How much agricultural land is there close to residential areas? An assessment at the national scale in France

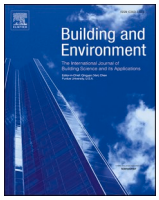
Nicolas Guilpart, Iris Bertin, Muriel Valantin-Morison, Corentin M Barbu

Building and Environment 226 (2022) 109662

Contents lists available at ScienceDirect

Building and Environment

journal homepage: www.elsevier.com/locate/buildenv



How much agricultural land is there close to residential areas? An assessment at the national scale in France

Nicolas Guilpart *, Iris Bertin, Muriel Valantin-Morison, Corentin M. Barbu

Université Paris-Saclay, AgroParisTech, INRAE, UMR Agronomie, 91120, Palaiseau, France

ARTICLE INFO

Keywords:
Pesticides
Agriculture
Exposure
Residents
Pesticide-free buffer zones
France

ABSTRACT

In 2019, aiming at reducing resident's exposure to pesticides, the French government announced mandatory pesticide-free buffer zones of 3–20 m around inhabited areas. As pesticide reduction is often associated with lower productivity, this raised questions about the amount of agricultural area located around residential buildings, which has not yet been quantified in France. The best available data describing spatial organization of crops at the field parcel scale and location of residential buildings over the whole French territory were combined to calculate the amount of agricultural area within 10 m, 50 m, 100 m, and 150 m (a distance advocated by some environmental NGOs) to residential buildings for 23 crop types. Results show that 0.2%, 5%, 16%, and 29% of the total national agricultural area is located within 10 m, 50 m, 100 m, and 150 m to residential buildings, respectively. The proportion of crop-specific national area that is close to housings is low at 10 m (0–1%) and increases up to 10–58% depending on crop type at 150 m. About 32%–45% of vineyards and 37%–53% of orchards national area, two crop types with high pesticide use intensity, are located within 150 m to residential buildings. We conclude that (i) the implementation of pesticide-free buffer zones around housings may have a strong impact on agricultural production at the national scale because of likely associated yield and quality losses on large areas, and (ii) the large presence of treated crops close to residential buildings requires attention for its potential effect on residents' exposure to pesticides.

1. Introduction

In agriculture, pesticides are commonly used by farmers to protect their crops against pests, diseases and weeds, which can cause substantial production and quality losses. For example, a recent study estimated global crop losses caused by combined pests and diseases to range between 17% and 30% for wheat, maize, rice, potato and soybean [1]. However, pesticides have also well-documented negative effects on the environment [2,3] and human health [4,5]. Aiming at reducing the later, the French government announced in December 2019 mandatory pesticide-free buffer zones around inhabited areas [6]. The objective was to reduce the exposure to agricultural pesticides in populations living close to fields. The width of the mandatory pesticide-free buffer zones may vary between 3 and 20 m according to the crop species, pesticide active compounds (these restrictions do not apply to organic farming products), and whether techniques to reduce drift or exposure to drift are used by farmers. However, the appropriate width for these pesticide-free buffer zones is highly debated. On the one hand, larger buffer zones (up to 150 m) are advocated by some environmental NGOs and several French mayors to reduce the exposure of inhabitants to agricultural pesticides [7]. On the other hand, the French ministry of Agriculture and some leading French farmers unions raised concerns about larger buffer zones, which are expected to erode the competitiveness of French agriculture as they would represent a large share of the national agricultural area [8]. Surprisingly, no estimate of the amount of agricultural area around residential buildings is available in France. Therefore, the objective of this paper is to quantify the amount of agricultural area and the type of crops (in relation with their pesticide use intensity) around residential buildings in France.

Beyond the important media coverage of this debate, two key points arising from the scientific literature justify to pay attention to crops grown close to residential areas. First, 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 [9,10]. 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 [11].

* Corresponding author.
E-mail address: nicolas.guilpart@agroparistech.fr (N. Guilpart).

https://doi.org/10.1016/j.buildenv.2022.109662
Received 19 July 2022; Received in revised form 28 September 2022; Accepted 29 September 2022
Available online 8 October 2022

Some studies found positive associations between higher levels of pesticides in house dust and crop production area within up to 1000 m from housings [12–14]. Second, all crops are not treated in the same way. Perennial crops like apples, wine grapes and plums usually display higher pesticide use intensity than annual field crops, especially some spring crops like maize and sunflower that receive substantially lower amount of pesticides. For example, in France over the 1989–2013 period, apples orchards received in average 32.5 standardized unit doses of pesticides per year, while sunflowers received only 2.2 standardized unit doses of pesticides per year [15]. Types of applied products (i.e. fungicides, insecticides, herbicides) also vary by crops. Some crops rely heavily on fungicides with low amount of insecticides (e.g. wine grapes, wheat), while others use a larger share of insecticides (e.g. apples, plums, rapeseed) [15]. This is important because all pesticides do not have the same effects on human health as they differ in toxicity and exposure-related processes [4]. Finally, despite successive national action plans, the use of agricultural pesticides is still increasing in France, which reinforces the overall issue of the impact of pesticides on human health [16–18].

Therefore, quantifying the amount of agricultural area located close to housings appears essential, as well as identifying which crops are grown on this area. Our hypotheses were that (i) major crops in France in terms of production area (pastures, wheat, barley, maize, and rapeseed) will also be dominant crops close to housings at the national scale, (ii) due to the regional specialization of French agriculture, dominant crops in the vicinity of housings will vary by region, (iii) the share of crop-specific national production area close to housings might be higher for crops known to be close to residential areas (e.g. wine grapes), with potential higher economic impacts of pesticide-free buffer zones for these crops.

2. Material and methods

2.1. Data sources

2.1.1. The French land parcel identification system

To identify where crops are grown, the French Land Parcel Identification System (LPIS) was used. This database provides spatially explicit information of crops grown in French field parcels (i.e. field geometry and crop type) over the whole French territory, and has been used in previous research to describe the spatial organization of crops at different scales [19,20]. The French LPIS has been set up in 2002 and is updated every year on the basis of the farmers' Common Agricultural Policy (CAP) declarations. Data for the year 2018 were used, which was the most recent year available at the time of the study. This represents over 6 million field parcels covering about 27 Mha. Cultivated crops are classified into 23 groups (Table A1). A group of crops may correspond to a single crop like wheat, or to several crops (apples, plums, and pears belong to the "orchards" group). In 2018, the French LPIS had an overall good coverage of national production area, with more than 98% for all field crops, about 85% for pastures and permanent grasslands, 92% for temporary grasslands, and 95% for tree nuts. For perennial crops other than tree nuts, the coverage was good but lower with 70% for orchards, 72% for vineyards, and 66% for olive trees (see Ref. [21] and Table A1). The French LPIS represents the best available data for spatial distribution of crops in France in terms of spatial and temporal resolutions, spatial coverage, and disaggregation by crop type. The French LPIS data are publicly available for download at https://geoservices.ign.fr/rpg.

2.1.2. Map of residential buildings in France

The location of residential buildings in France was provided by the BD TOPO® database [22]. This database provides a map of the whole French territory in 2019 where each building is represented by a polygon, with attributes describing the nature of the building, its use, state, date of creation and modification. The term "building" encompass all "constructions above the ground, used to shelter humans, animals, objects, for the production of economic goods or for the provision of services and refers to any structures built or erected permanently on its site" [22]. The "use" attribute has the following levels: agricultural, commercial and services, industrial, religious, sports, annex, residential or undifferentiated. However, due to a lack of interoperability of databases used in the development of the BD TOPO®, the "use" attribute of buildings could not be filled in some municipalities, where all buildings are then reported as "undifferentiated" use. Therefore, in this study, a focus was made on buildings with "residential" and "undifferentiated" uses. This includes residential buildings and those with unknown uses, but excludes buildings with agricultural, commercial and service, industrial, religious and sports uses and annexes. The BD TOPO® database is publicly available for download at: https://geoservices.ign.fr/bdtopo.

2.2. Quantification of agricultural area and crop types close to housings

2.2.1. Pre-processing of LPIS data

Duplicated polygons have been removed and polygons with topological issues have been fixed as in Ref. [19]. Minor spatial overlaps can occasionally occur between polygons, which has not been fixed but always represents less than 5% of the polygon surface area.

2.2.2. Buffer zones around residential buildings

Buffer zones of 10 m, 50 m, 100 m, and 150 m were created around residential buildings using the *st_buffer()* function of the *sf* R package [23]. These values were chosen to be representative of the pesticide-free buffer zones width range proposed by the French government (3 m–20 m) and advocated by environmental NGOs (up to 150 m). The smaller width was set to 10 m because the spatial resolution of the BD TOPO® ranges between 2.5 and 10 m [22]. This procedure likely underestimates the size of buffer zones as defined by the French government because it considers distances to residential buildings and not distances to the outside limit of the unbuilt amenity space surrounding buildings (Fig. 1). A lack of interoperability of available databases prevented us to use the distance to the outside limit of the unbuilt amenity space surrounding buildings.

2.2.3. Agricultural area and crop types within buffer zones

Buffer zones around residential buildings were overlapped with the French LPIS data to calculate: (i) total surface area of buffer zones (agricultural area and non-agricultural area), (ii) total agricultural area within buffer zones, and (iii) agricultural area by crop type within buffer zones. We distinguished between treated (e.g. wheat, wine grapes) and non-treated (e.g. temporary and permanent grasslands) crops (see Table A1 for details). To estimate the potential economic impact of pesticide-free buffer zones by crop type, the ratio between the crop type area within buffer zones and the total national area of this same crop type was calculated.

2.2.4. Typology of French departments according to crop types close to housings

The hypothesis was made that due to the regional specialization of French agriculture, dominant crops close to housings will vary by region. To test this hypothesis, the relative importance of each crop type within the 150 m buffer zone by French department (a department is an administrative unit corresponding to the NUTS-3 level of administrative units nomenclature in the European Union) was calculated, and a principal component analysis (PCA) was run followed by a hierarchical ascendant clustering (HAC) with the Ward method to identify groups of departments with similar relative importance of crop types within their buffer zones. The PCA was performed with the *rda()* function of the *vegan* R package [24], and the HAC was performed using the *agnes()* function of the *cluster* R package [25].

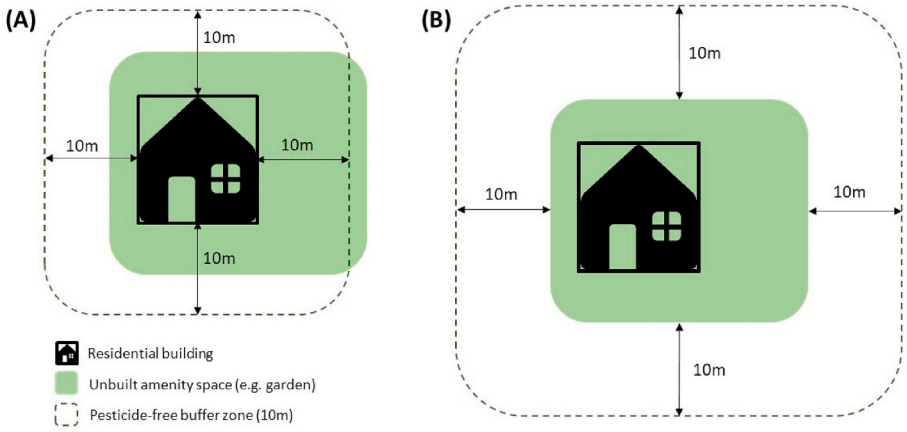


Fig. 1. Definition of buffer zones around residential buildings, when considering (A) distance to the residential building (as defined by the French government), and (B) distance to the outside limit of unbuilt amenity space (e.g. garden) surrounding the building (as done in this study).

3. Results

3.1. Land use around residential buildings at the national scale

3.1.1. About one third of national agricultural area is located within 150 m of residential buildings

At the national scale 0.06 Mha, 1.5 Mha, 4.5 Mha and 7.9 Mha of agricultural land were found within 10 m, 50 m, 100 m, and 150 m of residential buildings, respectively (Fig. 2A). This represents 0.2%, 5%, 16%, and 29% of the total national agricultural area. Roughly half of this agricultural area is composed of non-treated crops, whatever the distance to residential buildings (Fig. 2A). Agricultural land represents 4% (10 m) to 46% (150 m) of all land uses around residential areas, and treated agricultural area represents 1% (10 m) to 21% (150 m) of all land uses around residential buildings (Fig. 2B).

3.1.2. Grassland is the major crop type around residential buildings, followed by cereals, oilseed rape and vineyards

Permanent grassland is, by far, the dominant crop type around residential buildings (Table 1). But with 56% of agricultural area within 10 m of residential buildings and 38% within 150 m, its relative importance decreases when distance to buildings increases. This shows that permanent grasslands are more likely located close to residential buildings. Wheat is the second major crop type found around residential buildings with a relative importance of 7% (10 m) to 13% (150 m), followed by maize with a relative importance of 6% (10 m) to 11% (150 m) (Table 1). The relative importance of both crops increases with the distance to residential buildings, showing they are preferentially located further from residential buildings. Then come temporary grasslands (5–6%), barley (2–4%), oilseed rape (2–4%), other cereals (2–4%), and vineyards (3%). Whatever the distance to residential buildings, the order of dominant crop types changes only marginally, and grasslands (permanent and temporary), wheat, barley, maize, oilseed rape and vineyards altogether represent about 80% of the agricultural area around residential buildings (Table 1).

3.2. The proportion of national area within buffer zones is higher for perennial crops

As a first step in the estimation of potential economic impacts of pesticide-free buffer zones on agriculture, the proportion of crop-specific national area within buffer zones around residential buildings was estimated. This proportion increases with the distance to residential buildings across crop types: 0–1% at 10 m, 1–17% at 50 m, 5–40% at 100 m, and 10–58% at 150 m (Fig. 3). The share of the crop-specific national area located close to residential buildings is higher for perennial crops than annual crops, whatever the size of the buffer zone. For example, at 150 m, this value reaches 45% for vineyards, 53% for orchards, 56% for tree nuts, 58% for olive trees, 31% for maize, 22% for wheat, 20% for barley, and 19% for oilseed rape (Fig. 3).

3.3. The amount of agricultural area and the relative importance of crop types around residential buildings vary by region

The amount of total agricultural area (treated and non-treated) around residential buildings displays a strong spatial pattern, with higher values in the north-west and south-west, and lower values in the east of France (Fig. 4A). Higher values of treated agricultural area around residential buildings are found in the west of France (e.g. Côtes d'Armor, Ile-et-Vilaine, Gers) (Fig. 4B), while higher values of non-

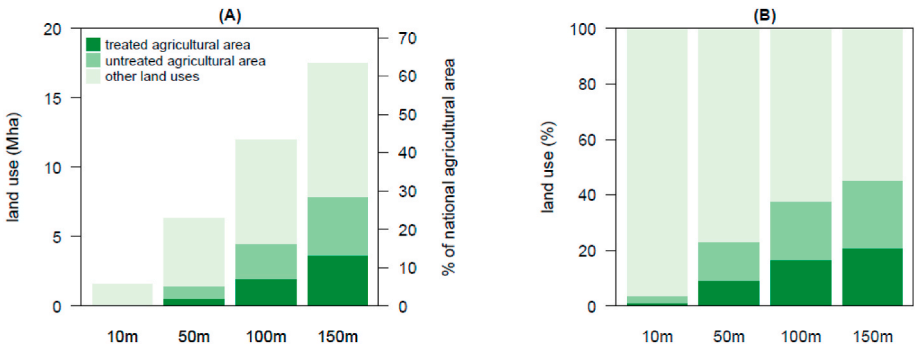


Fig. 2. Land use surrounding residential buildings at national scale in France. (A) Surface areas (Mha) of different categories of land use surrounding residential buildings. (B) Relative importance (%) of different categories of land use within given distances to residential buildings.

Table 1
Dominant crops close to residential buildings in France: production area by crop type as a function of distance to residential buildings at the national scale. Crops were ordered by decreasing area at 150 m to residential buildings.

Crops	Distance to residential buildings								Total France	
	10 m		50 m		100 m		150 m			
	crop production areas in hectares (ha)									
Permanent grassland	32 206	(56%[a])	656 737	(45%)	1 820 570	(40%)	2 972 003	(38%)	7 679 401	(28%)
Wheat	3928	(7%)	159 298	(11%)	560 118	(12%)	1 053 525	(13%)	4 853 018	(18%)
Maize	3466	(6%)	134 925	(9%)	468 259	(10%)	864 303	(11%)	2 831 986	(10%)
Temporary grassland	2846	(5%)	86 797	(6%)	281 067	(6%)	500 336	(6%)	1 445 501	(5%)
Barley	1366	(2%)	54 597	(4%)	187 884	(4%)	347 959	(4%)	1 762 932	(6%)
Oilseed rape	1105	(2%)	45 100	(3%)	159 137	(4%)	301 802	(4%)	1 611 054	(6%)
Other cereals	1047	(2%)	43 396	(3%)	151 957	(3%)	279 976	(4%)	974 101	(4%)
Vineyards	1579	(3%)	49 142	(3%)	155 236	(3%)	262 242	(3%)	583 222	(2%)
Fodder	1214	(2%)	43 478	(3%)	145 602	(3%)	261 950	(3%)	889 843	(3%)
Pastures	2450	(4%)	38 620	(3%)	123 377	(3%)	232 672	(3%)	1 982 450	(7%)
Sunflower	541	(1%)	24 617	(2%)	88 843	(2%)	165 998	(2%)	547 955	(2%)
Set-aside land	1528	(3%)	39 440	(3%)	103 682	(2%)	163 415	(2%)	449 821	(2%)
Vegetables and flowers	648	(1%)	20 006	(1%)	62 221	(1%)	107 090	(1%)	406 845	(1%)
Other crops	2166	(4%)	23 191	(2%)	56 885	(1%)	92 253	(1%)	271 056	(1%)
Other industrial crops	254	(0.4%)	10 049	(0.7%)	35 857	(0.8%)	68 484	(0.9%)	558 351	(2%)
Orchards	486	(0.8%)	12 016	(0.8%)	35 426	(0.8%)	57 449	(0.7%)	107 531	(0.4%)
Other oil crops	164	(0.3%)	7604	(0.5%)	27 525	(0.6%)	51 752	(0.7%)	183 711	(1%)
Protein-rich crops	195	(0.3%)	7920	(0.5%)	27 697	(0.6%)	51 667	(0.7%)	237 507	(1%)
Fibre crops	75	(0.1%)	3319	(0.2%)	11 820	(0.3%)	22 625	(0.3%)	123 235	(0.4%)
Tree nuts	189	(0.3%)	4757	(0.3%)	13 929	(0.3%)	22 393	(0.3%)	40 037	(0.1%)
Grain legumes	61	(0.1%)	2641	(0.2%)	9322	(0.2%)	17 145	(0.2%)	69 104	(0.3%)
Olive trees	123	(0.2%)	1864	(0.1%)	4380	(0.1%)	6272	(0.1%)	10 848	(0.04%)
Rice	7	(0.01%)	146	(0.01%)	605	(0.01%)	1337	(0.02%)	12870	(0.05%)
Total	**57 644**	**(100%)**	**1 469 659**	**(100%)**	**4 531 398**	**(100%)**	**7 904 650**	**(100%)**	**27 632 382**	**(100%)**
% of total national agricultural area	**0.2%**		**5%**		**16%**		**29%**		**100%**	

[a] Relative importance of crop type within corresponding distance to residential buildings.

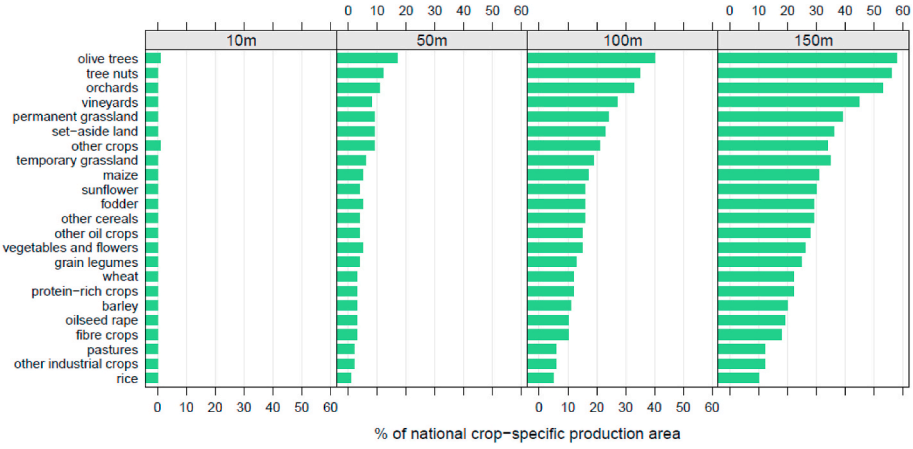


Fig. 3. Percentage of national crop-specific production area within 10 m, 50 m, 100 m, and 150 m of residential buildings in France, by crop type. Crops were ordered by decreasing percentage at 150 m.

treated area are found in the north-west and south-center (e.g. Manche, Saone-et-Loire, Aveyron) of France (Fig. 4C).

The hierarchical clustering procedure allowed us to identify 6 groups of departments with similar relative importance of crop types around residential buildings (Fig. 5, Figure A1, Figure A2). Three groups (Groups 3, 4 and 6) display a high proportion (>50%) of non-treated crops, dominated by permanent grasslands (Groups 3 and 6) and pastures (Group 4). They are located in the east and south-center of France. The three other groups are dominated by treated crops, dominated by (i) wheat, maize and barley in the west (Group 1), (ii) wheat, barley, oilseed rape and maize from the north to La Rochelle via Paris (Group 2), (iii) vineyards in the south (Group 5).

4. Discussion

4.1. On the proximity between cultivated crops and residential buildings

With up to 29% of the total national agricultural area within 150 m of residential buildings, our results reveal a high proximity between crops and residential buildings (Fig. 2A). However, when considering a distance of 10 m to residential buildings, which is representative of the distances defined by the French government at the time of the study, this proportion drops to a very low 0.2%. We hypothesized that major crops in France in terms of production will also be dominant crops close to housings. Our results confirms this hypothesis, with grasslands (permanent and temporary), wheat, barley, maize, and oilseed rape being the dominant crops close to residential buildings (Table 1). However,

permanent grasslands were found to be over-represented, and wheat and to a lesser extent other major field crops (i.e. barley, maize, and oilseed rape) to be under-represented close to housings as compared to their relative importance at the national scale (Table 1). Because they are non-treated crops, the dominance of grasslands close to housings can be expected to contribute to a decrease in the exposure of residents to agricultural pesticides. However, the importance of treated crops like wheat, barley, maize and oilseed rape within 150 m to residential buildings requires attention for its potential effect on residents' exposure to pesticides. Indeed, significant positive effects of the area of field crops within 10 m–1000 m from home have been found on levels of pesticides in house dust in France [12] and the USA [13,14], although the effects on human health are very difficult to estimate [9]. Given the important share of orchards and vineyards in the vicinity of residential buildings in some departments (Fig. 5) and the very intensive use of pesticides on these crops [15], they might be a more acute though much more localized issue. Quantifying the proportion of total population living close to agricultural fields (e.g. using population density maps, or buildings characteristics like size and height as a proxy to the number of people living in the building) at both national and local scales, and estimating how the proximity between cultivated crops and residential areas evolves in time due to urbanization deserves further research.

4.2. On the potential impacts of pesticide-free buffer zones on agricultural production

As currently defined by the French government (i.e. 3-20 m to housings), pesticides-free buffer zones are not likely to have a strong impact on agricultural production at the national scale, as only 0.2% of the total national agricultural area is found within 10 m to residential buildings (Fig. 2A). However, larger buffer zones widths might have important effects on agricultural production, at least for some crops. The most striking example are vineyards, of which 27% and 45% of the national area is found within 100 m and 150 m to residential buildings, respectively (Fig. 3). Vineyards are in the top-3 of the most intensively treated crops in France [15] because of a number of pests and diseases that can lead to considerable losses of yield and quality, and even complete crop failure, like powdery mildew [26], downy mildew [27], and bunch rots [28]. Despite a number of existing tools and strategies to reduce pesticide use in viticulture [29], pesticide use intensity remains high in vineyards (the average treatment frequency index was 12.4 in 2019, see Table A2), and a pesticide-free management system is still considered unfeasible [30]. If a reduced pesticide use intensity appears feasible, the most recent evidence suggests it would likely come with a strong reduction in grape yield. Indeed [31], analyzed the evolution of pesticide use in 244 vineyards from farms voluntarily participating in a pesticide reduction program over 10 years and 12 winegrowing regions in France. On average, they found a 33% reduction in pesticide use (as measured by the treatment frequency index) and a 19% reduction in yield – although with substantial variation across regions. Therefore, the implementation of large (i.e. 100 m–150 m) pesticide-free buffer zones around housings could be expected to have a strong impact on wine production at the national scale, which represented about 20% of the economic value of total national agricultural production in 2018 [32]. This conclusion holds for olive trees, tree nuts and orchards as well, which have more than 40% of their national area within 150 m to residential buildings (Fig. 3), although their economic importance at the national scale is lower than for vineyards. This confirms our hypothesis that the share of crop-specific national production area located close to housings might be high for some crops, with potential important economic impacts of extended pesticide-free buffer zones. Impacts of large pesticide-free buffer zones might also be important for other crops like maize, wheat, barley and oilseed rape, for which 19%–31% of the national area is found within 150 m to residential buildings (Table 1). As an example, a recent meta-analysis estimated that halving pesticide use of wheat in France would decrease the French wheat production by 2–3 Mt, which represents about 15% of the French wheat export [33]. Finally, some farms might have a large share of their fields located very close to housings so that a high share of their production area would fall within pesticide-free buffer zones. The potential impacts of pesticide-free buffer zones would therefore be expected to vary across farms. This would deserve further research and a specific attention in possible future legislation.

4.3. Options for reducing pesticide use close to residential areas

The negative effects of pesticides are not limited to their impacts on human health, and reducing their use is a challenge for the global agriculture [2,3]. However, because of the accumulating evidence showing that non-farmworkers living close to agricultural areas are exposed to higher levels of pesticides than residents living further away [9,10], it appears relevant to consider whether specific measures aiming at encouraging pesticide reduction could be applied to cultivated areas close to housings. A number of agronomic strategies have been identified as options to decrease pesticide use in both annual [33–36] and perennial crops [29–31,37–39]. Discussing all these options is out of the scope of this study, but we would like to highlight two key points. First, a simple option is to preferentially grow crops with a low pesticide use intensity close to housings [15]. However, this strategy is of limited interest for perennial crops like vineyards, orchards, and olive trees, which are often located close to housings and rely heavily on pesticides. This makes perennial crops a complicated issue in this regard, especially those for which Protected Designation of Origins are common like vineyards. Second, we highlighted that a large share of the national agricultural area is located close to residential buildings. We found about 2 Mha of treated agricultural area within 100 m of residential buildings. Conversion of these 2 Mha to organic farming (pesticides-free buffer zones do not apply to organic farming) would add 7% of the national agricultural area to the current 8.5% in organic farming (assuming no overlap), so that the objective of 15% of organic farming at the national scale by 2022[1] would be reached. Therefore, focusing efforts to reduce pesticides use close to housings might be worth to consider.

4.4. Towards a national quantification of residents' exposure to pesticides that takes into account local agricultural activities

Figs. 4 and 5 highlight the large variation in both the amount of agricultural area close to residential buildings and the dominant crop types grown in that area. This confirms our hypothesis that due to the regional specialization of French agriculture, dominant crops close to housings will vary by region. Groups of departments with similar relative importance of crops close to residential buildings were identified. This analysis suggests that exposure to pesticides of people living close to agricultural fields is likely to vary by region, both in intensity and with respect to the nature of pesticides because all crops are not treated with the same intensity nor with the same pesticides [15]. For example, most common perennial crops (e.g. vineyards, apple, peach, apricot, plum, and cherry) usually have a treatment frequency index (TFI) ranging from 8 (plum and cherry) to 30 (apple), while TFI of annual crops (except potato) ranges from 1.8 for soybean to 6.4 for oilseed rape (Table A2). Likewise, some crops rely more on herbicides than others (TFI for herbicides is 2.6 for sugar beet and 0.4 for vineyards), and this can also be observed for fungicides (TFI for fungicides is 11.7 for potato and 0.1 for sunflower) and insecticides (TFI insecticide is 2.1 for oilseed rape and 0.1 for barley) (see Table A2).

Moreover, departments where non-treated crops dominate close to housings (e.g. groups 3, 4 and 6 in Fig. 5) were identified, as well as

[1] Programme Ambition Bio 2022, https://agriculture.gouv.fr/ambition-bio-2022-plan-dactions-des-acteurs-de-lagriculture-et-de-lalimentation.

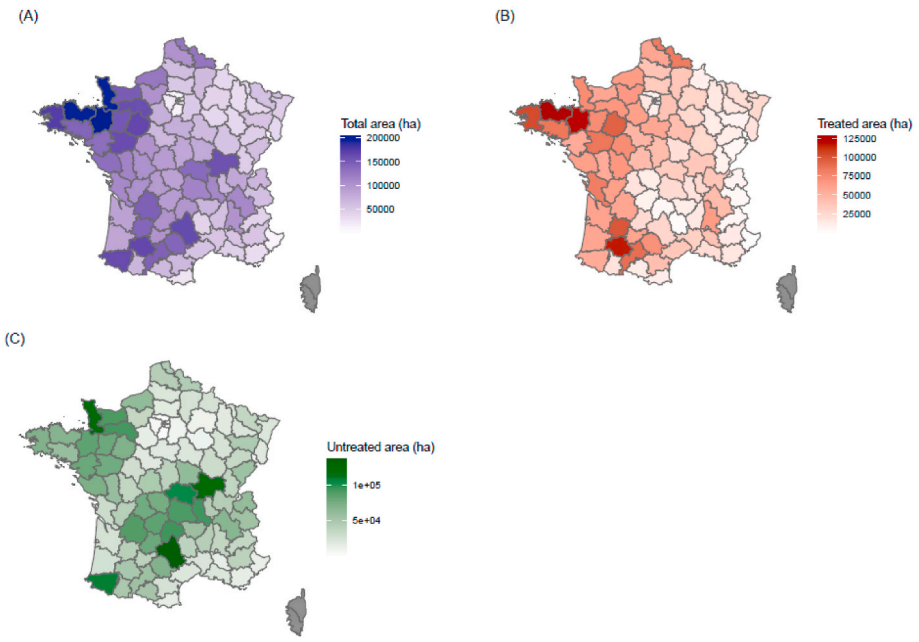


Fig. 4. Total agricultural area (A), treated agricultural area (B), and non-treated agricultural area (C) within 150 m to residential buildings by department in France.

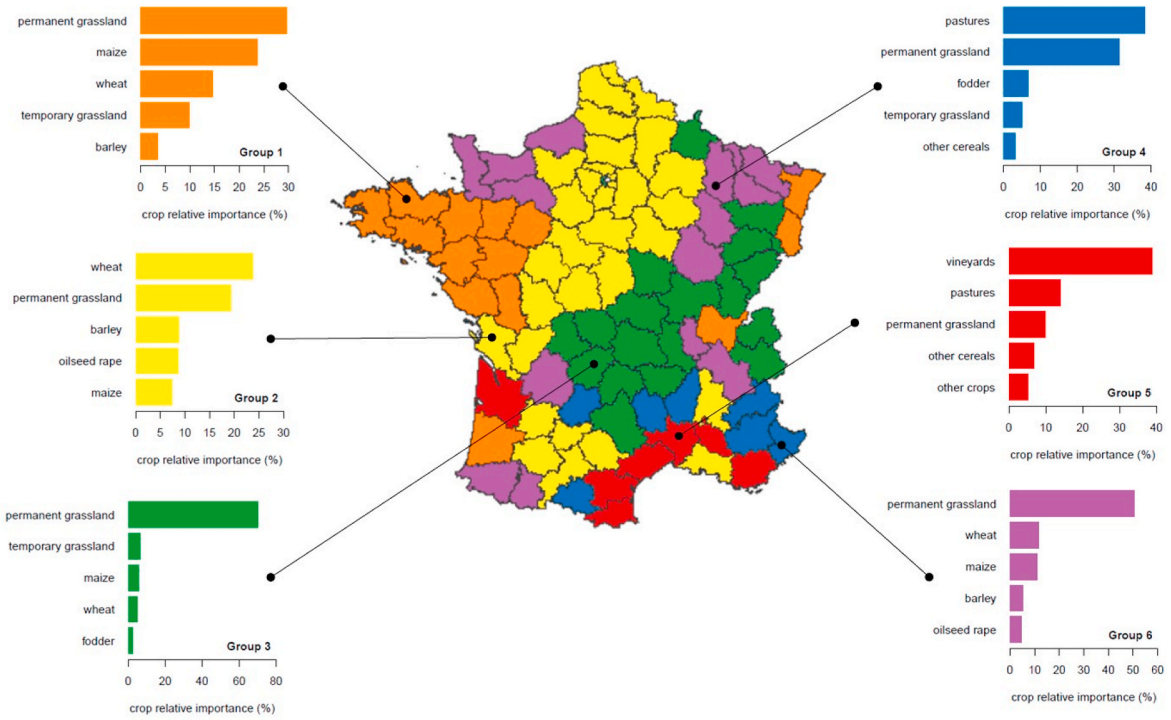


Fig. 5. Typology of French departments according to the relative importance of crop types within 150 m to residential buildings. Relative importance (excluding non-agricultural land uses) of the top-5 crop types are shown by group of departments.

departments where more intensively treated crops (e.g. vineyards in group 5) dominate close to housings. Although our results do not allow for a quantification of the exposure to pesticide of people living close to agricultural fields, we believe it provides an important step in this direction. Indeed, residents living close to treated fields might be exposed to pesticides through two main pathways: (i) spray drift, which occurs during pesticide application and depends on spraying material, crop height (drift being lower for small crops), and weather conditions during spraying [40,41], (ii) volatilization, which occurs after spraying (from a few days to several weeks) and is influenced by the physico-chemical characteristics of active compounds, environmental conditions (temperature, soil moisture, soil type, crop species), and agricultural management practices [42,43]. Coupling of our data with local crop-specific pesticides use might provide further insights into resident's exposure to pesticides, both at the national scale and in specific departments where intensively treated crops are closed to housings.

4.5. *Limits of the approach*

In this study, the best available data describing spatial organization

of crops and residential buildings were used. Nevertheless, some specific features of these data must be highlighted as they may slightly impact the results. First, the spatial accuracy of BD TOPO® data ranges between 2.5 m and 10 m [22]. This might lead to some error, especially over short distances like the 10 m buffer zone considered here, although it is hard to estimate if an over- or under-estimation is more likely.

Second, as explained above, the "use" attribute of buildings in the BD TOPO® data was not always reported, which led us to consider all buildings with "residential" and "undifferentiated" uses. This includes residential buildings and those with unknown uses, but excludes buildings with agricultural, commercial and service, industrial, religious and sports uses and annexes. This may lead to overestimate the agricultural area close to housings.

Third, the most recent data at time of the study were used, which are for the year 2018 for the French LPIS and 2019 for the BD TOPO®. This slight discrepancy should not affect our results as no major changes from one year to another for both types of data are expected. Crop rotations are used by farmers in France [44], but this is expected to have no significant impact on our results for the following reasons: (i) perennial crops like permanent grasslands (and to a lesser extent temporary grasslands that usually last 3–5 years), vineyards, orchards, and tree nuts are not subject to crop rotations; (ii) field crops like wheat, barley, rapeseed, and maize are indeed grown in rotation, but despite long-term shifts that occur on decadal time-scales (e.g. the rise in oilseed rape between 1990 and 2010), production areas of these crops remain pretty stable in the short-term (e.g. 3–5 years) at both national and local scales [15,45]. This suggests the probability for these crops to be grown close to residential buildings to be constant from one year to another. Therefore, the year 2018 can be considered representative of the period 2016–2020.

Fourth, the French LPIS data is based on farmers' declarations to the CAP, and some areas may not be declared for various reasons. In 2018, the French LPIS had a very good coverage for all field crops (98% of national production area) and tree nuts (94%), and a medium-good coverage for orchards (70%), vineyards (72%), and olive trees (66%) (Table A1). This might lead to an overestimation (resp. underestimation) of the proportion of national area under orchards, vineyards, and olive trees area that is close to housings if areas that are not declared are far from to (resp. close to) housings. This uncertainty is difficult to quantify but does not change the main conclusions presented here at the national scale. Indeed, assuming all non-declared areas are not within 150 m of residential buildings still gives high estimates of 32% of vineyards, 37% of orchards and 38% of olive trees within 150 m of residential buildings at the national scale. However, non-declared areas appear to be concentrated in a few departments: 52% of non-declared areas of vineyards, orchards and olive trees is located within 7 departments only (Gironde, Vaucluse, Hérault, Marne, Gard, Var, Aude) (Table A3). This may lead to some bias in the typology of departments according to the relative importance of crop types close to housings presented in Fig. 5, especially an underestimation of departments belonging to Group 5, in which vineyards is the dominant crop type close to housings. In support of this hypothesis is the fact that absolute values of non-declared areas are much higher for vineyards than orchards and olive trees at both national scale and local (i.e. department) scales (Table A3).

5. Conclusions

In this paper, the amount of agricultural land close to residential buildings in France was estimated using the best available data describing spatial organization of crop types (French LPIS) and residential buildings (BD TOPO®). The results revealed that 29% of national agricultural area was located within 150 m to residential buildings, a proportion that drops to 0.2% when a distance of 10 m to residential buildings is considered. Roughly, half of crops cultivated close to residential buildings are not treated (e.g. grasslands and pastures). The other half is dominated by wheat, maize, barley, oilseed rape and vineyards, although with substantial local variation. The large presence of treated crops, and intensively treated crops in some French departments, close to residential buildings requires attention for its potential effect on residents' exposure to pesticides. The proportion of crop-specific national area that is close to residential buildings is low at 10 m (0–1%), but increases rapidly with the distance to reach 10–58% across crop types at 150 m and is always higher for perennial crops (e.g. vineyards, orchards, olive trees) than annual crops. This suggests the implementation of pesticide-free buffer zones around housings may have a strong impact on agricultural production at the national scale because of likely associated yield and quality losses on large areas. This issue is especially important for perennial crops as they (i) are often grown close to housings, (ii) cannot easily be moved away from housings, (iii) display a high pesticide use intensity as compared to other crops, (iv) show a high probability of yield and quality losses associated to decreased pesticide use. Together, these results highlight the need to take into account local agricultural activities to address the issue of exposure to pesticides of people living close to agricultural fields; but also the high impact of potential large pesticide free buffer zones on French agricultural production.

CRediT authorship contribution statement

Nicolas Guilpart: Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis, Conceptualization. **Iris Bertin:** Writing – original draft, Visualization, Formal analysis, Data curation. **Muriel Valantin-Morison:** Writing – review & editing, Methodology. **Corentin Barbu:** Writing – review & editing, Methodology, Formal analysis, Data curation.

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.

Data availability

Data will be made available on request.

Acknowledgements

The authors thank Carole Bedos and Jean-Paul Douzals for stimulating discussions about this work. Nicolas Guilpart thanks Anne-Laurence Agenais for her initial suggestion to quantify the amount of agricultural land close to housings in a scientific way.

Appendices.

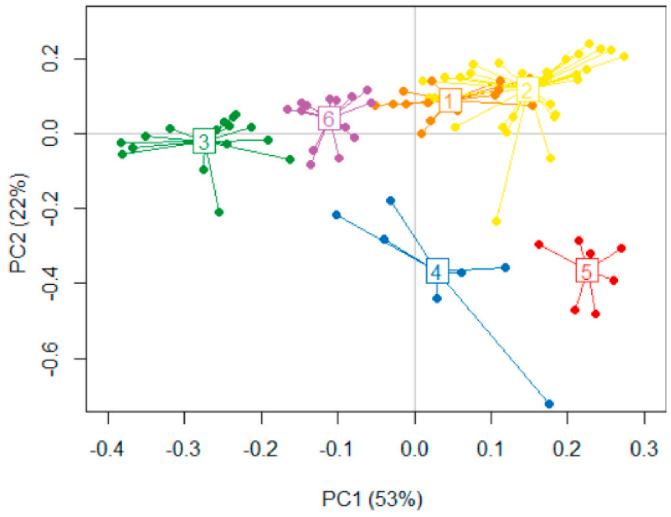


Fig. A1. Principal component analysis on the relative importance of crops within 150 m to residential buildings in French departments. Colors indicate the 6 groups of departments that were identified (see Figure A2).

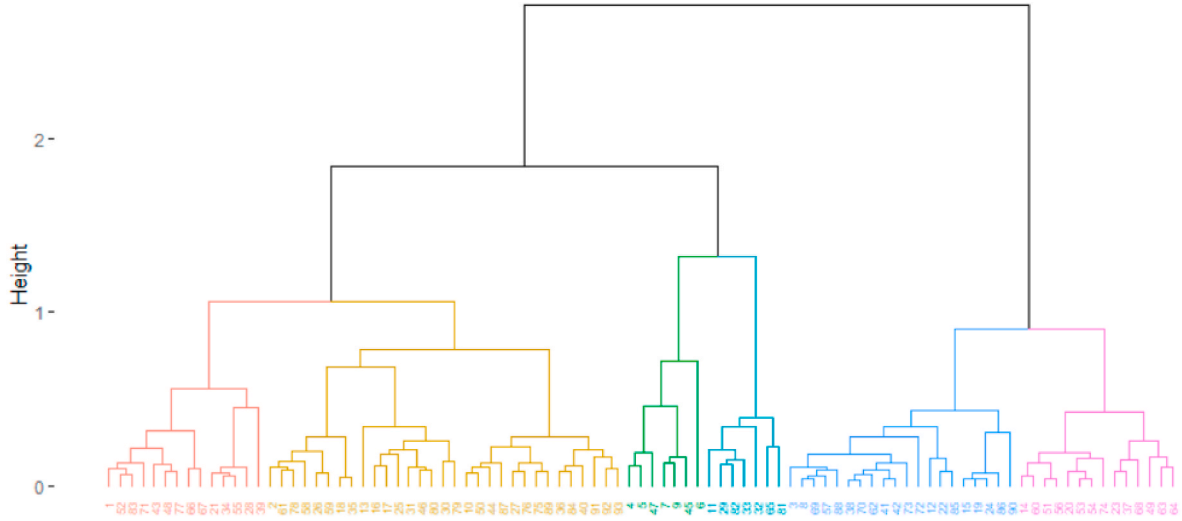


Fig. A2. Cluster dendrogram from the hierarchical ascendant clustering used to identify groups of French departments with similar relative importance of crops within 150 m to residential buildings. Colors indicate the 6 groups of departments that were identified.

Table A1
List of crop types and corresponding crop species, management (treated and non-treated), and share of national production area covered by LPIS data in 2018 (estimated by [21].

Crop type	Crops	Management	Share of national area covered by LPIS data in 2018
Wheat	Soft wheat	Treated	99,2%
Maize	Maize	Treated	99,0%
Barley	Barley	Treated	99,8%
Other cereals	Buckwheat, durum wheat, oats, rye, sorghum, spelt, triticale, other cereals	Treated	99,5%
Oilseed rape	Oilseed rape	Treated	99,5%
Sunflower	Sunflower	Treated	98,4%
Other oil crops	Peanut, non-textile linen, rape, soybean, other oil crops	Treated	98,7%
Protein-rich crops	Beans, faba bean, lupin, pea	Treated	98,1%
Fibre crops	Hemp, textile linen	Treated	99,4%
Set-aside land	Set-aside land	Non-treated	92,9%
Rice	Rice	Treated	100%
Grain legumes	Lentils, chickpea	Treated	99,9%
Pastures	Pastures	Non-treated	86,6%
Permanent grasslands	Permanent grasslands	Non-treated	85,8%
	Temporary grasslands	Non-treated	92,2%

(continued on next page)

Table A1 (*continued*)

Crop type	Crops	Management	Share of national area covered by LPIS data in 2018
Temporary grasslands			
Orchards	Citrus, small red berries, peach, plums, pears, apples, cherry	Treated	70,0%
Vineyards	Grapevine	Treated	72,5%
Tree nuts	Carob, chestnut, hazelnut, walnut, pistachio	Treated	94,8%
Olive trees	Olive trees	Treated	65,9%
Vegetables and flowers	Potato, greenhouse crops, open field vegetables, ornamental horticulture	Treated	92,0%
Other industrial crops	Non-fodder beet, aromatic plants, aromatic plants for perfume, medicinal plants, hops, tobacco, tomato	Treated	98,5%
Fodder	Fodder beet, forage carot, forage cabbage, temporary dactyl, temporary fescue, fodder grass, fodder lentil, forage lotus, fodder lupin, clover, sweet clover, alfalfa, fodder pea, other grasses, other annual fodder	Non-treated	98,6%
Other crops	Other crops	Non-treated	93,6%

Table A2

Pesticide use intensity of some selected crops in France. Pesticide use intensity is measured by the national-scale average treatment frequency index (TFI), which represents the number of full recommended doses of plant protection products applied per crop growing cycle. The higher the TFI, the higher the pesticide use intensity. Also shown is TFI by category of products: herbicides, fungicides, insecticides, seed coating and others. Data have been sorted by decreasing order of total TFI.

Crop species	Herbicides	Fungicides	Insecticides	Seed coating	Others	Total
Annual crops*						
Potato	2.5	11.7	1.4	0.8	0.3	16.5
Oilseed rape	1.9	1.1	2.1	0.8	0.4	6.4
Sugar beet	2.6	1.7	0.2	1	NA	5.5
Soft wheat	1.8	1.6	0.2	0.9	0.6	5.1
Pea	1.3	1.2	1.2	0.8	NA	4.6
Barley	1.7	1.1	0.1	0.9	0.5	4.4
Durum wheat	1.5	1.4	0.1	1	0.3	4.2
Fababean	1.1	0.8	0.6	0.5	0.1	3.2
Maize (grain)	1.6	NA	0.2	0.9	0.1	2.8
Sunflower	1.3	0.1	0.1	0.8	0.3	2.7
Triticale	1.2	0.5	0	0.8	0.1	2.6
Maize (green)	1.4	NA	0	0.9	NA	2.4
Soybean	1.5	NA	NA	0.1	0.1	1.8
Perennial crops**						
Apple	0.3	19.5	8.1	NA	1.6	29.5
Peach	0.4	10.4	7.4	NA	0	18.4
Vineyards***	0.4	10.1	1.8	NA	NA	12.4
Apricot	0.3	6.4	2.5	NA	0.1	9.3
Plum	0.2	4.9	3.1	NA	0.1	8.3
Cherry	0.2	3.9	4.0	NA	0.1	8.2

* Data for annual crops are for the year 2017. Source [46].
** Data for perennial crops (except vineyards) are for the year 2018. Source [47].
*** Data for vineyards are for the year 2019. Source [48].

Table A3

Estimation of area not included in the French LPIS for vineyards, orchards and olive trees in 2018. Data have been sorted by decreasing order of total area of vineyards, orchards, and olive trees. ***Source:*** [21].

Area		By crop type			Total (orchards + vineyards + olive trees)		
		Vineyards (ha)	Orchards (ha)	Olive trees (ha)	Total (ha)	Percentage of national total	Cumulative percentage
France		217707	44905	6383	268994	100%	100%
Department							
33	Gironde	38323	254	0	38576	14%	14%
84	Vaucluse	17702	4658	213	22573	8%	23%
34	Hérault	20762	696	468	21926	8%	31%
51	Marne	18305	6	0	18311	7%	38%
30	Gard	11426	3185	119	14730	5%	43%
83	Var	10210	1088	1906	13205	5%	48%
11	Aude	10502	260	120	10882	4%	52%
66	Pyrénées-Orientales	7845	2827	43	10715	4%	56%
69	Rhône	8210	640	0	8850	3%	59%
13	Bouches-du-Rhône	2263	5105	572	7940	3%	62%
26	Drôme	3927	3665	118	7710	3%	65%
71	Saône-et-Loire	6728	7	0	6735	3%	68%
21	Côte-d'Or	6347	58	0	6405	2%	70%
10	Aube	6030	54	0	6084	2%	72%
49	Maine-et-Loire	4151	518	0	4668	2%	74%

(*continued on next page*)

Table A3 (*continued*)

Area		By crop type			Total (orchards + vineyards + olive trees)		
		Vineyards (ha)	Orchards (ha)	Olive trees (ha)	Total (ha)	Percentage of national total	Cumulative percentage
24	Dordogne	2143	2309	0	4453	2%	76%
37	Indre-et-Loire	3614	162	0	3776	1%	77%
16	Charente	3559	208	0	3766	1%	79%
68	Haut-Rhin	3692	42	0	3734	1%	80%
7	Ardèche	2072	1460	30	3561	1%	81%
17	Charente-Maritime	3401	131	0	3532	1%	83%
82	Tarn-et-Garonne	474	2749	0	3223	1%	84%
44	Loire-Atlantique	2935	281	0	3216	1%	85%
47	Lot-et-Garonne	735	2225	0	2959	1%	86%
89	Yonne	2734	173	0	2907	1%	87%
2	Aisne	2768	117	0	2885	1%	88%
67	Bas-Rhin	2125	71	0	2196	1%	89%
18	Cher	2026	163	0	2189	1%	90%
2B	Haute-Corse	1249	518	341	2108	1%	91%
38	Isère	231	1832	0	2063	1%	91%
6	Alpes-Maritimes	60	44	1463	1567	1%	92%
39	Jura	1477	11	0	1488	1%	93%
46	Lot	880	243	0	1123	0%	93%
4	Alpes-de-Haute Provence	249	281	592	1123	0%	93%
41	Loir-et-Cher	1070	50	0	1120	0%	94%
14	Calvados	0	1090	0	1090	0%	94%
58	Nièvre	1016	8	0	1024	0%	95%
32	Gers	815	200	0	1015	0%	95%
35	Ille-et-Vilaine	0	961	0	961	0%	95%
73	Savoie	750	91	0	841	0%	96%
81	Tarn	614	203	0	816	0%	96%
42	Loire	302	384	0	687	0%	96%
72	Sarthe	206	452	0	658	0%	96%
85	Vendée	419	233	0	652	0%	97%
64	Pyrénées-Atlantiques	352	214	0	566	0%	97%
1	Ain	447	44	0	491	0%	97%
19	Corrèze	66	401	0	467	0%	97%
86	Vienne	392	72	0	464	0%	97%
76	Seine-Maritime	0	433	0	433	0%	98%
40	Landes	211	197	0	408	0%	98%
31	Haute-Garonne	226	165	0	391	0%	98%
45	Loiret	84	295	0	379	0%	98%
79	Deux-Sèvres	225	117	0	342	0%	98%
22	Côtes d'Armor	0	335	0	335	0%	98%
74	Haute-Savoie	182	96	0	279	0%	98%
29	Finistère	0	262	0	262	0%	98%
27	Eure	0	256	0	256	0%	99%
23	Creuse	2	1	244	246	0%	99%
61	Orne	0	245	0	245	0%	99%
12	Aveyron	100	145	0	245	0%	99%
63	Puy-de-Dôme	204	40	0	245	0%	99%
95	Val-d'Oise	0	231	0	231	0%	99%
2A	Corse-du-Sud	137	12	71	219	0%	99%
5	Hautes-Alpes	28	103	82	214	0%	99%
77	Seine-et-Marne	66	140	0	206	0%	99%
56	Morbihan	1	173	0	174	0%	99%
53	Mayenne	0	164	0	164	0%	99%
36	Indre	135	28	0	163	0%	99%
52	Haute-Marne	110	47	0	157	0%	99%
87	Haute-Vienne	3	134	0	137	0%	100%
55	Meuse	4	130	0	134	0%	100%
9	Ariège	8	112	0	120	0%	100%
70	Haute-Saône	75	39	0	114	0%	100%
59	Nord	0	101	0	101	0%	100%
50	Manche	0	101	0	101	0%	100%
54	Meurthe-et-Moselle	50	45	0	94	0%	100%
57	Moselle	70	20	0	90	0%	100%
65	Hautes-Pyrénées	69	3	0	72	0%	100%
60	Oise	0	65	0	65	0%	100%
28	Eure-et-Loir	1	63	0	64	0%	100%
3	Allier	59	0	0	59	0%	100%
78	Yvelines	1	46	0	46	0%	100%
80	Somme	0	34	0	34	0%	100%
88	Vosges	23	10	0	33	0%	100%
25	Doubs	17	15	0	32	0%	100%
8	Ardennes	0	26	0	27	0%	100%
62	Pas-de-Calais	0	18	0	18	0%	100%
91	Essonne	0	12	0	12	0%	100%
43	Haute-Loire	9	0	0	9	0%	100%

(*continued on next page*)

Table A3 (*continued*)

Area		By crop type			Total (orchards + vineyards + olive trees)		
		Vineyards (ha)	Orchards (ha)	Olive trees (ha)	Total (ha)	Percentage of national total	Cumulative percentage
15	Cantal	3	1	0	4	0%	100%
90	Territoire de Belfort	0	3	0	3	0%	100%
93	Seine-Saint-Denis	0	0	0	0	0%	100%
94	Val-de-Marne	0	0	0	0	0%	100%
48	Lozère	0	0	0	0	0%	100%

References

[1] Serge Savary, Laetitia Willocquet, Sarah Jane Pethybridge, Esker Paul, Neil Mcroberts, Andy Nelson, The global burden of pathogens and pests on major food crops, NAt. Ecol. Evol. 3 (March) (2019) 430–439.

[2] Flavia Geiger, Bengtsson Jan, Berendse Frank, Wolfgang W. Weisser, Mark Emmerson, Manuel B. Morales, Piotr Ceryngier, Jaan Liira, Tscharntke Teja, Camilla Winqvist, Sönke Eggers, Riccardo Bommarco, Pärt Tomas, Bretagnolle Vincent, Manuel Plantegenest, Lars W. Clement, Christopher Dennis, Catherine Palmer, Juan J. Oñate, Irene Guerrero, Violetta Hawro, Tsipe Aavik, Carsten Thies, Andreas Flohre, Sebastian Hänke, Christina Fischer, Paul W. Goedhart, Pablo Inchausti, Persistent negative effects of pesticides on biodiversity and biological control potential on European farmland, Basic Appl. Ecol. 11 (2) (2010) 97–105.

[3] F.H. Tang, M. Lenzen, A. McBratney, F. Maggi, Risk of pesticide pollution at the global scale, Nat. Geosci. 14 (4) (2021) 206–210.

[4] Ki-hyun Kim, Ehsanul Kabir, Shamin Ara Jaha, Exposure to pesticides and the associated human health effects, Sci. Total Environ. 575 (2017) 525–535.

[5] Polyxeni Nicolopoulou-Stamati, Sotirios Maipas, Chrysanthi Kotampasi, Panagiotis Stamatis, Luc Hens, Chemical pesticides and human health: the urgent need for a new concept in agriculture, Front. Public Health 4 (July) (2016) 1–8.

[6] Anon. n.d. "Arrêté Du 27 Décembre 2019 Relatif Aux Mesures de Protection Des Personnes Lors de l'utilisation de Produits Phytopharmaceutiques et Modifiant l'arrêté Du 4 Mai 2017 Relatif à La Mise Sur Le Marché et à l'utilisation Des Produits Phytopharmaceutiques et de leurs adjuvants visés à l'article L. 253-1 du code rural et de la pêche maritime." Journal Officiel de La République Française N°03-02 du 29 décembre 2019. NOR: AGRG1937165A. https://www.legifrance.gouv.fr/eli/arrete/2019/12/27/AGRG1937165A/jo/texte.

[7] USDA, New French Pesticide Buffer Zone Regulation Angers French Farmers and NGOs, 2020.

[8] Reuters, French Farm Minister Says against 150m-wide Pesticide Buffer Zones, Reuters, 2019.

[9] Clémentine Dereumeaux, Clémence Fillol, Philippe Quenel, Sébastien Denys, Environmental Health, Santé Publique France, and Saint Maurice Cedex, Pesticide exposures for residents living close to agricultural lands : a review, Environ. Int. 134 (May 2019) (2020), 105210.

[10] Raphaëlle Teysseire, Guyguy Manangama, Isabelle Baldi, Camille Carles, Patrick Brochard, Carole Bedos, Fleur Delva, Assessment of residential exposures to agricultural pesticides : a scoping review, PLoS One 15 (4) (2020), e0232258.

[11] Raphaëlle Teysseire, Guyguy Manangama, Isabelle Baldi, Camille Carles, Patrick Brochard, Carole Bedos, Fleur Delva, Determinants of non-dietary exposure to agricultural pesticides in populations living close to fields : a systematic review, Sci. Total Environ. 761 (2021), 143294.

[12] Rémi Béranger, Elise Billoir, John R. Nuckols, Jeffrey Blain, Maurice Millet, Marie-laure Bayle, Bruno Combourieu, Thierry Philip, Joachim Schüz, Beatrice Fervers, Agricultural and domestic pesticides in house dust from different agricultural areas in France, Environ. Sci. Pollut. Control Ser. 26 (19) (2019) 19632–19645.

[13] Nicole C. Deziel, Laura E. Beane Freeman, Barry I. Graubard, Rena R. Jones, Jane A. Hoppin, Kent Thomas, Cynthia J. Hines, Aaron Blair, Dale P. Sandler, Honglei Chen, Jay H. Lubin, Gabriella Andreotti, Michael C.R. Alavanja, Melissa C. Friesen, Relative contributions of agricultural drift , para-occupational , and residential use exposure pathways to house dust pesticide concentrations : meta-regression of published data, Environ. Health Perspective. 296 (3) (2017) 296–305.

[14] Mary H. Ward, Jay Lubin, James Giglierano, Joanne S. Colt, Calvin Wolter, Nural Bekiroglu, David Camann, Patricia Hartge, R. John, Nuckols, Proximity to crops and residential exposure to agricultural herbicides in Iowa, Environ. Health Perspective. 114 (6) (2006) 893–897.

[15] Nicolas Urruty, Tanguy Deveaud, Hervé Guyomard, Boiffin Jean, Impacts of agricultural land use changes on pesticide use in French agriculture, Eur. J. Agron. 80 (2016) 113–123.

[16] Blanche Collard, Corentin Barbu, Rémy Ballot, Thomas Poméon, Philippe Martin, Christian Dron, Analyse Des Variations Interannuelles Des Ventes de Produits Phytosanitaires et de l'indicateur NODU: Rapport Du Projet AVINODU, 2020.

[17] Laurence Guichard, François Dedieu, Marie-hélène Jeuffroy, Jean-marc Meynard, Reau Raymond, Isabelle Savini, Le Plan Ecophyto de Réduction d'usage Des Pesticides En France : Décryptage d'un Échec et Raisons d'espérer, Cah. Agric. 26 (2017), 14002.

[18] Laure Hossard, Laurence Guichard, Céline Pelosi, David Makowski, Lack of evidence for a decrease in synthetic pesticide use on the main arable crops in France, Sci. Total Environ. 575 (2017) 152–161.

[19] Thomas Delaune, Malick S. Ouattara, Rémy Ballot, Christophe Sausse, Irène Felix, Fabienne Maupas, Mathilde Chen, Muriel Morison, David Makowski, Corentin Barbu, Landscape drivers of pests and pathogens abundance in arable crops, Ecography 44 (2021) 1429–1442.

[20] F. Levavasseur, P. Martin, C. Bouty, A. Barbottin, V. Bretagnolle, O. Thérond, O. Scheurer, N. Piskiewicz, RPG explorer: a new tool to ease the analysis of agricultural landscape dynamics with the land parcel identification system, Comput. Electron. Agric. 127 (2016) 541–552.

[21] P. Cantelaube, B. Lardot, Construction d'une Base de Données Géographiques à Échelle Fine Exhaustive Sur l'occupation Agricole Du Sol : Le « RPG Complété ». Partie 2 : Attribution Des Cultures Aux Parcelles Susceptibles d'accueillir Les Surfaces Agricoles Hors RPG, 2021. *Version 1. Note*.

[22] IGN, BD TOPO® Version 3.0 - Descriptif de Contenu - Juillet 2019, 2019.

[23] Edzer Pebesma, Simple features for R: standardized support for spatial vector data, R Journal 10 (1) (2018) 439–446.

[24] Jari Oksanen, Guillaume F. Blanchet, Michael Friendly, Roeland Kindt, Pierre Legendre, Dan Mcglinn, Peter R. Minchin, R.B.O. Hara, Gavin L. Simpson, Solymos Peter, M. Henry H. Stevens, Eduard Szoecs, Package 'vegan, Commun. Ecol. Package. (2013). Version 2(9).

[25] M. Maechler, P. Rousseeuw, A. Struyf, M. Hubert, K. Hornik, Cluster: cluster Analysis basics and extensions, R Package (2013). *Version 1.14.4*.

[26] A. Calonnec, P. Cartolaro, C. Poupot, D. Dubourdieu, P. Darriet, Effects of uncinula necator on the yield and quality of grapes (vitis vinifera) and wine, Plant Pathol. 53 (4) (2004).

[27] Cesare Gessler, Ilaria Pertot, Michele Perazzolli, *Plasmopara viticola* : a review of knowledge on downy mildew of grapevine and effective disease management, Phytopathol. Mediterr. 50 (1) (2011) 3–44.

[28] Christopher C. Steel, John W. Blackman, Leigh M. Schmidtke, Grapevine bunch rots: impacts on wine composition, quality, and potential procedures for the removal of wine faults, J. Agric. Food Chem. 61 (22) (2013) 5189–5206.

[29] I. Pertot, T. Caffi, V. Rossi, L. Mugnai, C. Hoffmann, M.S. Grando, C. Gary, D. Lafond, C. Duso, D. Thiery, V. Mazzoni, G. Anfora, A critical review of plant protection tools for reducing pesticide use on grapevine and new perspectives for the implementation of IPM in viticulture, Crop Protect. 97 (2017) 70–84.

[30] Florine Mailly, Laure Hossard, Jean-marc Barbier, Marie Thiollet-scholtus, Christian Gary, Quantifying the impact of crop protection practices on pesticide use in wine-growing systems, Eur. J. Agron. 84 (2017) 23–34.

[31] Esther Fouillet, Delière Laurent, Nicolas Chartier, Nicolas Munier-Jolain, Sébastien Cortel, Bruno Rapidel, Anne Merot, Reducing pesticide use in vineyards. Evidence from the analysis of the French DEPHY network, Eur. J. Agron. 136 (March) (2022), 126503.

[32] INSEE, Comptes Nationaux de l'agriculture En 2018, 2019.

[33] L. Hossard, A. Philibert, M. Bertrand, C. Colnenne-David, P. Debaeke, N. Munier-Jolain, M.H. Jeuffroy, G. Richard, D. Makowski, Effects of halving pesticide use on wheat production, Sci. Rep. 4 (2014) 4405.

[34] Martin Lechenet, David Makowski, Py Guillaume, Nicolas Munier-Jolain, Profiling farming management strategies with contrasting pesticide use in France, Agric. Syst. 149 (2016) 40–53.

[35] Martin Lechenet, Fabrice Dessaint, Py Guillaume, David Makowski, Nicolas Munier-Jolain, Reducing pesticide use while preserving crop productivity and profitability on arable farms, Nature Plants 3 (March) (2017) 1–6.

[36] Charlie C. Nicholson, Neal M. Williams, Cropland heterogeneity drives frequency and intensity of pesticide use, Environ. Res. 16 (2021), 074008.

[37] Mathilde Chen, François Brun, Marc Raynal, David Makowski, Delaying the first grapevine fungicide application reduces exposure on operators by half, Sci. Rep. 10 (1) (2020) 1–12.

[38] Laurent Delière, Philippe Cartolaro, Léger Bertrand, Naud Olivier, Field evaluation of an expertise-based formal decision system for fungicide management of grapevine downy and powdery mildews, Pest Manag. Sci. 71 (9) (2015) 1247–1257.

[39] Lucile Muneret, Denis Thiéry, Benjamin Joubard, Adrien Rusch, Deployment of organic farming at a landscape scale maintains low pest infestation and high crop productivity levels in vineyards, J. Appl. Ecol. 55 (3) (2018) 1516–1525.

[40] Jenny Kreuger, Tommy Arvidsson, Lars Bergstr, Spray drift as influenced by meteorological and technical factors, Pest Manag. Sci. 67 (2011) 586–598.

[41] Ohad Zivan, Yardena Bohbot-Raviv, Yael Dubowski, Primary and secondary pesticide drift profiles from a peach orchard, Chemosphere 177 (2017) 303–310.

[42] Carole Bedos, Pierre Cellier, Raoul Calvet, Enrique Barriuso, Benoît Gabrielle, Mass transfer of pesticides into the atmosphere by volatilization from soils and plants : overview, Agronomie 22 (2002) 21–33.

[43] Laure Mamy, Bonnot Kevin, Pierre Benoit, Christian Bockstaller, Eric Latrille, Virginie Rossard, Dominique Patureau, Carole Bedos, Assessment of pesticides volatilization potential based on their molecular properties using the TyPol tool, J. Hazard Mater. 415 (2021), 125613.
[44] Benjamin Nowak, Audrey Michaud, Gaëlle Marliac, Assessment of the diversity of crop rotations based on network analysis indicators, Agric. Syst. 199 (January) (2022), 103402.
[45] Céline Schott, Catherine Mignolet, Jean Marc Meynard, Les Oléoprotéagineux Dans Les Systèmes de Culture: Évolution Des Assolements et Des Successions Culturales Depuis Les Années 1970 Dans Le Bassin de La Seine, OCL - Oleagineux Corps Gras Lipides 17 (5) (2010) 276–291.
[46] Agreste, Pratiques Culturales En Grandes Cultures 2017 - IFT et Nombre de Traitements, Chiffres et Données 3 (2019) 30.
[47] Agreste, Enquête Pratiques Phytosanitaires En Arboriculture En 2018 - IFT et Nombre de Traitements, Chiffres & Données 8 (2021) 12.
[48] Agreste, Enquête Pratiques Culturales En Viticulture En 2019 - IFT et Nombre de Traitements, Chiffres & Données 19 (2021) 13.