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Research article

Quantifying residents' exposure to agricultural pesticides using new geospatial approaches

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A R T I C L E I N F O

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A B S T R A C T

A better understanding of environmental exposure to agricultural pesticides is crucial for public health, regulatory and management purposes. Residents in close vicinity to agricultural fields are likely to be more exposed to pesticides. In that context, an innovative geospatial approach for mapping estimates of agricultural pesticide exposure was developed in this study. Data on pesticide application rates, high-resolution annual datasets of the geographic distribution of crops, and the 100 × 100m grid population dataset were utilized to complete this analysis in Wallonia (Belgium) over the period 2015–2019. Pesticide exposure metrics were estimated using a buffer-based exposure model by conducting neighborhood analysis within a 1000m buffer radius. Subsequently, a population weighted method was used to 'up-scale' the exposure data to administrative levels. In a limited validation effort, model estimates were compared with pesticide measurements in air collected at 12 stations during the period 2015–2016. The results present the first modeling map of environmental exposure to agricultural pesticides for the whole of the Walloon region. The northern part of the Sambre-Meuse axis demonstrates more intensive agriculture and the highest pesticide weighted exposure indices. The majority of the population resides near agricultural areas, with only 4 % living in regions that lack crops within a 1000m radius, primarily in the central areas of large cities. A positive trend association between pesticide measures in air and the index was observed at the different stations, nevertheless further validation efforts are needed to accurately compare the same active ingredients. This work gives a valuable basis for research and environmental health actions in Belgium. Maps highlight areas where human biomonitoring and epidemiological studies should be implemented to investigate the impact of potential environmental exposure to pesticides. This information helps policy-makers to take measures to control and reduce the load of agricultural pesticides in the environment.

1. Introduction

Plant protection products (PPP) are pesticides used primarily to protect plants and manage undesirable plant species. In this article,

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the term 'pesticide' is used as a synonym for 'plant protection product'. The widespread use of these pesticides in modern agriculture has raised increasing concerns about their adverse effects on both the environment and human health [1,2]. The health effects of pesticides on humans are well-documented, with research indicating links to cancers, neurological disorders, respiratory issues, adverse birth outcomes, and other health conditions [3–6]. Most of health problems are observed among farmers and rural residents living near pesticide application areas. People residing close to agricultural fields may be exposed to pesticides through direct spray drift or post-application processes, such as the volatilization of pesticide residues from crops and soil or wind erosion of contaminated soil particles [7–9]. As pointed out by Guilpart et al. [10], key points arising from the scientific literature justify to pay attention to crops grown close to residential areas. Two recent reviews provide evidence that non-farmworkers living close to agricultural areas are exposed to higher levels of pesticides than residents living further away [11,12]. Pesticide exposure appears to be largely correlated with the spatial organization of agricultural activities around residential areas, like residential proximity to treated fields, crop production area around the residence and amounts of pesticides applied in the vicinity [13]. Indeed, all crops are not treated in the same way. Perennial fruit crops like apples, wine grapes and plums usually display higher pesticide use intensity than annual field crops. This places many agricultural communities at increased risk for pesticide exposure and adverse health outcomes [14]. Given the many public health and environmental impacts associated with the use of pesticides, comprehensive pesticide application data and exposure assessment have been a high priority for environmental and health professionals, government agencies, and community groups. However, up to now, most countries do not yet have reporting of pesticide application by farmers. In Europe, the new regulation on statistics on agricultural input and output (SAIO) should be implemented in 2025 [15]. Moreover, environmental monitoring networks are still scarce to routinely measure pesticides in air, water and soil.

Belgium ranks among the European countries with the highest sales of pesticides per hectare of utilized agricultural area (UAA), with 4.9 kg of active ingredients sold per hectare of UAA in 2017 [16]. National sales data indicate that up to 6398 tons of PPP active ingredients (AIs) were sold in 2017 [17]. Professional users (such as farmers, park and garden contractors, rail network operators, etc.) accounted for 96 % (6129 tons) of these sales, while non-professional users made up the remaining 4 % (269 tons). The Walloon region in southern country notably features areas of intensive agricultural and forestry production, where a sizeable part of population may live in close proximity to various crop types.

Besides, recent large-scale biomonitoring surveys have revealed widespread presence of current pesticides across various age groups within the Walloon population [18,19]. The population studied, comprising 601 children (3–11 years), 283 adolescents (12–19 years old) and 261 adults (20–39 years old), showed on average detectable levels of at least five pyrethroid and/or organophosphorous metabolites, demonstrating the wide internal exposure of the population, with higher exposure for younger volunteers [18,19]. Various measures to reduce the use of PPPs were taken via the successive Walloon Pesticide Reduction Programs – PWRPs since a decade. As required by the Walloon government decree of July 11, 2013, professional pesticide users must respect minimum distance standards, or buffer, in the proximity of sensitive areas where any pesticide application is forbidden in order to reduce pesticide risks. Since 2018, those protected zones have been extended around areas frequented by vulnerable populations, such as schoolsites, nurseries, hospitals, old people houses and leisure facilities. Other measures include the "zéro phyto" (zero PPPs) for public space managers on June 01, 2019, the mandatory application of integrated pest management principles, or the prohibition of synthetic herbicides in private spaces since January January 1, 2020. Policy efforts have shown some effectiveness in reducing exposure [18,19], but complete elimination remains challenging and the global repercussions of pesticide dispersion in the environment remain largely unknown in Wallonia. A better understanding of environmental exposure to agricultural pesticides is therefore crucial, particularly in the context of public health, regulatory compliance, and management strategies. In the literature, Geographic Information Systems (GIS) have been increasingly used to develop pesticide exposure metrics for public health and epidemiological research [20–27]. The generated maps and metrics often rely on data related to the agricultural land use and, occasionally, estimates of pesticide application. However, such approach is subject to certain limitations and uncertainties. In this study, the authors offer new insights into modeling the geospatial distribution of pesticide exposure. By integrating data on pesticide application rates, crop distribution, and population

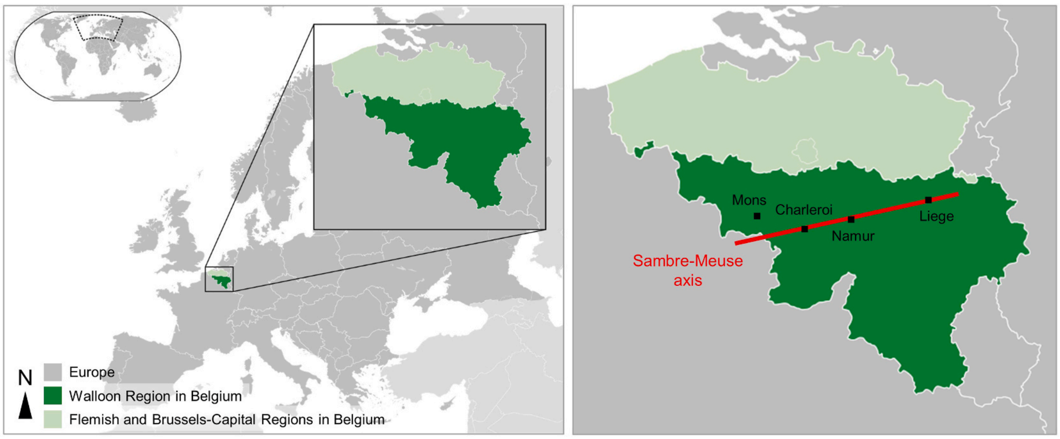

Fig. 1. Study area.

density, this study models pesticide exposure metrics, providing a comprehensive overview of the spatial distribution of pesticide exposure across the Walloon region and over a five-year period. Recently, the first map of pesticide usage on field parcels was produced, setting the methodology and used datasets [28]. From these primary results, the purpose now was to assess the potential pressure of pesticides outside crops, and particularly on the resident population. Hence, the study proposes a complementary and innovative geospatial approach to develop buffer-based pesticide exposure model and mapping pesticide exposure metrics. Zonal statistics are performed for quantifying residents' exposure to agricultural pesticides in Wallonia, and through the five Walloon provinces. This work focuses exclusively on modeling environmental exposure to agricultural pesticides.

2. Materials and methods

2.1. Study area

The study area is the Walloon region in Belgium, also called Wallonia (Fig. 1). It covers almost 17,000 km^2 and counts about 3,600,000 inhabitants, with a density of 215 inhabitants/km [2] in 2019 [29]. Wallonia is characterized by its rivers that have shaped both its physical appearance and urban development. The Sambre-Meuse axis defines the industrial area with the main urban poles (Mons, Charleroi, Namur and Liege) counting for more than 40 % of the Walloon population [30]. The northern part of the Sambre-Meuse axis, mostly urbanized, gathers the main agricultural and economic activities. The utilized agricultural area is highest in this region as the majority of cereals and industrial crops are grown here. Further south, the (mainly permanent) grasslands and wooded areas dominate. The southern part of the Sambre-Meuse axis is rural and much less densely populated.

2.2. Datasets and methodology

Data on pesticide application rates, high-resolution annual datasets of the geographic distribution of crops, and the 100 × 100m grid population dataset were utilized to complete this analysis in Wallonia over the period 2015–2019. The flowchart in Fig. 2 shows the main steps of the methodology developed for this study.

The initial step was to assign total yearly application rates to the corresponding crops, based on the agricultural region and agriculture type (conventional vs. organic). The methodology and datasets used for mapping pesticide use on field parcels have been fully described in Habran et al. [28] Briefly, pesticide application rates were sourced from the Department of Agricultural Economic Analysis (DAEA) in Wallonia, providing information on the amounts of pesticides applied to specific crops and total yearly application rates across four agricultural super-regions: Condroz, Arable land, Dairy grassland, and Livestock grassland. These regions vary in natural characteristics and agro-economic potential. Estimates are based on a reference sample of around 4 % of Walloon farms, with data extrapolated to all conventional farms for the 12 major crop types, accounting for 89 % of total agricultural area. For crop types lacking specific application rates, average rates were assigned per super-region. Organic crops were assumed to have zero pesticide application due to their minimal use. Crop data were obtained from the annual crop inventory by the Agriculture Department in Wallonia, providing detailed GIS mapping of field boundaries and crop types. This dataset also included information on organic agriculture and extra Christmas tree production. In the present study, the covered period was extended to 2015–2019 with new datasets available. Application rates have been averaged over the five years to account for crop rotation. In addition, the methodology was enhanced by including a pre-weighting step for active ingredients (AIs) in order to better consider potential risk of pesticides. The weighting factors established for Harmonized Risk Indicators - HRI under Directive 2009/128/EC [31] were applied to the estimated amounts of AIs of pesticides in order to fall in line with the European approach. AIs are grouped into four categories, in line with Regulation (EC) No 1107/2009 [32]. The weighting factors applied to each category (i.e. 1, 8, 16 or 64) are intended to reflect policy on the use of pesticides and to support the goal of the Sustainable Use of Pesticides Directive to reduce the risk and impact of pesticide use and promote alternative approaches or techniques [33]. French-English translation and validation of HRI factors assigned to the AIs used in Wallonia were performed. One micro-organism (*Bacillus Thuringiensis*) was removed from the analysis as of little toxicological concern (weighting = 0), and HRI weightings for a dozen missing substances was completed and validated by the Federal Public Service Health, Food Chain Safety and Environment. Hence, in the assessment of pesticide usage, we accounted for the application of 267 AIs in total on 12 crop classes (grassland, wheat, corn, beet, potato, barley, spelt, colza, peas, chicory, bean, and orchard) at average annual rates. After processing calculation of pesticide application rates with HRI weightings in an Access database, the Python code developed for the automated process in Habran et al. [28] was used to update the final map of pesticide use (expressed in kg x HRI/ha/year).

A grid-level exposure index was then estimated using a buffer-based exposure model by conducting neighborhood analysis in

Fig. 2. Flowchart with the methodology developed for this study. * The methodology for mapping pesticide use on field parcels is fully described elsewhere [28].

ArcGIS. This analysis enables focal statistics in the neighborhood of the processing cell. The weighted mean of AIs amounts was calculated in the neighborhood of each processing cell according the following assumptions. We assumed that a 1000m radius captured the intensity and diversity of exposure to agricultural crops, and that exposure is probably higher in the close vicinity to crops (see end of section 3.2). We considered therefore (i) a circular weighted neighborhood with (ii) a 1000m buffer radius, and (iii) linearly decreasing weights with distance (Fig. 3). Thereby, the calculated index gives an indication of the intensity of potential exposure taking into account both proximity to crops, the estimated amount of pesticides and acreage treated within 1000 m around each processing cell. Raster cells outside Walloon boundaries (i.e. in Flanders, France, The Netherlands, Germany and Luxembourg) were assigned value as 'NoData' and were not taken into account for processing into the neighborhood analysis. For this reason, it was preferable to set the focal statistics to 'Mean' instead of 'Sum' of AIs amounts.

Finally, a population weighted method [26] was used to 'up-scale' the exposure data to administrative levels to match up with public health datasets. Indeed, public health data are generally published for large area units (e.g., municipality, postcode) to protect the privacy of patients and human subjects. For studies that investigate area level associations between pesticide exposure and health, it is necessary to aggregate the grid-level exposure information to match the area level of municipality. The 100 × 100m grid population dataset from the Belgian Census of Population at January 1, 2020 (Statbel) was used for this processing. Specifically, the area level exposure is calculated as:

$$Exp = \frac{\sum_j Pop_j \, Exp_j}{\sum_j Pop_j}$$

where Pop_j and Exp_j are respectively the population size and the pesticide weighted exposure index for the jth population grid within the area unit. From the formula, we can see the area level exposure is estimated as the average exposure of the municipality population. The Walloon region counts 262 municipalities ranging from 6.8 to 215.4 km^2 (with a median of 51.0 km^2).

It should be emphasized that the legend of pesticide maps is not based on the specific values but represents merely the distribution of the calculated values, classified according to the method of natural breaks (Jenks) for shapefiles and displayed according the percent clip stretch type for rasters.

2.3. Zonal statistics by province

The distribution of the population according the intensity level of the potential exposure to agricultural pesticides was analyzed, and the number of people potentially exposed was determined by province. To perform this analysis, the grid-level exposure index was categorized in five classes. Firstly, four classes were defined based on the Jenks natural breaks classification, then the 0 values were extracted into a fifth class in order to identify areas with no crop within a 1000m radius (except organic crops, see methodology in Habran et al. [28]). The number and percent of people falling within each exposure index category were calculated for the five Walloon provinces by overlaying the 100 × 100m grid population data from the Census of Population.

2.4. Validation

Between May 2015 and May 2016, a previous study had monitored pesticide concentrations in air in Wallonia. The sampling strategy and analytical procedures used have been described in detail elsewhere [34]. In brief, a one-year measurement campaign of 46

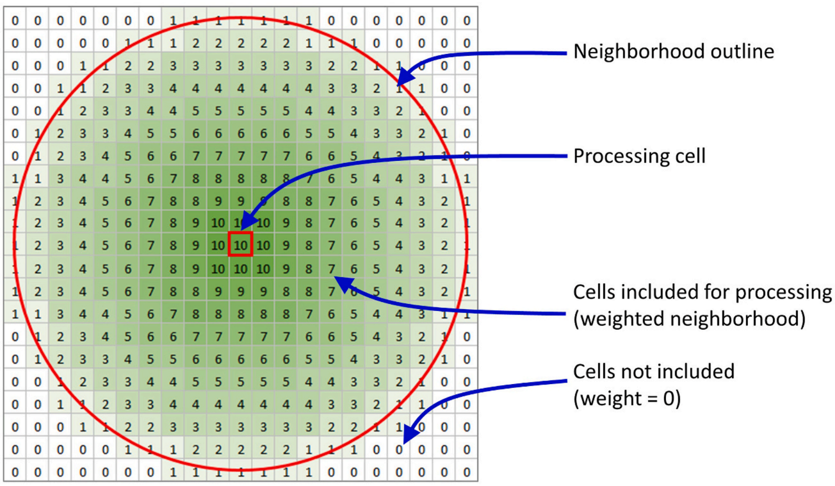

Fig. 3. Illustration of the weight kernel file with circular shape (radius = 10 cells of 100 m) used in this study for focal statistics.

currently used pesticides in ambient air was carried out in 12 different locations spread over Wallonia. The locations were characterized by different agricultural practices and pesticide uses (remote areas with no use of pesticides; urban sites; agricultural sites; livestock areas; sites surrounded by parks, gardens or railways where pesticide uses were suspected, etc.). The 46 pesticides analyzed in air were selected according to the ranking method described earlier [35] mainly focusing on toxicology endpoints, sales and uses at the national and regional levels, and their significant probability to be detected in air. Ambient air was sampled repeatedly over 2-week periods (i.e. 19 periods over the year). For the 12 sites, the Spearman's rank correlation was used to compare the mean concentrations for all pesticides measured in air with index values from the buffer-based exposure model calculated at the stations.

All exposure modeling steps in this study were implemented using ArcGIS (ESRI Inc. Version Pro 3.0.3) and the Jupiter Notebook with ArcPy.

3. Results and discussion

3.1. Hazard-weighted mapping of pesticide use

According to the results, top three major crops consuming both greater quantities and more hazardous pesticides are orchards, followed by potatoes and beets (Fig. 4). Fortunately, those crops represent less than 10 % of the total agricultural area, while grasslands, the least impacted crops, cover 46 % of the total agricultural area from the inventory. This crop ranking takes up HRI weighting to make distinction between different substances and their potential hazard associated. However, the methodology underpinning HRI has been criticized by key actors, such as the European Court of Auditors (ECA) [36] and the German Environment Agency [37]. Specifically, they identified that the indicators are limited by the different weighting factors used to calculate the risk of active substances contained in chemical pesticides, which are assigned depending on their regulatory status (e.g. 'low-risk', 'approved', 'candidates for substitution' and 'not approved') rather than on scientific evidence of harm [38]. As a result, both organizations made suggestions to increase the indicators' accuracy and reliability, and the European Commission recently committed to improve them [38]. Furthermore, comparison with the 2015–2019 unweighted pesticide map (Supplementary Fig. S1), and with the previous work covering the period 2015–2017 [28], highlighted the same spatial pattern and the same crop ranking, despite being based on 'quantity only' indicators. When looking at the quantities of pesticides sold in Belgium for each of the four EU categories, we see that the bulk of use concerns category 3. The HRI weighting factor is therefore not very discriminating for Belgium. In France, pesticide use intensity of some selected crops, measured by the average treatment frequency index (TFI), also shows similar ranking (Table A2 in Guilpart et al. [10]). Despite the limitations of European HRI weighting and its limited influence on the spatial pattern of pesticide metrics, this weighting step seems to us preferable to none, and enables us to remain in line with the European approach pending further improvements.

Other limitations and uncertainties are inherent to data used in such mapping based on estimated application rates for 12 major crops; they are fully described in Habran et al. [28] As a reminder, variations in pesticide practices within the same crop type, treatments for secondary crops, intercrops, field edges, seeds, or anti-germ use were not accounted for.

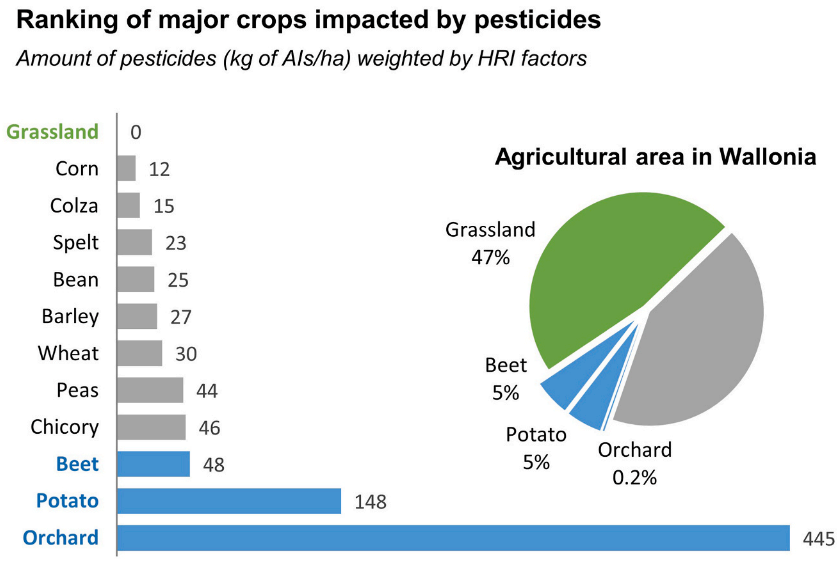

Fig. 4. Ranking of major crops impacted by pesticides, according to both the quantities of pesticides applied on field parcels (estimated amounts of AIs) and their hazardousness (HRI factors for AIs). The pie-chart shows the distribution of the agricultural surface of main crops in Wallonia over the period 2015–2019. Orchards, potatoes, and beets are the most impacted crops but represent less than 10 % of the total agricultural area, while grasslands are the least impacted and cover 46 % of the total agricultural area from the inventory. AIs: Active Ingredients; HRI: Harmonized Risk Indicators.

3.2. Modeling environmental exposure

This study gives the first map of modeling environmental exposure to agricultural pesticides for the entire region of Wallonia. Fig. 5 provides the successive results to estimate the pesticide pressure outside crops and finally to obtain a pesticide exposure metric by municipality, where the area level exposure is estimated as the average exposure of the municipality population.

Geographic analysis of the layers showed that the highest values of the grid-level exposure index (exposure index value = 925) are found in the middle of orchard fields surrounded by other likely treated crops where no one lives. By contrast, the lowest values (exposure index value = 0) are found in uninhabited or populated areas, with no treated crop in the vicinity (except perhaps organic crops). Fig. 6 gives the map of the five intensity levels of the potential exposure to agricultural pesticides with the corresponding superficies in Wallonia. The northern part of the Sambre-Meuse axis demonstrates more intensive agriculture and therefore the highest pesticide weighted exposure indices. It is important to bear in mind that this index only provides comparative information between areas in Wallonia as to the intensity of potential exposure. The index values cannot be used to predict pesticide concentrations or loads of pesticides, and do not refer to any risk threshold.

For this preliminary approach of exposure metrics in Wallonia, the neighborhood analysis (focal statistics) was performed according several assumptions. In comparison with previous similar approaches with buffer-based models that summarize the amount of estimated pesticide use [24,26], we enhanced the model using a weighted neighborhood based on the assumption that people are more likely to be impacted by pesticides sprayed in the close vicinity of their residence than by pesticides sprayed farther away [39]. In our weight kernel file (Fig. 3), we considered by default that pesticide dispersion decreases linearly. However, specific research on pesticide dispersion [39–41] could help to refine the weighted neighborhood, as well as its shape for a consideration of dominant wind direction and topography for instance. This study also did not consider the influences from pesticide application on adjacent areas in the neighbor regions.

Buffer size to estimate exposure to agricultural crops usually varies between 100m and 5000m according to literature [24–27, 42–47], with no real consensus [11,13,48], although a 1000m radius be increasingly adopted. In this study, we also opted for a 1000m radius to account for secondary transport processes [24,39–41] and to reflect continuous exposure. In contrast, a 100m radius for instance would mainly capture short-term exposure due to primary drift right after spraying. Moreover, exposure to emissions from volatilization can be higher than exposure to spray drift [40].

3.3. Validation

In a limited validation effort, model estimates were compared with pesticide measurements in air collected at 12 stations during the period 2015–2016. On the 46 pesticides studied in air, 6 insecticides, 18 herbicides and 18 fungicides were detected. Herbicides were measured in 68.3 % of samples throughout the year, whereas fungicides and insecticides were measured in 62.6 % and 13.2 % of the samples, respectively [34]. The mean concentrations measured in air (ng/m^3) were calculated for all pesticides per station over the complete monitoring years 2015 and 2016. Despite the limited dataset of measurements, it can provide insight into the ability of the model to predict environmental pesticide exposure from agricultural pesticide applications. The correlation between measures in ambient air and model estimates showed consistent result with a positive trend association, although not statistically significant (Spearman rank correlation $r = 0.54$, p-value = 0.068). Further validation efforts will be needed to confirm and validate the model predictions. The sample size should be larger with more sample sites, other matrices (in addition to air) should also be investigated and model estimates should be calculated for only the same AIs measured in air, at the same period.

Despite aforementioned assumptions and limitations related to datasets used [28], this geospatial approach to estimating exposure to agricultural crops has the merit of including the main determinants of environmental exposure [13]. For the first time, exposure metrics takes into account both proximity to crops, the estimated amount of pesticides and treated acreage, thus considerably improving the exposure characterization using GIS models [11]. Moreover, crop rotation (via multi-year datasets), location of organic fields, and hazard-based substance weightings were considered in this study to get a more realistic scenario of the chronic pressure from agricultural pesticides.

3.4. Regional quantification of residents' exposure

Based on datasets in this study, the population living in Wallonia in 2020 covers around 14 % of the Walloon territory. Most of the population lives in the vicinity of crops (at least of one field). Only 4 % live in areas without any crop within a 1000m radius (except perhaps organic crops), these inhabitants therefore show no environmental exposure to agricultural pesticides according to our model assumptions (0 values in Table 1). They are mainly located in the downtown areas of major cities such as Liege, Namur, and Charleroi. Our findings enable to display a gradient in the intensity of potential exposure according both proximity to crops, the estimated amount of pesticides and treated acreage. Hence, we observed that the majority of the resident population, approximately two-thirds, was exposed to the lowest levels (level 1, after the 0 values). Meanwhile, the proportion of residents with higher potential exposure gradually decreased (Table 1). This reflects that the majority of the population lives with few surrounding crops, or perhaps very nearby crops but consuming few or less hazardous pesticides, such as temporary and permanent grasslands or cereal crops. Figures in Table 1 are obviously linked to the exposure index discretization method chosen in this study (i.e. Jenks natural breaks classification). Other discretization methods might also be discussed and found suitable. In any case, the results enable the identification of the population potentially most exposed to agricultural pesticides in Wallonia, where more intensively treated crops dominate close to housings. In the present case, we targeted the 10 % the most exposed with exposure levels 3 and 4 (i.e. 358,709 people) or the 1 % the

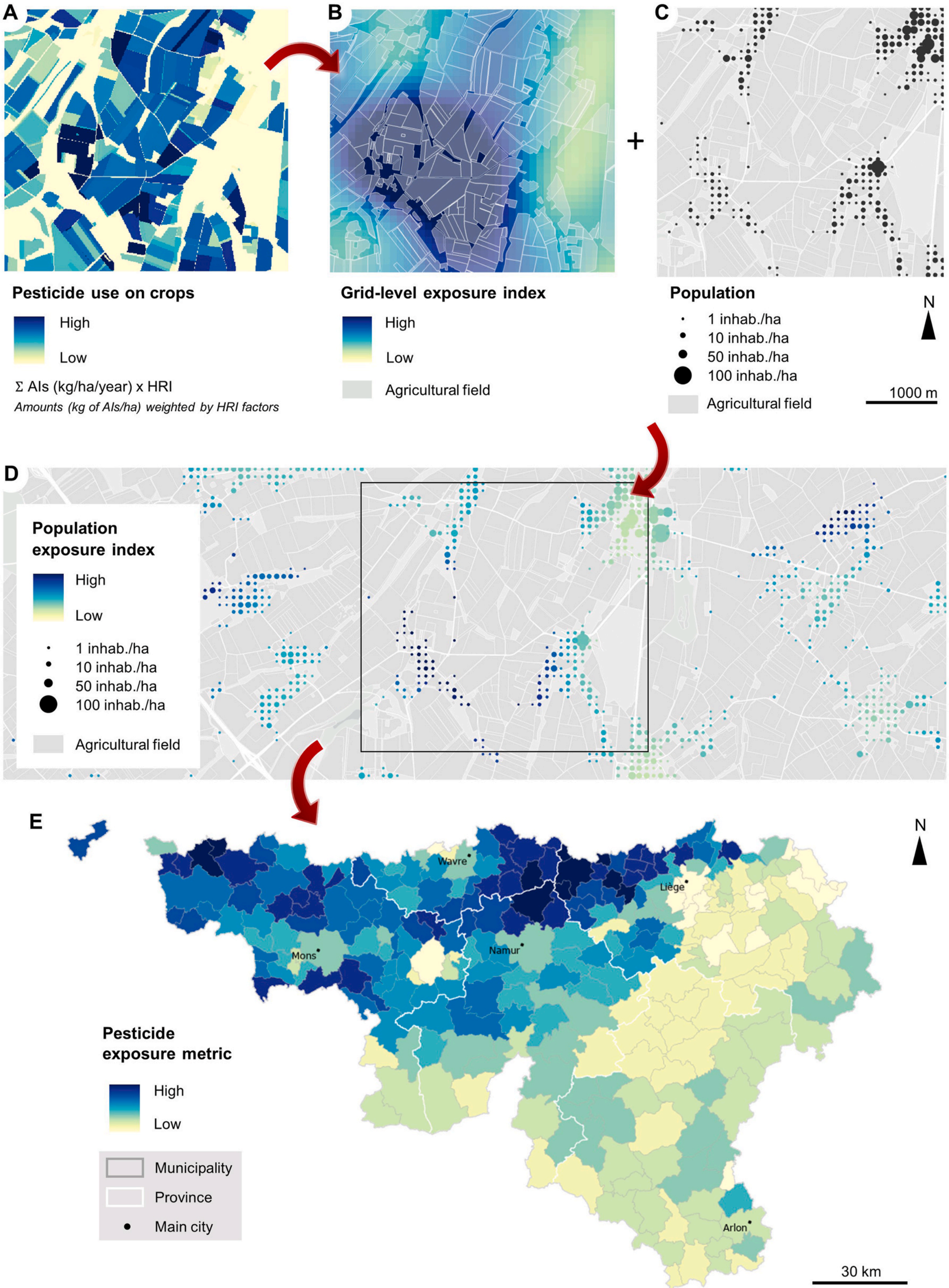

Fig. 5. Potential exposure to agricultural pesticides in Wallonia. **(A) Weighted pesticide map 2015–2019** - Estimated amount of pesticides applied to crops between 2015 and 2019 and weighted by HRI factors (expressed in kgxHRI/ha/year). **(B) Grid-level exposure index -** Buffer-based pesticide exposure model by neighborhood analysis (1000m radius), which takes into account both proximity to crops, the estimated amount of pesticides and treated acreage. **(C) 100 × 100m grid population in 2020. (D) Population exposure index -** Exposure index assigned to the

population data (crossing layers). **(E) Pesticide exposure metric by municipality -** Population exposure information aggregated to match the area level of municipality. The metric is estimated as the average exposure of the municipality population. AIs: Active Ingredients; HRI: Harmonized Risk Indicators.

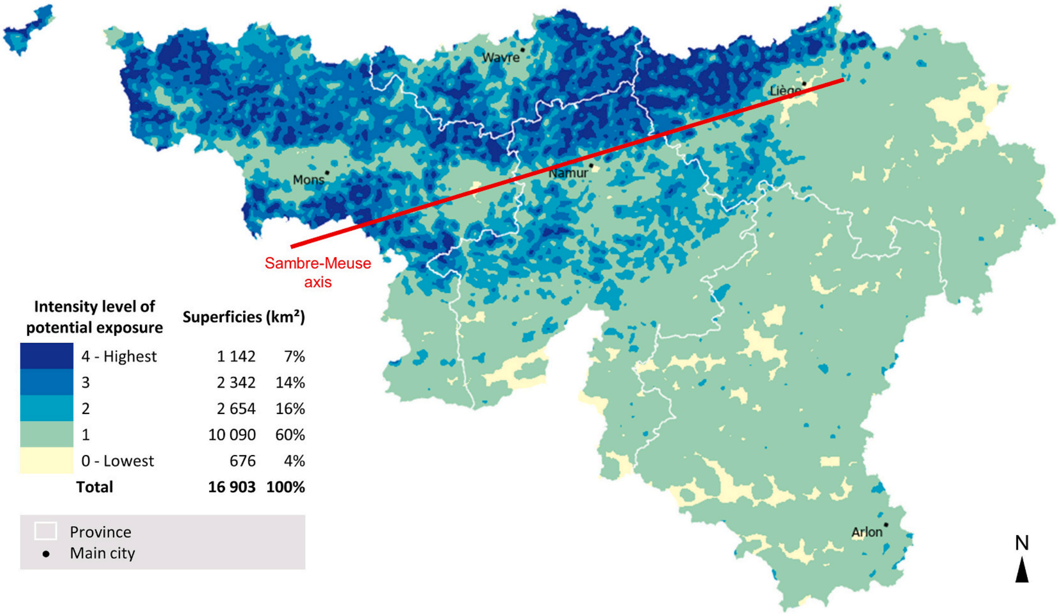

Fig. 6. Grid-level exposure index categorized in five classes, with corresponding superficies in Wallonia. The intensity level of the potential exposure to agricultural pesticides was categorized in four classes based on the Jenks natural breaks classification, then the 0 values were separated into a fifth class to identify areas with no treated crop within a 1000m radius.

Table 1
Potential population exposure to agricultural pesticides by province.

Province	Intensity level of potential exposure[a]					Total
	0 - Lowest	1	2	3	4 - Highest	population
Liege	114,219 (10 %)	802,470 (72 %)	108,471 (10 %)	65,367 (6 %)	18,801 (1.7 %)	1,109,328
W. Brabant	1157 (0 %)	213,893 (53 %)	123,151 (30 %)	62,600 (15 %)	4575 (1.1 %)	40,5376
Hainaut	39,142 (3 %)	772,547 (57 %)	367,763 (27 %)	151,293 (11 %)	13,751 (1.0 %)	1,344,496
Namur	6981 (1 %)	316,792 (64 %)	129,526 (26 %)	38,495 (8 %)	3827 (0.8 %)	495,621
Luxembourg	79 (0 %)	285,505 (100 %)	871 (0 %)	0	0	286,455
Wallonia	161,578 (4 %)	2,391,207 (66 %)	729,782 (20 %)	317,755 (9 %)	40,954 (1.1 %)	3,641,276

[a] The intensity level of the potential exposure to agricultural pesticides was categorized in four classes based on the Jenks natural breaks classification, then the 0 values were separated into a fifth class to identify areas with no treated crop within a 1000m radius (see Fig. 6).

most exposed with level 4 only (i.e. 40,954 people) (Table 1). We also observed that the distribution of the most exposed people is not the same throughout Wallonia. The provinces of Liege and Hainaut gathered the highest number of most-exposed residents (i.e. respectively 18,801 and 13,751 out of a total of 40,954 in Wallonia). While the province of Luxembourg is completely spared from a high environmental exposure to agricultural pesticides (Table 1).

A few studies have analyzed the association between the agricultural land use around the residence and internal exposure to pesticides from human biomonitoring data [44,49]. However, the lack of information about type of crops or pesticide use was a considerable limitation [44]. Our index overcomes such limitation by taking these determinants into account, and would enhance such association assessment. It is also worth noting that the entire methodology is easily transferrable to exposure estimation at the individual level (model processing at the individual's residential address), as well as in other region as long as datasets are available for the calculation. The study thus delivers a detailed and technically advanced analysis of pesticide exposure in a specific region using innovative geospatial methods. The methodology ensures that the results are representative of the entire region and allows researchers and policymakers to obtain a clear picture of pesticide distribution and exposure levels in Wallonia. The use of GIS and high-resolution data is particularly suitable for the study's geospatial approach, allowing precise grid-level analysis. The study provides three tiers of mapping results: i) the grid-level exposure index (Fig. 5B), identifying potential environmental hotspots that require monitoring and mitigation; ii) the population exposure index (Fig. 5D), essential for assessing of environmental determinants on an individual basis in biomonitoring surveys; and iii) the exposure metric by municipality (Fig. 5E), which supports ecological studies in investigating the relationships between exposure and health outcomes at a population or community level.

4. Conclusion

This study offers an important step towards a first estimation of the exposure to pesticide of people living in the vicinity of agricultural fields. Pesticide exposure metrics were estimated using a buffer-based exposure model by conducting neighborhood analysis in ArcGIS. The model takes into account both proximity to crops, the estimated amount of pesticides and treated acreage. Such geospatial approaches are beneficial in characterizing pesticide exposure for residents living close to agricultural lands as well as in non-domestic environments such as schools, nurseries, etc. Maps highlight areas where human biomonitoring and epidemiological studies should be implemented to investigate the impact of potential environmental exposure to pesticides. With this information, policy-makers will be able to identify potential priority areas and take measures to control and reduce the load of agricultural pesticides in the environment.

Further parameters and datasets could also be included in future developments, e.g. wind direction, topography, other pesticide sources like the location of agricultural sites for storage (potato stores), railway tracks, golf courses etc. As it stands, this characterization of exposure to agricultural pesticides using GIS models provides a valuable basis for environmental health research and policy in Belgium.

CRediT authorship contribution statement

Sarah Habran: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Project administration, Methodology, Formal analysis, Conceptualization. **Christelle Philippart:** Writing – original draft, Validation, Software, Methodology, Formal analysis, Data curation. **Vincent Van Bol:** Writing – review & editing, Methodology. **Raphaël D'Andrimont:** Writing – review & editing. **Hervé Breulet:** Writing – review & editing, Supervision.

Data availability

The data from the current study are available from the corresponding author on reasonable request.

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Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.heliyon.2024.e40050.

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