Mapping cropping systems and associated practices to characterize pesticide pollution over time

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Technical note

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Abstract.
To study the impact of pesticide uses in agriculture on human health, data on the types and quantities of pesticide active substances introduced into the environment over a long period of time are needed. However, when there is no systematic or available written records of pesticide applications, the characterization of environmental contamination remains challenging. In this technical note, we propose a method to organize heterogeneous information to represent the spatial dynamics of pesticide uses, with the case of Guadeloupe, French West Indies. Based on various data sources (paper maps, digital geographic data, articles and technical reports, pesticide products information, interviews), different databases were built: i) a land use database (1969-2019), with maps of the main three groups of crops in Guadeloupe: banana, sugar cane and market gardening; ii) a database of agricultural practices regarding the use of pesticides and their evolution over time for these groups of crops; iii) a database of available active substances according to time.
Homogenized datasets of banana, sugar cane and market gardening plots allow to visualize the crop distribution at different periods of time and the evolution trend of cultivated areas. The database on agricultural practices regarding the use of pesticide includes the description of different 'pesticide itineraries' - characterized by information on the cropping system and on the schedule of pesticide applications, and their evolution through time. The database on active substances includes two types of information: for each year since 1960, the characteristics of authorized active substances based on regulation, and of available active substances, based on farmers' practices in Guadeloupe. All databases are made available on an open data repository; they will be used to derive indicators of pesticide pressure and study the link between cancer cases and the presence of pesticides in the environment.

Key words: geographic mapping; geographic information systems; crop production; environmental pollution; Guadeloupe.

Résumé.
Cartographie des zones agricoles et des pratiques associées pour caractériser la pollution par les pesticides sur le long terme
Pour étudier l'impact de l'utilisation des pesticides dans l'agriculture sur la santé humaine, des données sur les substances actives introduites dans l'environnement sont nécessaires. Cependant, en l'absence d'enregistrement systématique des traitements effectués, la caractérisation de la contamination de l'environnement par les pesticides demeure un défi. Dans cette note technique, nous proposons une méthode pour représenter la dynamique spatiale des utilisations de pesticides à partir de sources de données hétérogènes, avec la Guadeloupe comme cas d'étude.
À partir de différentes sources de données (cartes en papier et numériques, articles, rapports techniques, informations sur les produits pesticides, enquêtes), différentes bases de données ont été construites : i) une base de données d'occupation des sols (1969-2019) pour les trois principaux systèmes de culture en Guadeloupe : banane, canne à sucre et

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maraîchage ; ii) une base de données sur les pratiques agricoles concernant l'utilisation des pesticides pour ces groupes de cultures ; iii) une base de données sur les substances actives disponibles.

Les jeux de données homogénéisés des parcelles de banane, canne à sucre et maraîchage permettent de visualiser la répartition des cultures à différentes dates. La base de données sur les pratiques agricoles concernant l'utilisation des pesticides comprend la description de différents « itinéraires pesticides », caractérisés par des informations sur le système de culture et sur le calendrier des applications de pesticides, qui ont évolué au cours du temps. La base de données sur les substances actives comprend deux types d'informations : pour chaque année depuis 1960, les caractéristiques des substances actives autorisées par la réglementation, et des substances actives disponibles, basées sur les pratiques des agriculteurs en Guadeloupe. Toutes les données produites sont mises à disposition sur un dépôt de données ouvert ; elles seront utilisées pour calculer des indicateurs de pression pesticide et étudier leur lien éventuel avec les cas de cancer.

Mots clés : *cartographie géographique ; systèmes d'information géographique ; production végétale ; pollution de l'environnement ; Guadeloupe.*

The use of pesticides in agriculture represents a proven risk to the health of users and population volatilisation [1]. To highlight this risk and identify mitigation measures, there is a need for risk assessment models using multiple scenarios, representative of a wide range of agricultural practices, soil and climatic contexts, at landscape level [2]. However, the development of such models remains a challenging task, notably because most of pesticide impacts are observed over the long term, with a time lag in which great variations in the factors determining the exposure of people can occur. These variations depend mainly on the types and quantities of pesticides introduced into the environment, which are determined by regulations (*i.e.* approval and withdrawal of active substances) and technical choices (*e.g.* type, frequency, dose and mode of application of pesticides).

However, determining how pesticides have been used over time is a challenge, as there are generally no systematic or available written records of pesticide applications. An approach is to consider variables that may act as proxies: it is the case for land use, a key variable in the assessment of pesticide pressures at the territory scale [3], as the cropping orientation of plots largely determines their use [4]. This approach requires both land use maps and information on pesticide applications on each crop. Land use maps are nowadays easily available in several countries, notably through the development of Earth Observation systems using satellite imagery. In France, a geographic database of agriculture areas is provided annually since 2010, based on the data reported by farmers (RPG - Graphical Parcel Register, database available from https://geoservices.ign.fr/rpg). However, digital land use maps are often not available for older periods. On the other hand, references about pesticide applications on crops are heterogeneous; they comprise public surveys about agricultural practices [5] and grey documentation in support services.

In this context, the aim of this technical note is to propose a method to organize heterogeneous available information in order to represent the spatial dynamics of pesticide uses. The case of pesticide application in Guadeloupe, French West Indies, was chosen. In this region, the issue of pesticides is of great importance due to the use of the organochlorine insecticide chlordecone and its impact on the development of cancers [6]. Three databases were built from different data sources: *i)* a land use database built from ancient and recent land use maps; *ii)* a database of agricultural practices regarding the use of pesticides and their evolution over 50 years for the main three groups of crops in Guadeloupe: banana, sugar cane and market gardening; *iii)* a database of available active substances according to time.

Materials and methods

Study area

Guadeloupe (1,434 km^2 and 387,629 inhabitants in 2018) is a French overseas department located in the Caribbean *(figure 1)*. It comprises two main islands (Basse-Terre and Grande-Terre). The climate is tropical. Rainfall shows great variability according to the geographical area and elevation which varies from sea-level to 1,467 meters at the top of the active volcano 'La Soufrière'. Accordingly, annual cumulative amounts range from 950 mm (on the eastern side of Grande-Terre and on the western coast of Basse-Terre), to more than 10,000 mm at the highest altitudes of Basse-Terre. Minimum temperatures are comprised between 20 and 24°C and maximum temperatures between 30 and 32°C all year long. There are three main types of soil: highland andosols, lowland nitisols and ferralsols. All of these soils have a high

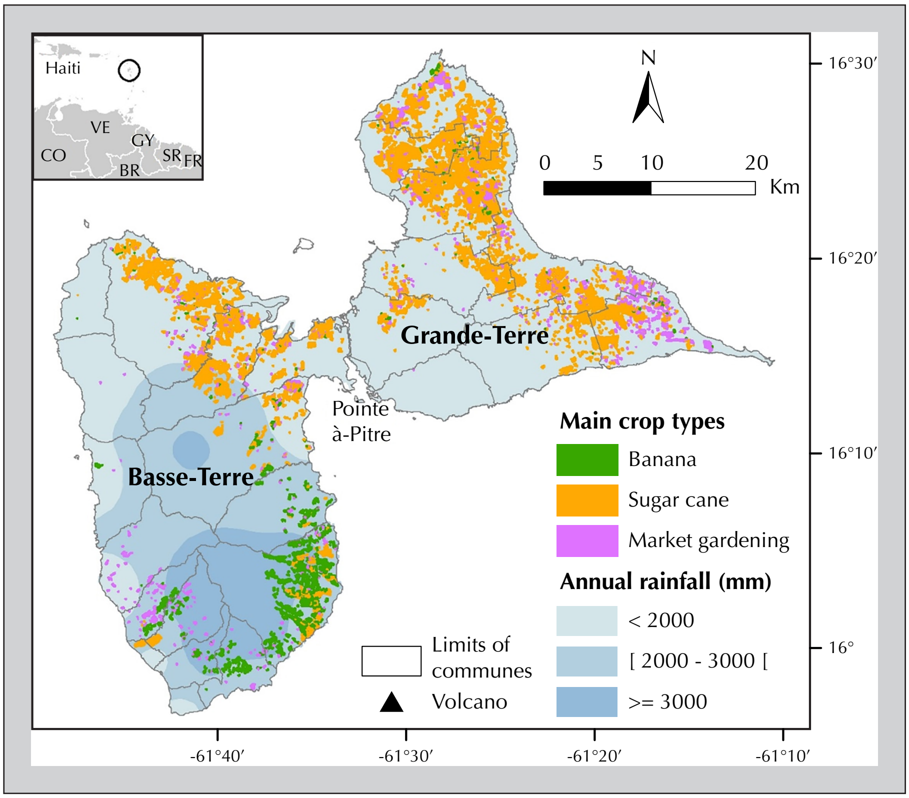

Figure 1. Location of Guadeloupe island (French West Indies). Guadeloupe main island is part of the Caribbean archipelago, 600 km north of Venezuela (VE: Venezuela, CO: Columbia, SR: Suriname, GY: Guyana, FR: French Guiana, BR: Brazil).
Sources of geographic data: National Geographic Institute, RPG - Graphical Parcel Register for the main crop types and BD TOPO data for the limits of communes (https://geoservices.ign.fr/); Meteo-France, annual rainfall (https://catalogue.karugeo.fr/geonetwork/srv/api/records/5f0b8549-a0c8-4329-9019-cf85ce718652).

Figure 1. *Localisation de l'île de la Guadeloupe (Antilles françaises). L'île principale de la Guadeloupe fait partie de l'archipel des Caraïbes, à 600 km au nord du Venezuela (VE : Venezuela, CO : Colombie, SR : Suriname, GY : Guyana, FR : Guyane française, BR : Brésil). Sources des données géographiques : Institut géographique national, RPG - Registre parcellaire graphique pour les principaux types de cultures et BD TOPO pour les limites de communes (https://geoservices.ign.fr/) ; Météo-France, pluviométrie annuelle (https://catalogue.karugeo.fr/geonetwork/srv/api/records/5f0b8549-a0c8-4329-9019-cf85ce718652).*

carbon content (over 2%), which favor soil retention of pesticides. Agricultural area (29,811 ha) is mainly composed of industrial crops including sugarcane (43%), grasslands (33%), and orchards and banana (10%) [7].

Mapping cropping systems

The use of pesticide products mainly depends on the cropping system. Several data sources, including old paper maps and recent digital databases, were used to map agricultural areas at different periods of time *(table 1)*.

Paper maps have been digitized and georeferenced to be integrated into a Geographic Information System (GIS) environment. Then, vectorization tools have been used to convert the scanned images (TIF format) into vector-based feature layers (shapefile format) (software: ESRI ArcMap and ArcScan Extension, Redlands, CA, USA). The different vectorization main tasks include: *i)* raster classification and cleaning – this step is used to extract the pixels corresponding to the contours of the agricultural plots; *ii)* conversion from raster to polylines and error correction; *iii)* conversion from polylines to polygons and error correction; *iv)* labelling. All tasks have been automated as much as possible but they all include a cleaning/checking step requiring user intervention.

Finally, the typology of the different maps - the geographic layers derived from paper maps and the more recent digital databases - has been homogenized for comparison *(figure 2)*. It includes three main crop classes: sugar cane, banana, and market gardening.

Table 1. Characteristics and sources of land cover maps.

***Tableau 1**. Caractéristiques et sources des cartes d'occupation du sol.*

Year / period	Format	Source
1969	Paper	National Geographic Institute
1987	Paper	Direction de l'alimentation, de l'agriculture et de la forêt (DAAF) – Guadeloupe, Ministry of Agriculture
2004 - 2010	Digital (shapefile)	AGRIGUA [16]
2010 - 2019	Digital (shapefile)	National Geographic Institute (https://geoservices.ign.fr/rpg)

Construction of a relational database to describe the uses of pesticides over time

For the three main groups of crops in Guadeloupe (banana, sugar cane and market gardening), a relational database was constructed to describe the use of pesticides and its evolution over time. We proposed the concept of pesticide itineraries (PI) to describe pesticide use on a crop group and its evolution. It can be characterized by two main types of information stored in different related tables *(figure 3)*:

- the characteristics of the cropping system relative to a PI: minimum and maximum duration of cultivation of a plot; length of fallow period; start, end and decline year of the PI considering that different PIs may follow each other over time, with newer ones progressively replacing older ones from the time of their introductions;
- the schedule of pesticide applications relative to a PI and carried out on a plot yearly: for each crop species, the application type (*e.g.,* treatment of the aerial parts of the plant, soil treatment, weeding, …), the target (*e.g.* cercosporiosis, soil insects, weeds, …), the pesticide type (*i.e.* fungicide, insecticide, or herbicide, ...) and the application modes (*e.g.* percentage of treated surface plot) and dates.

The PI database was filled with the information collected from literature review (including technical reports from Agriculture council, farming groups…), and interviews of farmers and agricultural technicians. For the banana cropping system, a lot of information on the use of pesticides was available from the MatPhyto database developed by Santé Publique France [8]. The variation of pesticide uses preferences across years in the MatPhyto database allowed identifying and characterizing the main PI.

The consistency of these PI was then verified through interviews of farmers working for a long time in banana cultivation (6), one agricultural technician, and one expert from academic research. Regarding sugar cane and market gardening crop systems, less documentation was available - the definitions of the PI were mainly obtained from literature review and interviews of farmers (11 for sugar cane and 10 for market gardening), agricultural technicians (5 for sugar cane and 6 for market gardening), and, one crop manager of a sugar factory.

Pesticide products and active substances database

To deal with heterogeneous and partial information on the use of pesticides over time in the three main cropping systems in Guadeloupe, two complementary approaches have been adopted.

The first one can be described as comprehensive and regulatory, and aims to identify the different pesticides potentially used through time. It is based on E-Phy - Anses database freely available from the French government website [9]. This database provides all the data on pesticide products with a marketing authorization in France since 1942. From the E-Phy database, which includes a total of 10 tables (csv format), we used the two tables 'products.csv' and 'products_uses.csv'. The following information was first extracted for all pesticide products: product name, crop species, target, product application dose (expressed in g/ha or in g/plant), active substance name, active substance concentration, marketing authorization date, and withdrawal date. Of note, a pesticide product can be described by several rows as a pesticide product may contain several active substances or its use may be allowed against several pests (targets) and/or for several crop species. On the other hand, many products may contain the same active substance. Product application doses were converted to active substance doses accounting for the concentration of active substance. Second, pesticide product information was summarized by year and active substance in a unique table, describing for each crop species, each application target and each year the available active substances and their mean recommended application dose. Finally, the previous table was filtered according to the crop species actually grown in Guadeloupe for the main cropping systems (banana, sugar cane, market gardening).

The second approach can be described as 'agronomic' as it is based on farmers' practices. It aims at a more

Figure 2. Illustration of the mapping process of two main crop types, Capesterre-Belle-Eau area, Guadeloupe, 1969-2019. Original paper maps (A, B) were digitized and processed within a GIS environment (C, D) to provide harmonized information with recent digital databases (E, F).

Figure 2. *Illustration du processus de cartographie des deux principaux types de cultures, région de Capesterre-Belle-Eau, Guadeloupe, 1969-2019. Les cartes papier originales (A, B) ont été numérisées et traitées dans un environnement SIG (C, D) pour fournir des informations harmonisées avec les bases de données numériques récentes (E, F).*

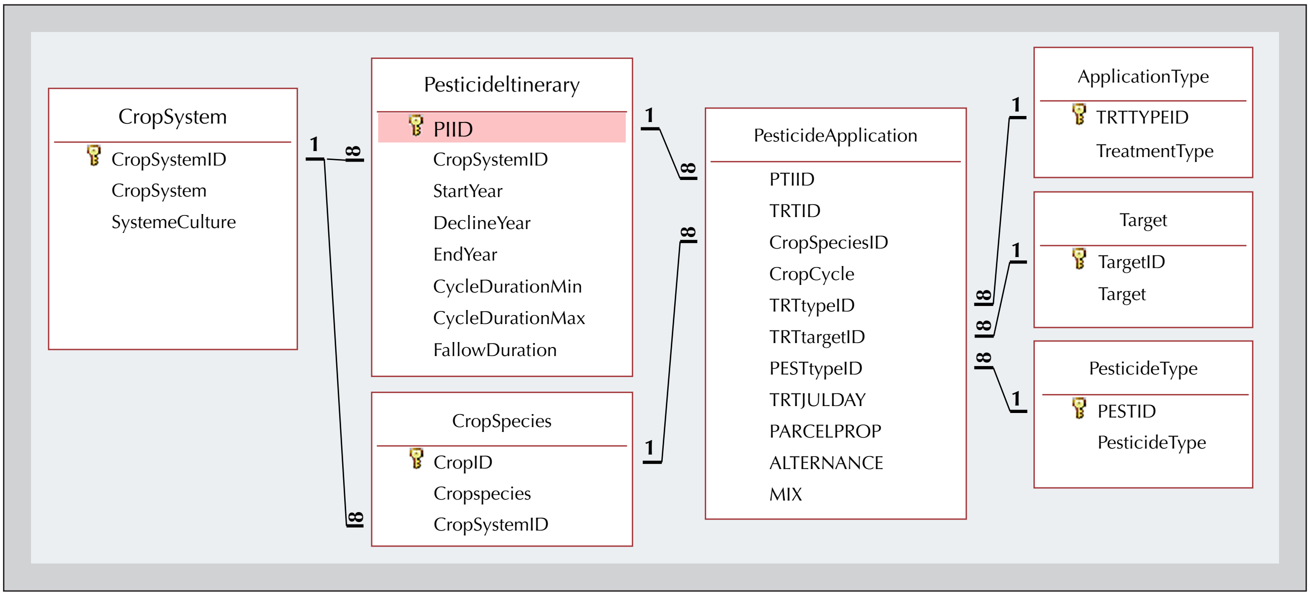

Figure 3. Database structure for the description of pesticide technical itineraries of different crop systems.

Figure 3. *Structure de la base de données pour la description des itinéraires techniques des pesticides dans différents systèmes de culture.*

precise description of the use of pesticides, notably by introducing the notion of preference of use for certain pesticides over others. Different data sources were used. Regarding the banana cropping system, data were extracted from MatPhyto database developed by Santé Publique France [8]. For each year from 1960 to 2015, this database lists the names of the active substances used in banana field, the frequency and dose of use, and the annual proportion of farmers who used a given active substance. For sugarcane and market gardening systems, the data were obtained from interviews with farmers and agricultural advisors. The products actually used in Guadeloupe, and the corresponding active substances, were thus listed. These agronomic databases of pesticide products and active substances are closely linked to the construction of the pesticide itineraries database: for banana, the variation of pesticide use preferences across years in the MatPhyto database allowed the dating of PI changes; for other crops, pesticide and PI information were collected during the same surveys.

Results

Land use database

Homogenized datasets of banana, sugar cane and market gardening plots allow to visualize the crop distribution at different periods of time and the evolution trend of cultivated areas. In Guadeloupe Island, over a 50-year period, cultivated surfaces strongly decreased *(figure 4)*. In the recent years, a sudden and important decrease of cultivated surfaces occurred in 2018 - possibly because of the impact of 'Maria' hurricane the year before *(figure 4)*.

Datasets of sugar cane, banana and market gardening plots digitized from 1969 and 1987 paper maps are available on an open data repository *(table 2)*. Of note, the use of the different data sources should be taken with caution, as, for example, cultivated surfaces may be underestimated in the RPG database which relies on farmer's declarations for European aids.

Pesticide itineraries database

The constructed 'PI' database allows the description of agricultural practices regarding the use of pesticides and their evolution through time between 1960 and 2020. According to the information collected, the use of pesticides in banana crop system was described by ten successive pesticide itineraries. As illustrated in *figure 5* for banana crop between 1987 and 2020, this results in important changes in the average annual number of pesticide applications through time: it remained stable around 14 applications / year until 1999, then peaked in 2004 with more than 17 applications / year, and decreased since 2009 to less than 6 applications / year in 2020. The use of insecticides stopped in 2015. Organic banana crop started in 2017.

Similar results were obtained for sugar cane and market gardening, with six and five successive pesticide itineraries, respectively, and a progressive decrease of the number of pesticide applications per year.

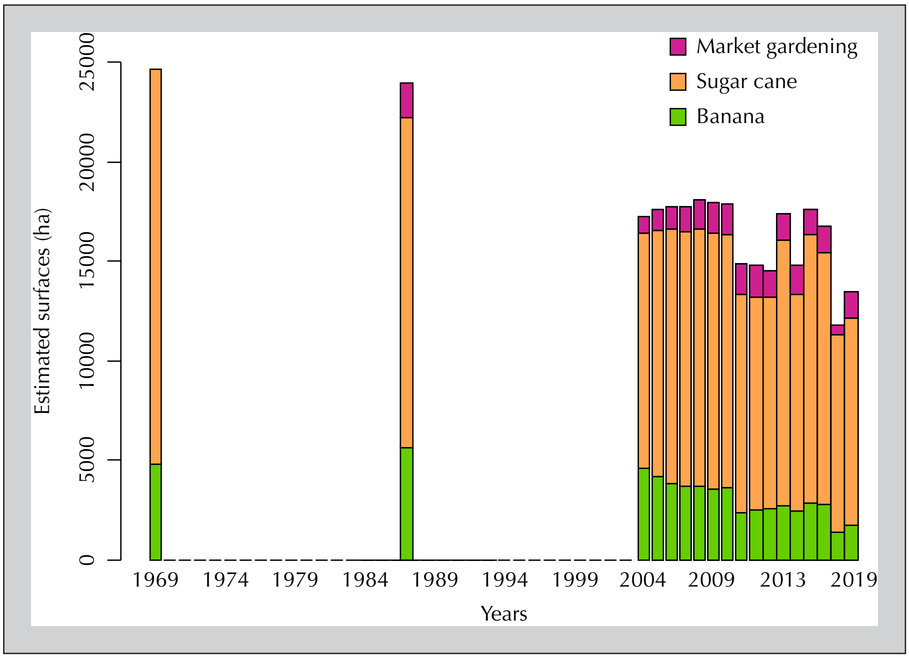

Figure 4. Evolution of main crop types surfaces, Guadeloupe island, 1969-2019.

Figure 4. *Évolution des surfaces des principaux types de cultures, île de la Guadeloupe, 1969-2019.*

Table 2. Data repositories of the different databases produced for the characterization of pesticide pollution over time, Guadeloupe Island.

Tableau 2*. Référentiels des différentes bases de données produites pour la caractérisation de la pollution par les pesticides au cours du temps, île de la Guadeloupe.*

Database	Name	File format	Digital object identifier (doi)
Land use	Banana and sugar cane plots, Guadeloupe Island, 1969	Shapefile	10.18167/DVN1/GCOYQD
Land use	Banana, sugar cane and market gardening plots, Guadeloupe, 1987	Shapefile	10.18167/DVN1/LYC8N8
Pesticide	Pesticide itineraries and pesticide active substance databases	Access database and text files	10.18167/DVN1/E4UNIU

Pesticide active substances database

The active substance table highlights changes in the number of available pesticide active substance to be used in a given cropping system, as well as changes in the application doses. *Figure 6* illustrates how the number of approved active substances to be used in banana crops evolved between 1987 and 2020: a significant decrease is observed since the year 2005 for all pesticide types (fungicides, herbicides and insecticides). The same trends are observed for the other cropping systems (data not shown).

The active substance table based on farmers' practices (2842 records) is available on an open data repository *(table 2)*. It should be noted that this database only reflects the recommended usages of pesticide products. Diverted uses, for example the use of sugar cane herbicide products in a market gardening plot, are not included.

Conclusions and perspectives

The characterization of pesticide uses over time and at the territory scale is crucial for the study of their potential health impacts. It requires information on the localization of agricultural crops, on the agricultural uses of pesticides, and on the availability of pesticide products. This technical note presented a method to reconstruct such information over a long period of time from heterogeneous data sources, with the example of banana,

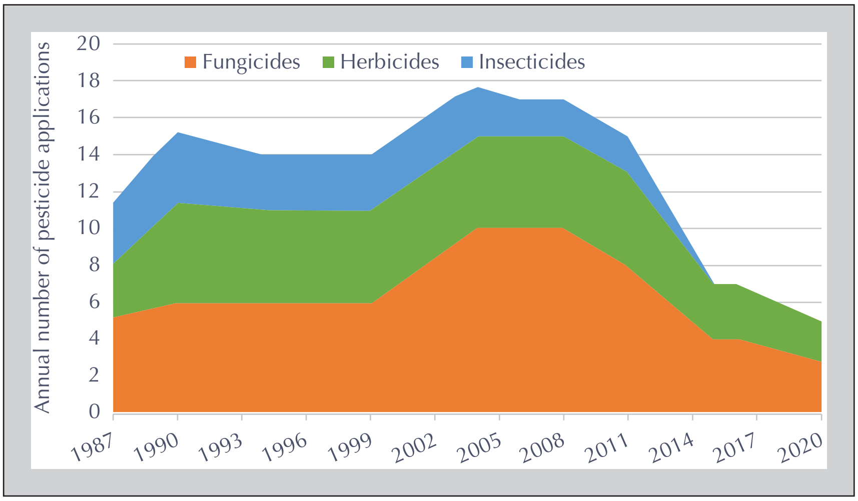

Figure 5. Pesticides applications in banana crops, Guadeloupe island, 1987-2019.

Figure 5. *Applications de pesticides dans les cultures de bananes, île de la Guadeloupe, 1987-2019.*

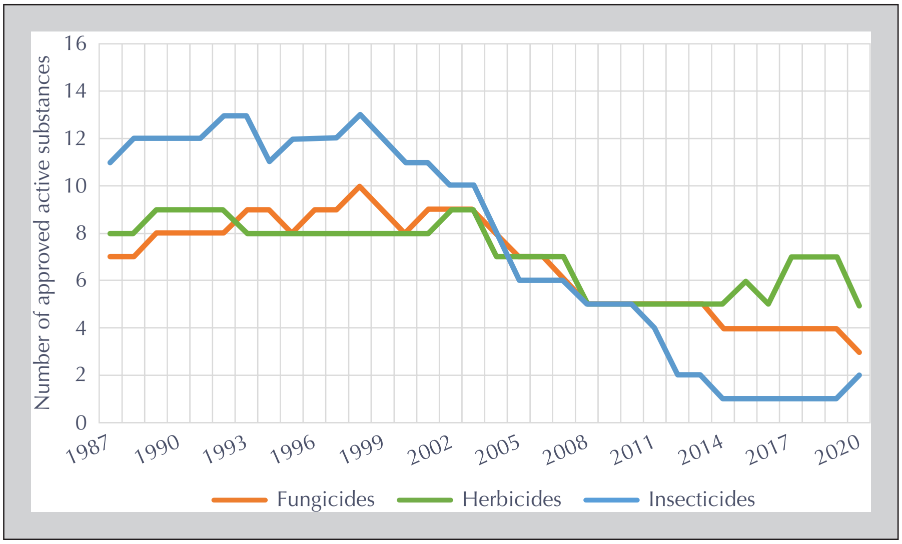

Figure 6. Number of approved pesticide substances for banana crops, Guadeloupe island, 1987-2019.

Figure 6. *Nombre de substances pesticides approuvées pour les cultures de bananes, Guadeloupe, 1987-2019.*

sugar cane and water gardening crops in Guadeloupe Island, French West Indies, since 1969. It provides unprecedented spatial and historical information to complement assessment studies that have been carried out at cultivated plot level (e.g. [10]).

Three different databases were constructed: a homogenized land use dataset of the three main crop systems, a database describing the changes in 'pesticide itineraries', *i.e.* agricultural practices related to the use of pesticide, and a database with the information on the evolution of available pesticide products and corresponding active substances. These databases can be completed with additional data from surveys (such as the MatPhyto study which ended in 2014), or additional data from interviews of the stakeholders of the agricultural sector.

The three databases resulting of this first work are made available on an open data repository and will be used to derive indicators of pesticide pressure and study the link between cancer cases and the presence of pesticides in the environment [11]. Of note, those data could be used to assess other impacts, such as biodiversity losses [12]. To this end, pesticide risk assessment models have to be developed to account for the fate of pesticides and estimate emissions into different compartments (air, soil, crops, groundwater). As perspective, the possibility of coupling the datasets presented in this technical note with models such as pestLCI [13], could be assessed. The resulting indicators should be interpreted with caution, as they are no direct measures of exposition, but indirect proxies. The validation of these models is essential and require measurements of active substances in the soil, which are available In Guadeloupe for some substance of interest such as chlordecone [14]. Finally, it should be noted that the impact of pesticide exposition indicators on cancer incidence has to be interpreted along with other demographic and socio-economic factors [15].

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