cannot be shared due to privacy constrains. A shortcoming of the RPG layer is that it does not cover all the agricultural parcels in France. We considered the option of enhancing the RPG layer by integrating missing information through the supplementary RPG *complété* dataset provided by the French government[24]. This integration had the potential to significantly expand the coverage of parcels throughout France. However, unlike the conventional RPG dataset, this additional layer lacked a harmonised classification system of crop type. Aligning the two datasets would have been a time-intensive process, posing challenges in ensuring consistency and uniformity between the datasets. As a result, despite the potential increase in coverage, the absence of a harmonised classification made this approach less feasible for our analysis. We assessed the percentage of crop missing by not considering RPG *complété* as a complemental map to the RPG and we focused on the Département La Haute-Vienne (NUTS code FRI23). By comparing all RPG *complété* parcels with the RPG ones, included in this administrative area, the land loss is 10%. But if looking at only intensive agricultural crops and permanent crops, the percentage loss is 0.5%. We conclude from this analysis that the enhancing from the RPG could be a marginal improvement.

Our approach to estimating exposure and risks to people living close to agricultural fields represents a worst-case scenario, both in terms of exposure estimation and toxicological considerations by assuming simultaneous application of all ASs on a parcel without considering the modes of action and potential combined effects. It is important to note that the EFSA OPEX guidance also acknowledges weaknesses in constructing scenarios for residents due to a lack of available data. EFSA aims to initiate data collection efforts to address these gaps in the near future. In establishing the model, we considered dilutions for dermal absorption in the case of spray drift in a generic manner, following an expert judgment framework rather than considering the actual label-specific dilutions, which would have involved nearly 2000 different PPPs. Granules formulations were not taken into account. Furthermore, the timing of application was not factored in, and in the combined exposure assessment, it was assumed that all products were used simultaneously on a hypothetical treatment day for the agricultural parcel. It is important to recognize that this represents a simplification and a worst-case scenario. The risk values of the map (Fig. 2) ranges from 0 to greater than 100. We need to be cautious in interpretation of these results and possible true concerns considering the worst-case assumptions detailed above. Also important to keep in mind is that this part of our work is looking into the theoretical risk to people in the vicinity of agricultural fields while this does not yet factor in whether there are people residing in these areas which follows in the next step. Values shown here should be only seen as a basis for comparing different regions and crops regarding risk ranges to residents. Upon analysing the map, it becomes evident that in the northern part of France, including Amiens, Rouen, Orléans, Troyes, and Reims, as well as in Bretagne and key wine-producing areas such as Alsace, Champagne, Burgundy, the Loire Valley, Bordeaux, and Provence, the potential risk could be elevated. Meanwhile, the risk falls into intermediate ranges almost everywhere else in France, except for the lower central part where the modelled risk falls within low risk levels for residents. The higher risk situations are likely related to outliers or peaks in sales data in specific postcodes. For example, although the modelled exposure and the population affected indicate low pesticide risk in the city of Marseille, the risk map classified this area in the upper category of risk. This discrepancy may be due to the high proportion of pesticide sold relative to the number of crop parcels, leading to a higher concentration of pesticides per parcel. If concentrating on single exposure routes (Supplementary Figure 6), it emerges that dermal transfer and spray drift are exposure routes of lower concern for resident, according to our potential pesticide applications. Entry into treated fields and vapour seem to be the ones driving the risk.

The next step then was to include the actual population distribution. The resulting map (Fig. 3) appears to be similar to the combined pesticide risk map. Some differences between the two maps, derive from the population distribution input: the first map in Fig. 3 does not take into account the actual population distribution, assuming instead a synthetic population distributed within 10 m of the fields. When real population data is incorporated, the risk areas are adjusted to reflect where people actually live, creating differences between the two maps. However, also from the applied transformations to the pesticide risk indicator map: vector to grid data, discretisation and quantile classification, and along with data averaging at postcode level. The map values range from 0 to 16, as a result of the multiplied scores, and values are grouped into 5 risk classes. It is worth noting that in the lower risk ranges [class 1 and 2], there may be instances where the estimated exposure and resulting combined risk is elevated, but the population residing in those areas is very small. Conversely, the more elevated estimated risk classes show regions where factors such as landscape configuration, population density, and pesticide exposure assessment converge, which could lead to higher levels of pesticide exposure for the residents. The overall pattern is similar to the combined pesticide risk map identifying mostly the same areas to be investigated further as before.

To gain deeper insights, we integrated the crop layer with the indicator map to perform an analysis of the crops involved in our study and assess which crops are most commonly cultivated near residential areas within agricultural sites. We accomplished this by creating a radius area of 100 m from the centroids of each indicator pixel and examining the composition of the radius area in terms of crop coverage versus the average value of the PRI indicator—Supplementary Figure 7. In the provided boxplots on the left, we present the distribution of indicator values within the 17 selected crops. On the right side of the figure, the bars, depict the distribution of crop coverage in France, measured in hectares. This representation allows us to visualize both the variation in indicator values across these 17 crops and their respective extents within the agricultural landscape of France. The two additional percentages at the bottom of the bars represent the proportion of crops extents in the selected areas in respect to the whole crop extent in France and the proportion of the composition of all crop areas included in the selected areas.

The extents of the observed 17 different crops, together, represent over 98% of the total analysed area. Additionally, Supplementary Figure 7 presents boxplots illustrating the distribution of the indicator values for each crop throughout France. Crops with an average PRI value greater than 8 (i.e. PRI risk class 4) like vineyards, spring barley, potatoes and sugar beets can be considered as crops impacting the pesticide exposure the most. More data are reported in Table 1.

These findings provide valuable insights into the crops contributing significantly to pesticide exposure in proximity to residential areas within agricultural sites. The predominant route of exposure can vary depending on the pesticide, application method, and environmental conditions. In many cases, dermal exposure is considered a significant route, especially for those directly handling pesticides, which is not included in this study. Operators, and workers are supposed to use personal protective equipment (PPE), whereas residents are unlikely to wear these kinds of protections. This is also why, entry into treated fields can be a significant route, especially for individuals living in close proximity to agricultural areas. Vapour exposure and spray drift are more likely to affect individuals in the immediate vicinity of application sites and they are routes of exposure directly dependent from the application methods. In addition, vapour exposure is influenced by climatic conditions and pesticide volatility. Spray drift is mainly influenced by wind speed and direction, droplet size, spray equipment and height of application[25].

On average, the proportion of people potentially exposed due to living in the proximity of agricultural fields compared to the entire French population is 13%. The map (Fig. 4) shows that the percentage of population potentially exposed to pesticides is quite low when looking at larger towns like Paris, Rennes, Lyon, Nantes, Toulouse and so on. This depends on the density of the population but also on the proximity to agricultural

	Million Hectares	% total analysed radius area	% in whole France
Sugar beets	0.01	1	3
Vineyards	0.05	3	8
Spring barley	0.01	1	3
Potatoes	0.01	0.6	6

Table 1. Crop composition of the 100-m zones surrounding selected agricultural areas (i.e. in close proximity to residential areas) and their extent vs. crop extent in France.

fields. Then, some natural parks are depicted too with low exposed population as well as the Mediterranean coastal area of France. In Table 2 the exposed population is presented according to the indicator risk classes.

The same timing considerations seen before, can be applied to our attempt to compare the data with the soil residue database (Supplementary material: Soil concentration comparison). In our work, pesticide residues in soil were calculated using the application rate resulting from the model we developed, applying the formula for calculating the Predicted Environmental Concentrations in soil (PEC soil) at time 0. This approach does not reflect the actual presence of pesticide residues in the soil. In calculating the PEC, we adhered to the FOCUS group's PEC soil guidance document, using a 20 cm soil depth distribution as the regulatory standard and as reported in the soil sample collection from LUCAS Soil Survey[26]. However, we recognize that for certain pesticides with strong soil adsorption properties, a thinner soil depth might more accurately reflect initial concentrations in a research context. Additionally, the LUCAS soil residue data sampling does not account for potential pesticide applications in selected agricultural fields; it focuses mainly on assessing the qualitative state of European soils. While it is a unique survey, it is more focused on the history of pesticide applications on specific agricultural plots. This results in a comparison of residue data obtained in different ways (modelled vs analysed in the soil dataset) and for different investigative purposes. Low correlation could also be a consequence to the result of deposit from spray drift from adjacent parcels (Supplementary Figure 9). However, this does not diminish the importance of conducting an analytical comparison. Observed soil residues tend to be higher than our conservative estimate (initial soil concentration). This is also what emerges from the comparison with water samples in Pistocchi's paper[5], and hints at a general underestimation of actual pesticide use/presence in the environment. One possible reason is the persistence of pesticides in the environment, reflecting past uses.

The Treatment Frequency Index (TFI) map provides insights into the intensity of pesticide application practices (Supplementary material: Treatment Frequency Index comparison). On the other hand, the aggregated distribution map (Supplementary Figure 11) provides a broader view of the spatial distribution of pesticides, encompassing multiple factors such as crop type, application rates, regional farming practices, and environmental conditions that contribute to overall pesticide presence. By comparing these metrics, researchers and policymakers can gain a more comprehensive understanding of pesticide usage trends, potentially identifying areas with high intensity of use as well as areas where specific types of pesticides are more prevalent. This comparative visual analysis could be valuable for informed decision-making in agricultural and environmental management. The two maps exhibit predominantly similar class distributions; however, the key disparity in visualisation arises from the differing scales: TFI is represented at the municipality level, whereas the Aggregated Distribution of AS is depicted at the crop level. Consequently, the colours denoting crops appear less dense compared to the municipalities represented in TFI, influencing the overall visual contrast between the two maps.

By concluding, the term "indicator" in its name signifies its role as a signal identifying agricultural areas in France where the combined use of various ASs could potentially expose the resident population to pesticide risks, sometimes at elevated levels. Profitable agricultural zones, like vineyards, motivate farmers to maximize the use of available land for farming, resulting in increased pesticide application intensity, higher crop density, and reduced fallow land, each contributing to higher pesticide exposure and risk. Ongoing research aims to characterize a small radius zone around urbanized areas throughout Europe, assessing the extent of these areas, the types of crops involved, and the PPPs used. Combining this analysis with the results of our study will provide a model for upscaling findings from a single member state to encompass the entire European continent.

Methods

In this section, we mainly describe our methodological approach combining various datasets to model pesticide applications on crops and the level of residents' exposure. Finally, the evaluation of the spatialisation with independent data source is described. The data (Table 3), their interaction and schema is presented in Fig. 5.

Data spatialisation

We used pesticide sales data in France as a surrogate for actual pesticide usage on crops in 2018. This fine-grained data, detailed at the postcode level, representing a territorial unit finer than NUTS3 (i.e. 6051 postcodes at country level), was integrated with pesticide authorisations (PPP dataset) and field-level agricultural data (RPG) to estimate pesticides applied per parcel. The harmonised EuroCrops[39] dataset aided in maintaining semantic legend consistency of the crop type classes. After cleansing the dataset to remove entries with missing data, we obtained 1.5 million records. We matched each active substance (AS) to authorised crops (i.e. crops for which the use of specific Plant Protection Product was officially authorised by regulatory authorities), creating 43 million records. Since pesticide labels vary in crop specificity (ranging from specific crops to general categories), we considered all potential matches but discarded 75% of the hypothetical applications that did not correspond to actual crop parcels. We then allocated AS and pesticide product quantities across parcels within each postcode,

	% average population exposed	N° postcode involved
Risk class 1	9	65
Risk class 2	16	1734
Risk class 3	15	2108
Risk class 4	13	1311
Risk class 5	9	86

Table 2. Subdivision of exposed population by indicator risk classes.

Dataset	Description	Reference(s)
Pesticides		
Pesticide Sales—BNV-d	Database containing pesticide sales data in France from 2013 to 2021, based on declarations by registered distributors	[27,28]
PPP dataset	Digitalized data on plant protection products, fertilizers, and more from the French government	[29,30]
PPDB—Pesticide Properties Database	Comprehensive database including pesticide chemical identity, physicochemical, human health, and eco-toxicological data	[31]
EUPDB—EU Pesticide Database	EU database with details on approved and non-approved substances used in plant protection products	[32]
Open EFSA	Platform for accessing information related to the European Food Safety Authority's (EFSA) scientific work	[33]
LUCAS-Soil Survey	The 'Land Use/Cover Area frame statistical Survey Soil' (LUCAS Soil) is an extensive and regular topsoil survey that is carried out across the European Union to derive policy-relevant statistics on the effect of land management on soil characteristics	[34]
TFI—Treatment Frequency Index	The Pesticide Treatment Frequency Index created by the Solagro Group	[35]
Agriculture		
Registre Parcellaire Graphique (RPG)	Geo-dataset of agricultural parcels and crop type	[36]
Population		
Gridded Population Data	Data consisting of gridded information at a 200-m resolution. Includes variables related to individuals' age distribution, household characteristics, and income. Derived from tax files	[37,38]

Table 3. List of used datasets with description and references are split into three categories: pesticide, agriculture and population.

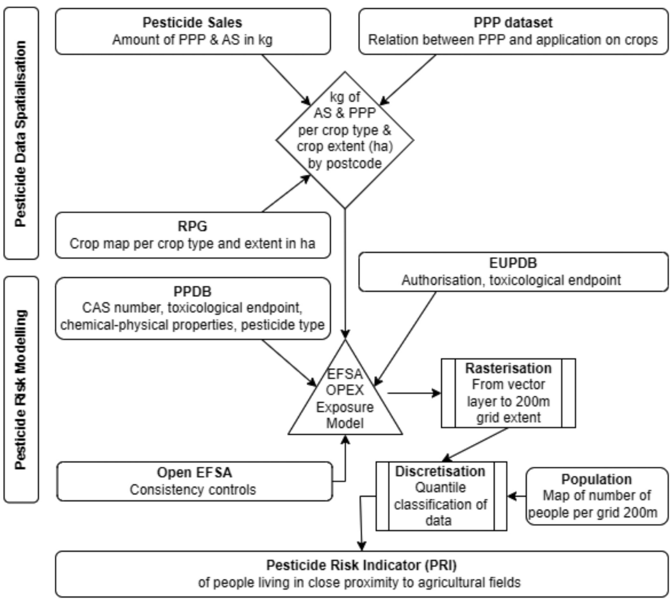

Fig. 5. Overview of data utilisation in designing the Pesticide Risk Indicator (PRI): the diagram illustrates the specific segments of various datasets employed and their respective applications in the pesticide risk indicator's development.

proportionate to the area of each crop. This relative pesticide load, expressed in kilograms, did not factor in recommended application doses[29]. Instead, we determined the pesticide load on a crop by multiplying the AS quantity with the proportion of the authorised crop area within the postcode. The Pesticide Load (PL_{ijk}) can be calculated with Eq. (1) where *i* is a given active substance, *j* is the postcode and *k* the crop considered. The *PL* is obtained by multiplying the quantity (kg) of a given Active Substance, AS_i in a given postcode (j) by the proportion of authorised crop (k) for that active substance within the postcode:

$$PL_{ijk} = \mathrm{AS}_{ij} \times \left(\frac{\text{authorised Crop}_{ijk}}{\sum_{k=1}^{n} \text{authorised Crop}_{ijk}} \right) \quad (1)$$

All procedures were automated using a combination of R, PostgreSQL, and QGIS[23,40–42] on the Big Data Analytics Platform of the JRC[43]. The link to have access to the spatial data can be found in section Data access FTP of Supplementary material.

Pesticide exposure and risk assessment

This spatialisation procedure served to provide the pesticide application rates for the calculation of the modelled exposure and consequently the risk. Exposure is defined as the concentration or amount of an agent that reaches a target organism, system, or population within a specific frequency and duration[44,45]. It is characterised through exposure scenarios which describe the circumstances of exposure, including sources, pathways, and amounts involved, and the organisms or populations exposed[46]. These exposure scenarios are used to build exposure models that employ algorithms and equations to quantitatively estimate exposure doses via oral, dermal, or inhalation routes. The modelled values are compared to a reference value known as the Acceptable Operator Exposure Level (AOEL). The AOEL represents the maximum amount of AS to which an operator (or resident) may be exposed without experiencing adverse health effects, expressed in milligrams of AS per kilogram of body weight per day. The ratio between the estimated value from the models and the AOEL generates a Risk Quotient. A Risk Quotient below one indicates an acceptable risk, while values above one require further refined assessment to determine whether risk management measures need to be taken. Our assessment, based on EFSA's 2022 guidance[45], focused on residents (non-workers) exposed to pesticides near treated areas. We examined exposure through four main routes: spray drift, vapour, surface deposit, entry into treated fields, using the 50th percentile of exposure as recommended by EFSA. Data for the assessment came from multiple databases, and results were validated using EFSA's OPEX tool[45]. Risk was mapped at the parcel level, considering a 10-m distance from the edges of agricultural fields. This distance was used to estimate exposure for various routes, including vapour and spray drift, where proximity to the field significantly influences exposure levels. Additionally, dermal transfer is strictly dependent on the percentage of drift, whereas entry into treated fields is an occasional activity not related to distance but can occur due to proximity to agricultural parcels. This approach aligns with EFSA's guidelines, which generally consider these four exposure routes. The assessment considered adults and children separately, assuming body weights of 60 kg and 10 kg, respectively. The combined risk map is the results of the sum of four exposure routes. Vapour exposure: it occurs when pesticides volatilise into the air and individuals inhale the vapour. This can happen during and after the application of pesticides. Spray Drift: it involves the movement of pesticide droplets away from the target area during application. Drift can occur due to wind or improper application techniques. Entry into Treated Fields: this route of exposure occurs when individuals enter areas recently treated with pesticides. It involves direct contact with treated surfaces, soil, or plants. Dermal Transfer: it involves the direct contact of pesticides with the skin. This can occur during the application of pesticides or through contact with surfaces, tools, or clothing that have been contaminated with pesticides. This is a worst-case approach, from exposure point of view, assuming simultaneous application of all AS on a parcel, but also from a toxicological point of view, since no consideration of the modes of action and related possible contribution to combined effects was applied.

Towards the indicator of risk from non-dietary exposure

In line with what has been presented, the combined risk map was integrated with the population distribution map. The risk map's resolution was adjusted to a 200-m grid to align with the population data. Only intersecting areas near agricultural fields were analysed to assess the risk to residential populations. Both maps were reclassified using a scoring system based on their quantile distributions, with values ranging from 1 to 4. These scores were then multiplied to generate an overall risk score, categorised into five levels of increasing risk (Supplementary Figure 8). The product of these maps yielded a discrete indicator that maps potential residential pesticide risk in agricultural zones. The final map can be displayed as individual pixels or aggregated by postcode, calculating an average value for each area.

Population affected

We also analysed the percentage of population potentially affected within the different indicator classes at postcode level. We performed this by dividing the number of people potentially exposed in our analysis with the total population living in the same area delimited by postcode boundaries. The resulting ratios were depicted into a map. It is to be noted that there is a discrepancy in the datasets utilised with the data on pesticide sales and crop mapping being from the year 2018, while the population distribution map is derived from the 2017 population census.

Validation of the spatialisation

To assess our results, efforts were made to utilise accessible data on residues of ASs in the soil. For this purpose, we used a pesticide soil residue database from the LUCAS in-situ survey[34,47,48]. LUCAS Soil surveys 2018 for France has 683 locations sampled with pesticide residues in Soil [mg AS/kg of soil] covering 118 AS and pesticide metabolites. The coordinates of the selected soil French sites were used to extract corresponding pesticide dataset information from LUCAS Soil dataset. At the parcel level, our spatialised layer provided information on application rates or quantities of ASs. To convert these application rates into soil residues, the guidelines of the FOCUS (FOrum for the Co-ordination of pesticide fate models and their Use) Work group on Soil Modelling was followed, specifically using the first-tier equation that assumes worst-case concentrations immediately after application (t0)[49,50].

The equation used is as follows:

$$\text{Initial PECsoil} = \frac{\text{Application Rate} \times (1 - \text{Foliar Interception})}{100 \times \text{soil depth} \times \text{Bulk density}} \tag{2}$$

In this study, we assumed no foliar interception (value set to zero), used a soil depth of 20 cm as per the soil dataset (as required by regulatory standard[49,50]), and applied the bulk density values specific to each site. We compared the calculated soil concentrations of active substances (AS) in mg/kg with measured pesticide residues. Only 50 pesticides were common between our spatial database, which had 388 substances, and the soil database with 118 substances, due to differences in the inclusion of metabolites, non-approved AS, and sales data for approved or recently withdrawn substances. The number of sites analysed was reduced from 683 to 519 after excluding those not in the RPG layer. We matched pesticide residue data by postcode and crop type using both datasets, focusing on AS residues for the same crop and location according to LUCAS site positions.

Data aggregation

AS aggregated distribution: to enhance the visualisation of areas and crops with potentially widespread pesticide use, we created aggregated distribution maps for ASs throughout France. We normalised the total spatialised ASs in each crop at the postcode level, scaling the dimensionless values from 0 to 1 for a comprehensive analysis. We made the decision to visually compare the Treatment Frequency Index (TFI[35,51,52]), focusing on pesticide use intensity based on application rates and recommended doses, with the aggregated distribution map that normalises total spatialised ASs in each crop at the postcode level. This comparative analysis aims to provide a comprehensive understanding of pesticide usage patterns by considering both intensity and spatial distribution across different agricultural areas.

Data availability

Data is provided within the manuscript in the 'Data Access FTP' section of the Supplementary Material. In addition, all datasets used in this study are thoroughly documented within the manuscript (Table 3), enabling readers to replicate our analysis.

Code availability

The code and resulting layers are available via FTP, as detailed in the 'Data Access FTP' section of the Supplementary Material. For privacy and data security reasons, internal links have been removed.

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Declarations

Competing interests
The authors declare no competing interests.

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