

Assessing the environmental impact of pesticide use in banana cropping systems

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Abstract

In the French West Indies, high pest pressure on cropping systems has triggered high inputs of pesticides, especially in banana cropping systems. These pesticides then disperse in soil, ground and surface water, threatening ecosystem and human health. Reducing the environmental impact of banana cropping systems in this area requires i) predicting environmental states according to cropping systems evolution, ii) identifying key factors triggering pollution, and iii) proposing measures to reduce impact. Since farmers apply pesticides at the field scale while environmental impacts spring up at the watershed scale, multi-scale environmental impact assessments of pesticide use are required. Therefore, our work focuses on the characterization of i) pollutant input (type of molecule, quantity applied, frequency), ii) pollutant transfers, through hydrological modelling, and iii) environmental state through water quality measurements.

Studies carried out at field scale, sub-watershed scale and watershed scale will be presented. They were located in Pérou river catchment in Guadeloupe and Galion river catchment in Martinique. Results provide a wide overview of the main hydrological processes involved in pesticides transfers towards rivers in tropical volcanic catchments. However, those studies focused either on chlordecone, an old organochlorine, or cadusafos, a nematicide used 10 years ago in banana cropping systems. Recent measurements performed at the watershed scale showed herbicides applied in sugarcane fields and banana post-harvest fungicides to be among the main pollutants in these rivers. Consequently, long-term and multi-residue monitoring is required to understand the fate of the different molecules applied in fields taking account of cropping systems evolution over time. This will be further performed thanks to the set-up of the observatory of agricultural-source pollution in the French West Indies (OPALE).

Keywords: Environmental evaluation, pesticides, water quality, multi-scale assessment.

INTRODUCTION

In the French West Indies, high pest pressure on cropping systems has triggered high inputs of pesticides, especially in banana cropping systems (Castillo et al., 2000; Henriques et al., 1997; McDonald et al., 1999). These pesticides then disperse in soil, in ground water, and towards surface water, threatening ecosystem and human health (Lewis et al., 2016).

Reducing the environmental impact of cropping systems requires understanding the relationship between pollutant pressure from cropping systems and their impacts on the environment. However, this relationship is not obvious, due to complex pollutant transfer processes after pesticide applications, from fields to water bodies. Thus, assessing the impact of changing pesticide use on water quality is challenging. Nevertheless, addressing this issue will enable us to predict environmental status according to cropping system evolution, and in turn to adapt measures to reduce impacts.

This implies first the identification of key factors triggering pollution through the characterization of i) pesticide input, ii) ecosystem contamination levels, as well as iii) pesticide transfer pathways. Water being a main vector of pollutant transfers, the characterization of hydrological processes occurring on the catchment is crucial. Moreover, since farmers apply pesticides at the field scale while environmental impacts spring up at the catchment scale, multi-scale monitoring systems are required to characterize pollutant transfers from the field to the river.

Hence, this paper aims to present a retrospective of multi-scale studies carried out on a pilot study area in Guadeloupe (FWI), during the last few years. First, recent results about the current pressure from agricultural pesticide use and the corresponding state of water contamination are presented. Then, the paper provides an overview of pesticide transfer processes evidenced in the same area and that enable a better understanding of the contamination dynamics of the water bodies.

MATERIAL AND METHODS

Study site

1. Climate, soils and land uses

The study area includes Pérou river and Pères river catchments in the municipality of Capesterre-Belle-Eau, Guadeloupe in the French West Indies. It is located on the volcanic island of Basse-Terre and is characterized by a humid tropical climate with annual rainfall increasing from 2,000 to more than 10,000 mm from the outlet towards highest reliefs. Two main soil types are highland Andosols and lowland Nitisols (Crabit et al., 2016). The complex volcanic geology of the catchment explains the stratification of ground water flows linked to the lithology, leading to a compartmentation of the aquifers (Charlier et al., 2015). Pristine rainforest covers the upstream half area of the catchment (55% of catchment), while the intermediate area is mainly covered by banana (*Musa* spp.) (35% of catchment). The downstream part of the catchment is mainly covered by banana fields but also includes sugarcane fields and urban areas. The Utilised Agricultural Land covers 518.2 ha, 385.4 ha of which are cultivated.

2. Farm types

Export dessert banana production predominates four of the five main farm types (Table 1). There is little production of vegetables in the catchment, and only as secondary crops production after banana (Dulcire and Cattán, 2002).

Table 1. Main farm types in the Pérou catchment (after Gentil, 2014)

Farm type	Main farm product	Other farm products	Crop area
"Smallholder banana farming"	Banana ⁽¹⁾	-	3-10 ha
"Banana and diversified"	Banana ⁽¹⁾	vegetables, plantain	4- 24 ha
"Industrial banana farming"	Banana ⁽¹⁾	rotation crop	15-72 ha
"Planter-breeder"	Banana ⁽¹⁾ , livestock	-	> 15 ha
"Industrial sugarcane"	Sugarcane	-	30-150 ha

⁽¹⁾Export dessert banana

Indicators to estimate pesticide pressure

In 2014, 23 of the 40 farms of the Pérou catchment were surveyed to characterize their cropping systems and report their use of pesticides. Three pesticide input indicators based

on treatment frequency index (TFI) were also calculated (Gentil, 2014). At the field-scale, the TFI-crop was calculated as the number of treatments of the fixed standard dose of active substance, per hectare and during the crop production cycle. For banana cropping systems, post-harvest treatments applied in farm sheds were also taken in account in the calculation.

However, the main drawback of TFI-crop is that it doesn't take into account the duration of the crop production cycle that may vary from a few months to a few years, making the comparisons between crops difficult. Thus, an averaged TFI, called TFI-cropping system, was calculated to represent the mean pollutant pressure exerted by a cropping system (including crop rotations) over time. It is the sum of TFIs of all crops included in the crop rotation, expressed on an annualized basis by dividing by the total duration of crop production cycles included in the cropping system.

Finally, the TFI-farm accounts for all crops present on the farm and represents the farm-level pollutant pressure. It is calculated as the sum of all TFI-cropping systems of the farm, weighted by their respective surface area compared to the total surface area of the farm.

Assessment of environmental state of water bodies

The environmental state of water bodies was assessed at the catchment scale, which is the scale that integrates all processes of pollutant input and transfers. In 2014, the Pérou and Pères rivers were both sampled at their outlets. Automatic samplers (Sigma SD900) were used to collect water according to flow during 1 week. This was repeated three times during the weeks 26, 28 and 38. Finally, we obtained 3-weekly integrative water samples for each river.

Then, multi-residue pesticides analyses were performed, including active molecules currently used by farmers as well as prohibited but persistent organochlorine molecules such as chlordane (CLD). These analyses were performed by the LDA26 in Valence, France, under the French accreditation committee "COFRAC" and norm NF17025.

Monitoring design to characterize hydrological processes and pesticide transfers

Prior to 2014, different monitoring approaches were already carried out at field scale, sub-catchment scale and catchment scale depending on the targeted objectives. We summarize them here and refer to the published papers describing them in more detail.

1. At field scale

Several field-scale studies aimed to assess the influence of spatial heterogeneity due to cropping patterns in banana plantations on water fluxes and pesticide transfers, focusing experiments on the fate of a nematicide (cadusafos) applied in banana plantations until 2008 (Cattan et al., 2007a; Cattan et al., 2007b; Saison et al., 2008). Monitoring was conducted in a banana field (6,000 m²) on Andosols between 2001 and 2002 (Neufchâteau experimental station). The following measurements at the storm-event time scale were taken: incident rainfall, stem flow and through-fall at three banana stages, percolation fluxes (using lysimeters) at the base of banana plants and in the interrow, surface runoff, and cadusafos concentrations in percolation water and surface runoff water.

2. At sub-catchment scale

Sub-catchment scales studies aimed to i) understand the hydrological behaviour of a small farmed headwater catchment and ii) identify pathways and residence time of surface and ground water contamination by cadusafos (Charlier et al., 2008; Charlier et al., 2009). They were carried out on the Féfé sub-catchment (17.8 ha), in the upstream area of the Pérou catchment, between 2003 and 2006. Hydrological measurements were performed at annual and storm-event time scales for rainfall depth, river discharge, shallow and deep

water levels. Cadusafos concentrations were measured in soil (one sampling before cadusafos application, three samplings after), in stream and in ground water (six piezometers from 1.5 to 5m depth and two piezometers from 15 to 30m depth).

3. At catchment scale

The catchment scale study aimed to i) identify primary flow paths involved in pesticide contamination of surface and ground water, and ii) quantify the pesticide fluxes to assess pollution levels and duration at the scale of the heterogeneous Pérou river catchment, including farmed and forested areas. The observation of the fate of CLD in waters was the primary objective since it is an important issue in the French West Indies (Crabit et al., 2016). Hydrological monitoring was designed to split the Pérou catchment into three main sub-catchments: rainforest SC1, upstream cropping areas SC2, and downstream cropping areas SC3. A monitoring network was implemented to measure : i) rainfall from five rain gauges scattered on the catchment following an altitudinal gradient, ii) river discharge at the three outlets, iii) water table levels using two shallow piezometers, located in SC2 and SC3 sub-catchments. Measurements were conducted during the hydrological year 2009-2010. Four sampling campaigns were conducted on the Pérou catchment between 2003 and 2012 to analyse CLD soil content in the 30-cm topsoil layer. Overall, 64% of the cultivated plots were sampled, which account for 69% of the cultivated area of the catchment.

RESULTS AND DISCUSSION

Pollutant pressures

Our results showed that in banana production systems, all farmers systematically applied fungicides and made frequent use of herbicides. In sugarcane production systems, only herbicides were used, whereas the use of insecticide was central in vegetable production systems. All production systems surveyed on the catchment used rodenticides.

Many different types of pesticides are applied in the study area (Figure 1). Herbicides are by far the most used (77%) and account for nearly 75% of the quantities of pesticides imported into Guadeloupe (all crops combined). Fungicides used in banana cropping systems (foliar and post-harvest) represent 16 % of used substances. Insecticides and nematicides are less than 10% of pesticide quantities imported into Guadeloupe, which highlights the effectiveness of fallow practice recently developed in banana cropping systems to reduce damages from insects and nematodes. Indeed, the use of active substances decreased by 35% between 2006 and 2013, which was ascribed to the reduction of nematicide use (Cardinet and Fabre, 2015).

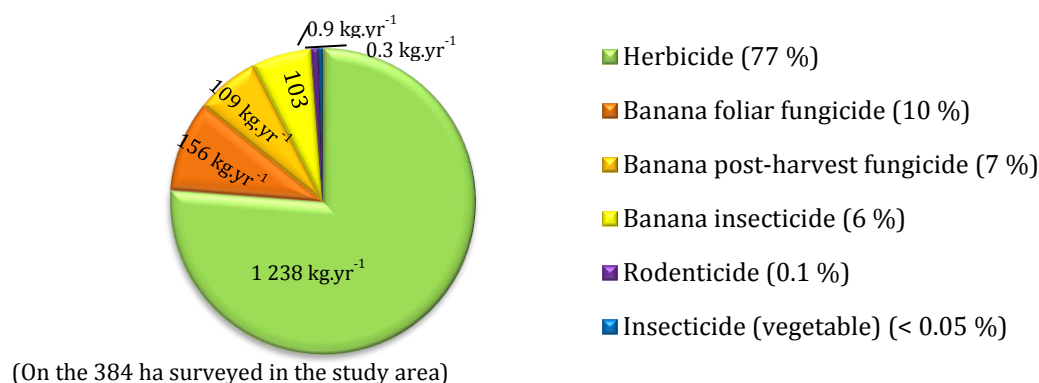


Figure 1. Use of the different types of pesticides applied in the study area (after Gentil, 2014)

Despite the use of fallows instead of nematicides, banana cropping systems still exert

the most important pesticide pressure, compared to other cropping systems in the study area. The TFI for banana crop reached 15, which is higher than other crops such as pineapple (TFI <8) and much higher than the TFI for sugarcane (average TFI of 2) which represents the second cropping area (Figure 2).

The development of monitoring methods to regularly update pesticide pressure databases is henceforth required. Relevant indicators that connect cultural practices and environmental impacts while reducing the cost of data collection have to be designed. An approach geared toward the development of pressure typologies according to farm types instead of monitoring pesticides quantities at the field-scale may thus be further considered.

Contamination of water bodies

The contamination levels of the rivers are generally high, with the river Pères being the most contaminated, with total concentrations for all pesticides reaching more than 4 µg.L⁻¹. Three types of molecules were mainly detected (Table 2): post-harvest fungicides used in banana sheds, herbicides used in sugarcane fields, and old organochlorine insecticides (including CLD) already known to contaminate these water bodies. Although most of the observed contamination comes from the organochlorine molecules, the contribution to pollution from the new molecules being currently used is of importance: 0.48 to 2.36 µg.L⁻¹ in the river Pérou (up to 44% of total pesticide concentrations) and 0.07 to 0.69 µg.L⁻¹ in the river Pères (up to 53%).

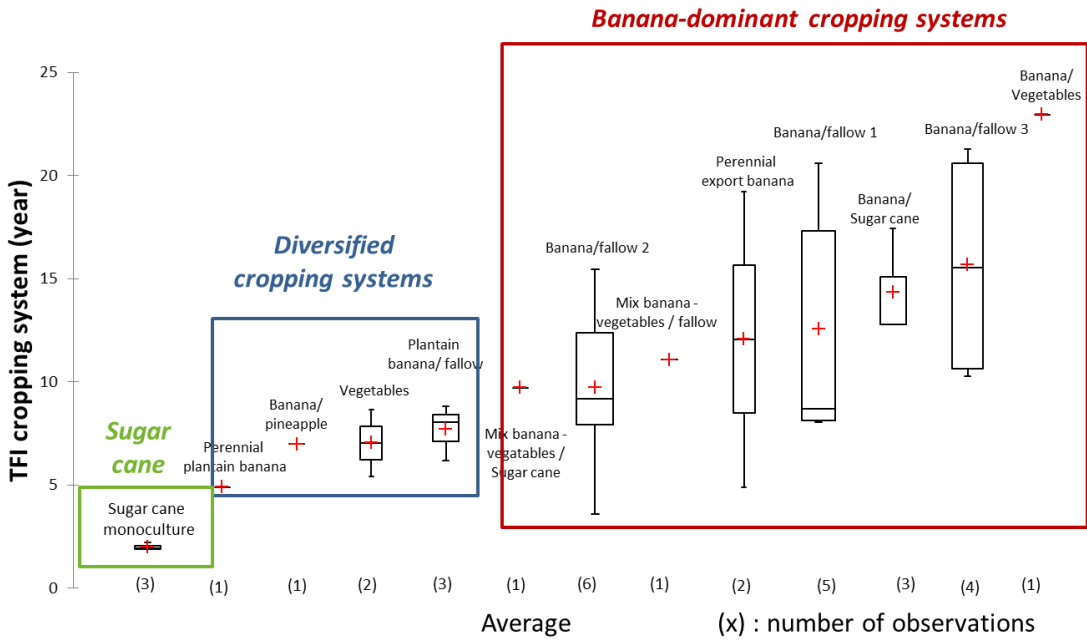


Figure 2. TFI of the main cropping systems present on the study area (after Gentil, 2014)

The detection of bitertanol, a post-harvest fungicide prohibited since 2011, may be ascribed to either illegal misuse or pluri-annual residence time of the molecule in aquifers drained by the river. Only banana post-harvest fungicides (7% of quantities applied) and herbicides used in sugarcane field (24 % of the cropping area) were detected. Foliar fungicides were not detected, though representing 10% of the quantities applied on the catchment. Further investigation is needed to understand the fate of these fungicides.

Table 2. Concentrations of multi-residue pesticides measured for the rivers Pères and Pérou

river outlets. Integrative samples over 5 days.

concentration $\mu\text{g.L}^{-1}$	Week		
	26	28	36
Pères river	4.71	3.54	4.48
Postharvest fungicides	1.27	0.26	0.24
Azoxystrobin (*)	0.11	0.07	0.02
Bitertanol	0.80	0.04	0.09
Imazalil	0.08	0.05	0.03
Thiabendazole	0.28	0.10	0.10
Herbicide			2.12
2,4-D (*)			0.51
Asulam			1.45
Fluroxypyr (*)			0.16
Organochlorine insecticides	3.44	3.17	2.12
Chlordecone (*)	3.35	3.10	2.05
Chlordecone 5b Hydro	0.06	0.05	0.04
HCH Beta (*)	0.03	0.02	0.03
Other insecticides		0.11	
Piperonyl Butoxide (*)		0.11	
Pérou river	3.63	1.45	1.78
Postharvest fungicides	0.69	0.06	0.07
Azoxystrobin (*)			0.02
Bitertanol	0.69	0.06	0.05
Organochlorine insecticides	2.94	0.82	1.71
Chlordécone (*)	2.89	0.77	1.66
Chlordecone 5b Hydro			0.02
HCH Beta (*)	0.05	0.05	0.03
Other insecticides		0.57	
Piperonyl Butoxide (*)		0.57	

Water and pollutant transfer processes

Reviewing the earlier monitoring and experimental works provides a wide overview of the main hydrological processes involved at different scales in pesticide transfers towards surface and ground waters in a tropical volcanic catchment.

1. Rainfall redistribution by banana canopy

Cattan et al (2007a) demonstrated the importance of rainfall redistribution by banana canopy at the plot scale. The stemflow process locally concentrated water fluxes, triggering higher percolation fluxes at the base of banana plant compared to the interrow (Cattan et al., 2007b). The quantification of pesticide losses at the plot-scale showed that 72 % of total cadusafos losses occurred via percolation (49% under banana plant, 23 % in interrow), and 28 % via surface runoff (Saison et al., 2008). The higher pesticide infiltration under banana plants was ascribed to higher percolation amounts and pesticide applications that both occur at the base of banana plant. Although total infiltration fluxes represented only 0.5% of cadusafos initially applied, it was sufficient to contaminate water at concentration over the recommended threshold of $0.1\mu\text{g.L}^{-1}$.

2. Rapid and high percolation fluxes

The high soil infiltrability of Andosols ($K_s > 60 \text{ mm.h}^{-1}$) allows 90% of annual rainfall to infiltrate in soil despite high rainfall intensities during storm events (Charlier et al., 2008; 2011). The high resulting percolation fluxes trigger underground water transfers to be the main pathway for pesticide dispersion at catchment scale. Indeed, Charlier et al (2009) showed that rapid percolation processes caused the contamination of the aquifer by cadusafos in less than a week at the sub-catchment scale.

3. Residence time in aquifers

Results on ground-water dating carried out by Charlier et al. (2015) shows that the shallow aquifer (5-30 m depth) mainly recharged by cropping areas has a relatively short residence time (several years), while the deeper aquifer (30-80 m depth) mainly recharged at altitude has long residence time varying from 30 to 40 years. Authors highlighted a link between water age and the CLD contamination level, with highest concentrations ($>25 \mu\text{g.L}^{-1}$) for ground waters recharged during the application periods between 1970 and 1990, and relative lower concentrations (up to $10 \mu\text{g.L}^{-1}$) for ground waters recharged in the last decade.

4. Two contamination phases after pesticide applications

Two contamination phases after pesticide applications were shown to occur at the sub-catchment scale (Charlier et al., 2009). The first phase corresponded to event-dominated contamination from surface runoff, with higher pesticide concentrations during a short duration (3 weeks after cadusafos application). The second phase corresponded to chronic contamination from ground water drainage, with lower concentrations but higher loads over a longer period. These two contamination phases may have a different biological impact on the stream.

In the case of CLD, only chronic contamination from ground water was observed, as there have been no more applications since 1993, with highest concentrations during dry season. At the catchment scale, CLD concentrations increased from upstream to downstream in relation with the localization of highly contaminated aquifers ($\sim 10 \mu\text{g.L}^{-1}$) in downstream cultivated areas. Thus, although the non-contaminated forested upstream SC1 represents the main contribution to streamflow (80% discharge), CLD concentrations measured in the river steadily exceeded the standard threshold of $0.1 \mu\text{g.L}^{-1}$ (Charlier et al., 2015; Crabit et al., 2016).

CONCLUSION AND PERSPECTIVES

Banana cropping systems were expected to exert the highest pesticide pressure on water bodies, compared to other crop production systems, because of i) higher quantities applied (TFI), ii) rainfall redistribution by banana canopy that favoured water fluxes at the plant base where pesticides are generally applied. However, we observed unexpected results on pesticide presence in rivers: absence of banana foliar fungicide, but high concentrations of herbicides used in sugarcane fields. Thus, it is not a case of *"the less applied in field, the less concentrated in river"*, for there are complex processes involved in the dispersion of pesticides. A second implication is that surveying just one crop production system (banana or other) is not sufficient to explain and improve environmental pollution state. In our case, both actions toward sugarcane and banana production systems (including post-harvest treatments) should be engaged in order to improve water quality.

The hydrological monitoring highlighted that river contamination mainly came from ground water. Hence, due to residence time in aquifers of several years and transfer kinetics of pollutants, considerable time is needed for a change in cropping practice to have a measurable effect on water quality. However, even if the effect is not immediate, changing

cropping practice can be highly required, the case of CLD being the extreme example. Similar situations must not be repeated in the future.

Consequently, a long-term and multi-residue monitoring is required to understand the fate of the different molecules applied in fields taking account of cropping systems evolution over time. Such monitoring will be undertaken through the recently set-up observatory of agricultural-source pollution in the French West Indies (OPALE). This monitoring should help to identify cultural practices in crop production systems that contribute to river pollution.

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