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177

Research Report

Environmental Risks from Pesticide Use: The Case of Commercial Banana Farming in Northern Lao PDR

Andrew Wentworth, Paul Pavelic, Santi Kongmany, Touleelor Sotoukee, Khamla Sengphaxaiyalath, Kesiny Phomkeona, Phengxay Deevanhxay, Vanseng Chounlamany and Vongphapane Manivong

Research Reports

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Contents

Acronyms and Abbreviations

BS EN	British Standards European Norm
CEC	Cation Exchange Capacity
CU	Currently Used
DAFO	District Agriculture and Forestry Office
DDD	Dichlorodiphenyldichloroethane
DDE	Dichlorodiphenyldichloroethylene
DDT	Dichlorodiphenyltrichloroethane
DONRE	District Office of Natural Resources and Environment
EC	Electrical Conductivity
ETU	Ethylene Thiourea
EURL-SRM	European Union Reference Laboratory for Single Residue Methods
FAO	Food and Agriculture Organization of the United Nations
GAP	Good Agricultural Practices
GT	Gobthong Thoophom
IPM	Integrated Pest Management
ISO	International Organization for Standardization
IWMI	International Water Management Institute
K	Potassium
K_{oc}	Sorption Coefficient
LC_{50}	Lethal Concentration at which 50% of fish die after exposure
LOD	Limit of Detection
LOQ	Limit of Quantification
MAF	Ministry of Agriculture and Forestry
MC	Mixed Crop
MONRE	Ministry of Natural Resources and Environment
N	Nitrogen
NAFRI	National Agriculture and Forestry Research Institute
NB	New Banana
ND	Not Detected
NUOL	National University of Laos
OB	Old Banana
OC	Organochlorine (pesticides)
P	Phosphorus
OM	Organic Matter
OP	Organophosphate (pesticides)
PAFO	Provincial Agriculture and Forestry Office
PCB	Polychlorinated Biphenyl
PDR	People's Democratic Republic
PIRI	Pesticide Impact Rating Index
POP	Persistent Organic Pollutant
PVC	Polyvinyl Chloride
QuEChERS	Quick, Easy, Cheap, Effective, Rugged and Safe Method
SGS	SGS Vietnam Ltd. Analytical Laboratory
SPE	Solid Phase Extraction
WHO	World Health Organization

Summary

Commercial farming of banana (*Musa acuminata*, Cavendish subgroup) for export has rapidly expanded across the northern provinces of the Lao People's Democratic Republic (PDR) (otherwise known as Laos) since 2008 with the establishment of new plantations by Chinese companies. Banana farms' reliance on intensive agrochemical usage warrants examination of the possible negative consequences for environmental and human health. This study is the first in Laos to establish data and provide an understanding of pesticide occurrence in upland agricultural areas to better inform pesticide management. This report presents a preliminary assessment of the environmental risks from pesticide usage in commercial farming of bananas and other major crops in Houn district, Oudomxay province.

Initially, a scoping mission was conducted by the study team across three northern provinces (Luang Namtha, Phongsaly and Oudomxay). Environmental samples (surface water, groundwater, soil and sediment) were subsequently collected from a single focal site in Oudomxay province on two occasions in 2016 during the dry and wet seasons. Samples were analyzed for pesticide residues in the laboratory, and the results were used to determine the association between crop type and concentrations of pesticide residues. We also compared laboratory results against a low-cost pesticide residue detection method, the Gobthong Thoophom (GT) test kit, and a simple pesticide risk assessment tool called the Pesticide Impact Rating Index (PIRI).

The scoping mission revealed that bananas were predominantly grown on fields that had previously been cultivated with other crops, indicating that bananas were replacing other crops instead of being grown on previously non-agricultural land. In Oudomxay province, bananas had mostly replaced maize, while in Luang Namtha province, they supplanted irrigated paddy rice and sugarcane. The intensity of banana farming was found to be strongly associated with access to surface water for irrigation. Irrigated farming favors denser planting, in turn requiring greater inputs of pesticides and fertilizers.

The focal site in Houn district extended across two adjacent watersheds, which included banana farms of different ages as well as land cultivated with several other commercial crops. Laboratory analysis of 46 soil, sediment and water samples was carried out to quantify the concentrations of 40 pesticides and breakdown products during the wet and dry seasons in 2016. The results of this analysis revealed a stark contrast between samples from banana farms and other crop types. Banana farm samples had higher concentrations of residues from pesticides currently used (CU) compared with samples from adjacent farms producing maize, rubber, upland rice and gourd. We also detected residues from highly persistent organochlorine (OC) pesticides no longer used in Laos. These legacy pesticides included dichlorodiphenyltrichloroethane (DDT), heptachlor, dieldrin and lindane among others.

The potential environmental risk from pesticides and pesticide breakdown products was found to be substantial. Concentrations of two CU compounds—imidacloprid and paraquat—in the wet season surface water (stream) samples obtained from a banana farm exceeded the World Health Organization (WHO) environmental water quality guidelines. Furthermore, three OC pesticides – heptachlor, aldrin and dieldrin – exceeded limits set by WHO's drinking water quality guidelines in dry season surface water and groundwater samples. These OC pesticides are highly persistent in the environment and tend to bioaccumulate, which means they pose a considerable risk to people who consume contaminated surface water, groundwater or aquatic species from the local area.

Neither the PIRI model nor the GT test kit results were comparable to laboratory analysis. The risk level output from the PIRI model was not a good predictor of residue concentration. It is uncertain whether the discrepancies between PIRI's impact ratings and observed residue concentrations were caused by poor model performance or a potential failure in our sampling to capture the periods of highest risk. Results from the GT test kit were inconsistent with the observed residue levels except for highly contaminated soils, indicating that the GT test kit was not sensitive enough to detect low-to-moderate levels of organophosphate pesticide residues.

Environmental monitoring of the major commercial banana growing areas is a necessary and important means of assessing the levels of risk and identifying appropriate mitigation measures. To achieve this goal, the Government of Lao PDR should take active steps to provide appropriate training to the provincial and local-level staff from relevant ministries (e.g., natural resource management, agriculture) to be able to monitor and report on pesticide residues as per international standards.

Further measures available to reduce the environmental risks from hazardous pesticides include:

- increasing efforts towards eliminating the import and use of the most hazardous and persistent pesticides;
- targeted education programs for banana farm company managers and workers about the associated hazards as well as the implementation of best practices, including the judicious selection and use of pesticides and other Integrated Pest Management (IPM) techniques;
- identifying and protecting water resources with a high risk of contamination, especially those used for drinking purposes; and

- ensuring that vegetated buffers and sediment traps around farms are mandated to detain farm runoff long enough for CU pesticides to degrade to safe levels before entering watercourses.

These measures should be explored and advocated in an integrated approach to ensure pesticide levels are contained to achieve acceptable environmental and human health risks.

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Introduction

Commercial banana farming[1] for export has grown rapidly across Laos in recent years. The size of the industry doubled from 2009 to 2015, increasing from 13,599 hectares (ha) to 28,577 ha; approximately 17% of the 169,000 ha used to cultivate permanent crops in Laos (FAO 2016; NAFRI 2016). However, compared with top banana-producing countries such as the Philippines and Ecuador, which cultivate approximately 456,641 ha and 180,337 ha of bananas, respectively, the extent of banana farming in Laos remains small (FAO 2016).

Commercial banana farms in Laos rely heavily on agrochemical inputs to protect and enhance their crop. This is because the commercial variety of banana grown in Laos and most other banana-producing countries, the Cavendish, is vulnerable to a host of pests and diseases (dela Cruz et al. 2008; Newley et al. 2008; Jones 2009). Also, high-density monocrop planting regimes common among commercial banana farms increase the risk of pest outbreaks and can deplete soil nutrient stocks (Hernandez and Witter 1996; Fröhlich et al. 2013; Marín et al. 2003). A large variety of pesticides are deployed in banana farms to prevent crop damage from fungal and insect outbreaks. High usage of pesticides leads to potentially negative consequences for environmental and human health. Reports of fish die-offs in water bodies near commercial banana plantations in Laos have raised concerns about the industry's environmental impacts (MAF 2014a; NAFRI 2016).

Public interest in Laos regarding the environmental impacts of banana farming has escalated since 2014. This was due to the national media reporting on the government's concern about suspected health risks for farmworkers as well as water contamination associated with heavy agrochemical use on banana farms in Bokeo province (Figure 1). In response, the National Agriculture and Forestry Research Institute (NAFRI) conducted a social, economic and institutional assessment of the sustainability of commercial banana production. It was found that growth in banana farming has been driven primarily by investment from Chinese companies, typically by direct land-leasing or contract arrangements to meet the demand for Cavendish bananas in China and globally (NAFRI 2016). Bananas for export are grown mainly in the northern provinces of Bokeo, Luang Namtha, Oudomxay, Xayabury and Phongsaly, because they are located relatively close to Chinese markets. Although banana farmers, either as contract workers and/or by leasing their land to banana companies, earned a net income around five to ten times greater than the farming of other crops (maize and cassava), it was uncertain whether the longer-term negative effects of pesticide usage on human and environmental health might outweigh the short-term livelihood benefits (PEI-NERI 2015).

Global Review of Environmental Impacts of Commercial Banana Farming

Commercial banana plantations require substantial water inputs over the 10-month growing season from February to November. According to the handbook on banana production by the Food and Agriculture Organization of the United Nations (FAO), annual water requirements range from 1,200 millimeters (mm) in the humid tropics to 2,200 mm in the dry tropics (Brouwer and Heibloem 1986). As with other crops, commercial banana farms typically employ irrigation wherever crop water requirements exceed rainfall during the growing season. In locations where water is scarce during the banana-growing season, banana farms' high water usage has the potential to introduce conflict among water users competing for limited supply.

Heavy pesticide usage on banana farms has been linked to severe soil and water quality degradation in several banana-producing regions, including Costa Rica, Mexico and the French West Indies (Castillo et al. 2000, 2006; Geissen et al. 2010; Aryal et al. 2012; Comte et al. 2018). High precipitation rates in the tropics, where bananas are typically grown, create favorable conditions for off-site pesticide transport (Henriques et al. 1997; Racke et al. 1997; Lewis and Glendenning 2009). Similarly, high irrigation rates increase the risk of pesticide transport. The dominant transport mechanisms from the application site to water resources include lateral surface runoff from fields (either in solution or bound to sediment particles), vertical leaching through the soils and groundwater, and aerial drift (Hernandez and Witter 1996) (Appendix 1, Figure A1). It is important to note that off-site pesticide

[1] Commercial banana farms are defined here as large-scale farming operations that produce bananas for export.

transport to surface water can spike for a short period after pesticides are applied or after rainfall events (Gilliom 2007). This presents a significant challenge for researchers attempting to understand both acute and chronic risks from pesticide usage, especially in remote tropical locations where rainfall is frequent and access is limited.

Due to their diverse chemical properties, different types of pesticides have varying degrees of impact, which may be further differentiated in water, soil, air and biota. For example, research conducted in southeast Mexico found that intensive usage of the bis-dithiocarbamate fungicide mancozeb resulted in high concentrations of manganese and zinc (two main ingredients in mancozeb) in soil, whereas surface and subsurface waters were polluted by the mancozeb breakdown product, ethylene thiourea (ETU) (Geissen et al. 2010). Research conducted in Costa Rica found that drinking water from shallow wells located within banana plantations had significantly higher concentrations of manganese due to mancozeb applications than those located only a few kilometers away (van Wendel de Joode et al. 2016). Another assessment of pesticide pollution in Mexico found that the mean residue concentrations of cadusafos, diazinon, ethoprophos, terbufos, chlorpyrifos, chlorothalonil, imazalil and thiabendazole in surface water and sediment samples exceeded the aquatic quality criteria values, posing a chronic risk to aquatic organisms (Nowell and Resek 1994; Castillo et al. 2000). The same study found that the effluent from chemical mixing tanks inside banana plantations, banana packaging facilities and pesticide storage sheds contained the highest levels of contamination (Castillo et al. 2000). In addition to pesticide pollution, banana farms have also been linked to nutrient pollution. A study in Mexico found that water samples from areas with intense banana cultivation had nitrite contents in exceedance of safety standards for drinking water (1.0 mg/L) and aquatic life (0.2 mg/L) (Aryal et al. 2012).

Pesticides, in addition to nutrient pollution, can have significant impacts on aquatic ecosystems. A recent study conducted in Costa Rica found that macroinvertebrate communities upstream of banana farms were more diverse compared with sites located downstream (Svensson et al. 2018). Noticeably, downstream sites tended to be dominated by a single taxon or a small number of related taxa with a greater tolerance for low-oxygen conditions.

Commercial banana farms also pose a risk to soil fertility because typical high-density planting regimes can deplete soil nutrient stocks if not fertilized

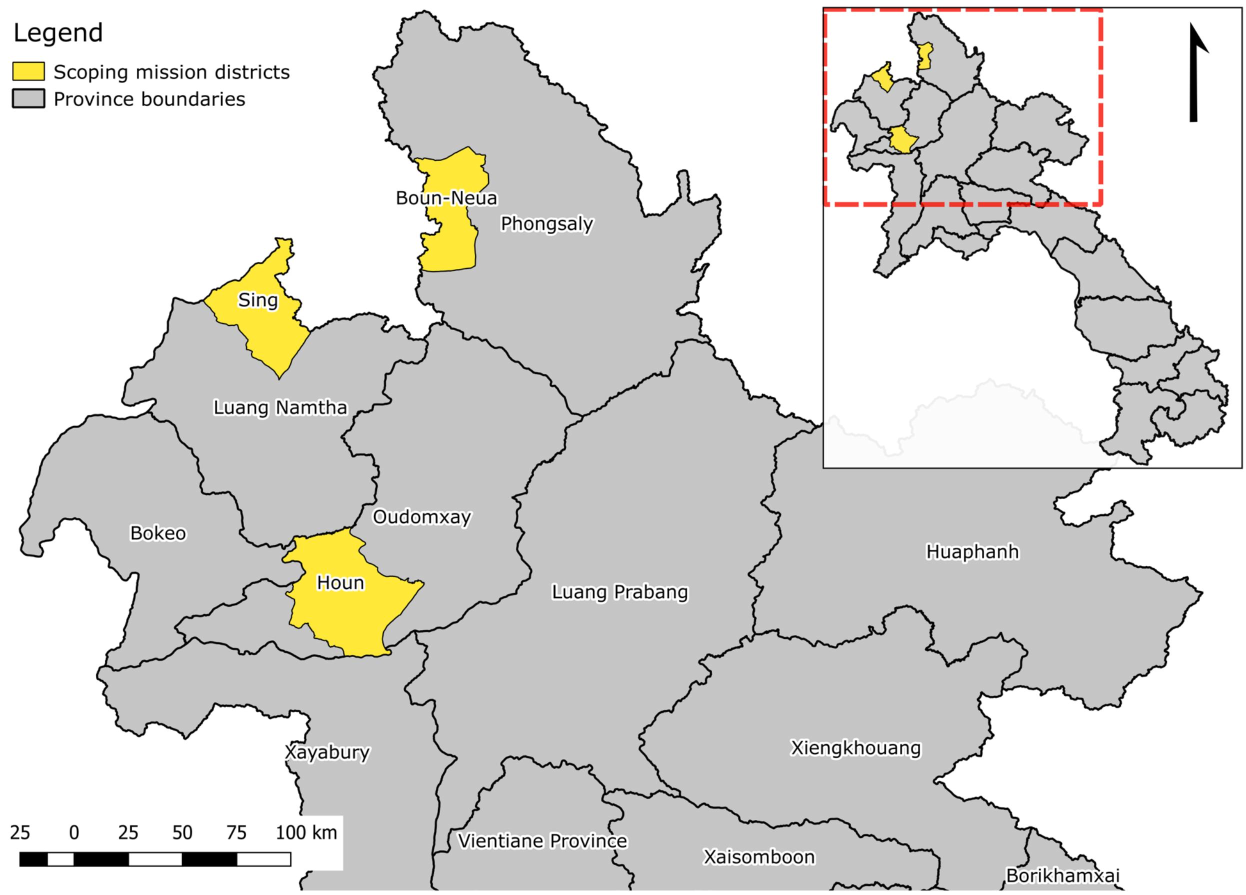

Figure 1. A map of province administrative boundaries and the districts visited as part of the study (highlighted in yellow).

appropriately (Powers 2004; Aryal et al. 2012). Densely planted bananas, like many other commercial crops, absorb inorganic nitrogen faster than it can be naturally replenished by soil mineralization (Hernandez and Witter 1996; Powers 2004). A study conducted in Costa Rica found that within 10 years, soil stocks of organic carbon and total nitrogen decreased by 37% and 29%, respectively, after a land-use shift from forest to banana (Powers 2004). Organic carbon losses were likely the result of reduced soil productivity and carbon inputs from forest vegetation, whereas nitrogen was lost as exported produce, nitrogen gas emissions and in hydrologic processes.

Roper and Gupta (1995) compared the effects of tillage and no-till practices on soil biota and found that various microbial groups, including bacteria and fungi, are affected by pesticides to varying degrees depending on the type of chemical. Pesticide residues in the soil can reach concentrations that are harmful to beneficial soil biota, but such conditions are not typical outside of highly contaminated sites (Scheunert et al. 1995; Gevao et al. 2000).

Previous research on banana farming systems in Laos documented the approximate area being cultivated in each province, typical contractual arrangements between farmers and investors, driving factors for foreign investors, and the commonplace availability of banned pesticides in shops and on farms (Vázquez 2013; Friis 2015; Higashi 2015; NAFRI 2016). However, significant gaps remained in the information available, especially relating to pesticide usage on banana farms (i.e., specific compounds used, frequency and amount of application, etc.) and the location of the farms with respect to topography and water resources affecting potential pathways for negative environmental impacts (Appendix 2).

Pesticide Usage in Laos

Pesticide usage in Laos has grown steadily in recent years as many farmers have switched from subsistence farming to commercial production of a range of agricultural commodities for export, including bananas (Fröhlich et al. 2013; Phoumanivong and Ayuwat 2013; Bartlett 2016). The average pesticide application rate per unit area of arable land is reported to be much smaller in Laos than in neighboring countries (Schreinemachers et al. 2015). Application rates in the country were estimated at 0.1 kg/ha based on total imported quantity (none are produced domestically) in relation to the total area of land in commercial production. This compares to 2.9 kg/ha in Cambodia, 8.4 kg/ha in Thailand, and 16.2 kg/ha in Vietnam. However, it is commonly known that a substantial proportion of pesticide imports in Laos are unregistered. Thus, the actual rates of usage are likely higher (Vázquez 2013; Schreinemachers et al. 2015).

The Government of Lao PDR ratified the Stockholm Convention in 2002 and the Rotterdam Convention in 2010 to eliminate the usage of certain pesticides deemed too hazardous for safe usage (FAO 2013; Vázquez 2013). For example, Persistent Organic Pollutants (POPs), including the organochlorine (OC) compounds dichlorodiphenyltrichloroethane (DDT), lindane and heptachlor, were banned under the Stockholm Convention due to their long-term environmental persistence. Similarly, the herbicide paraquat was banned under the Rotterdam Convention in 2010. According to the FAO Integrated Pest Management (IPM) program, POPs are no longer used in Laos and their current usage is, therefore, not considered a problem (FAO 2013). However, past POP usage has created a hazardous legacy in some areas where residues persist. A 2011 study of POP contamination in sediments of the Lower Mekong River Basin found that samples from canals bordering urban development in the prefecture of Vientiane Capital contained concentrations of polychlorinated biphenyls (PCBs) and DDTs that exceeded sediment quality guidelines (277 µg/kg dry weight) (Sudaryanto et al. 2011).

While POP usage is reported to have been eliminated, the banned herbicide paraquat is still imported through unofficial channels and is widely used (FAO 2013). The unregulated nature of many pesticide imports hinders efforts to keep accurate statistics and enforce pesticide regulations. An October 2015 survey of farmers and pesticide shopkeepers in Xiengkhouang province estimated that farmers had applied 99,500 kg of herbicides over 20,800 ha of cropland (4.8 kg/ha) in the previous 12 months, nearly 50 times the official national average of 0.1 kg/ha (Bartlett 2016; Provincial Agriculture and Forestry Office of Xiengkhouang Province 2016a, 2016b).

Increased pesticide usage has resulted in greater pesticide exposure among farmers (during application) as well as people outside the agriculture sector who are exposed to the contaminated produce. Blood testing conducted in Xiengkhouang province in 2016 found that 49% of the 767 tested people had unsafe levels of cholinesterase inhibition caused by exposure to certain types of pesticides (organophosphate [OP] and carbamate) (Rassapong 2016). Further testing in Xiengkhouang and Vientiane Capital found that a higher percentage of people consuming vegetables from the market (45%) had unacceptable levels of cholinesterase inhibition as compared to farmers (35%) (Rassapong et al. 2018).

In response to earlier studies in northern Laos that had demonstrated the negative impacts of pesticide use on local communities and the environment (NAFRI 2016; Rassapong 2016), the Government of Lao PDR issued the Decree on Pesticide Management in 2017 (Government of Lao PDR 2017). The Decree defines the principles, regulations and measures regarding the use of pesticides, product labeling, import/export, and pesticide transport, storage and disposal. The Ministry of Agriculture and Forestry (MAF) is directed to be the entity with the primary responsibility to coordinate the implementation of measures specified within the Decree at the province, district and village levels. The Decree specifies that pesticide labeling must feature text in the Lao language as well as images to indicate the pesticide's hazard level and guidance on relevant safety measures. Pesticides classified by MAF as 'extremely hazardous' and 'highly hazardous' are prohibited without special authorization from MAF. It is also prohibited to allow pregnant women or children younger than 15 years of age to use pesticides. Finally, the Decree encourages the implementation of IPM for natural pest control and Good Agricultural Practices (GAP) to decrease local impacts and minimize off-site pesticide transport.

Pesticide Risk Assessment Support Tools

Risk assessment support tools provide information about the impacts of pesticide hazards on a designated group (i.e., toxicity to humans or aquatic species). They include a wide range of approaches depending on the type of risks being addressed, such as pesticide residue test kits for rapid detection and mathematical models for simulating pesticide transport. Systematic methods for comparing the relative off-site impacts from different pesticides can be valuable tools for selecting pesticides with the least detrimental environmental impacts (Kookana et al. 2005). Risk indicators are one type of support tool that help natural resource managers and regulators assess the effects of pesticides on the environment. Several approaches and tools have been developed, ranging widely in their degree of complexity and the factors taken into consideration (i.e., economic and site-specific parameters) (Levitan 1997; Kookana et al. 2005). These studies indicate that, in general, the complexity of the model should not exceed the understanding of the system being investigated. In our study, we used two risk assessment support tools: a low-cost pesticide residue detection kit, the Gobthong Thoophom (GT) test kit, and a software package named Pesticide Impact Rating Index (PIRI) that outputs a qualitative pesticide risk indicator for water quality (G9 Company 1997; Kookana et al. 2005).

Pesticide residue test kits and similar rapid chemical analysis approaches allow the user to infer whether a sample is contaminated with pesticide residues. These approaches are most commonly used for food testing, but they have also been used to analyze environmental samples (G9 Company 1997; Thummajitsakul et al. 2015). Test kits benefit from their relative simplicity to use—they do not typically require specialized training or expensive laboratory equipment. However, a test kit's accuracy is not comparable with laboratory analysis and the results must be treated with an appropriate degree of caution. The test kit model that was used in this study (GT test kit) was based on the de la Huerga method and developed by the Food Division of the Thai Ministry for Public Health (de la Huerga et al. 1952; G9 Company 1997). The GT test kit estimates the abundance of two types of pesticides (OP and carbamates) by exposing the sample to the enzyme cholinesterase and observing what fraction of the enzyme is inhibited by chemical reactions with pesticide residues. Cholinesterase is an enzyme common among mammals and insects and is a critical component of the nervous system.

PIRI provides ratings for pesticides' off-site migration potential as well as consequent effects on aquatic organisms (Kookana et al. 2005). The model's simplicity and open access license make it accessible to non-experts. Furthermore, the data inputs required are generally available in Laos, including pesticide chemical properties, physical site characteristics, and basic climate data (Appendices 3 and 4). PIRI outputs do not represent the absolute risk but a relative risk rating to compare pesticides or land use practices within the study area (Kookana et al. 2005). A higher toxicity rating indicates that the estimated loading to surface water would have a larger impact on the target species. For example, a pesticide with an extremely high toxicity risk could indicate that a compound is present in large quantities and/or is particularly toxic to the target species. The toxicity rating can be calculated using toxicological thresholds for various species, including fish (rainbow trout [*Oncorhynchus mykiss*]), algae, daphnia (water flea) and humans. The mobility score, on the other hand, reflects the degree of risk that the compound will be transported from the field where it was applied to surface waters.

Study Objectives

There is very limited information available on pesticide use in Laos, which is, as yet, insufficient to understand the nature and extent of the potential environmental problems associated with banana and other types of commercial farms. Therefore, to address this major knowledge gap, the objectives of this study are to:

(1) build a qualitative understanding of commercial banana farming systems in northern Laos, taking into consideration land, water and agrochemical management;
(2) assess the environmental risks from pesticide usage in commercial banana farming, and compare this to other major commercially grown crops in the region;
(3) apply the PIRI model and evaluate its accuracy for estimating the environmental and human health risks from specific pesticide compounds in use; and
(4) test the utility of the low-cost GT test kit for detecting some commonly used pesticide compounds.

Methodology

We set about achieving our research objectives through four methods. First, we conducted a scoping mission in February 2016 to the three most prominent banana-producing provinces of Luang Namtha, Phongsaly and Oudomxay. Second, we collected environmental samples (surface water, soil, sediment and groundwater), and analyzed them in the laboratory to quantify the concentrations of pesticide residues and their breakdown products. Third, we implemented the PIRI risk assessment model to evaluate the relative risk associated with each pesticide. Fourth, we analyzed environmental samples using the low-cost GT test kit and compared these results against those from laboratory analyses.

Scoping Mission to Three Northern Provinces

Through the scoping mission, we built an understanding of commercial banana farming in the landscape across northern Laos, documented the specifics of land, water and agrochemical management in absolute terms and also in relation to other commercial crops, and identified a focal site where environmental samples would be collected to fulfill study objectives (2) to (4) above. The complete scoping mission documentation is included in Appendix 2, with a summarized version given below.

Farm visits and interviews with farmers, banana company staff and government officials were conducted to learn about farming practices, water management and trends in local agriculture (e.g., which crops were being replaced by bananas) (Figure 2). Photo records were taken of pesticides available in shops and empty containers discarded in fields or roadside garbage piles. Most pesticide containers were labeled in Chinese and had to be identified from an online database and translated using Google Translate (Institute for the Control of Agrochemicals 2021).

Study Area

The focal site was selected following the scoping mission based on the following criteria: (i) presence of banana farms with known ages; (ii) 'typical' field conditions; and (iii) proximity to farms growing other commercial crop types. Knowing the ages of banana farms in the study area was important to determine whether older plantations tended to be more polluted, potentially indicating the accumulation of residues over time. In such a scenario, we would expect to observe higher residue concentrations in samples from older farms. The 'typical' field conditions selected for the focal site were representative of irrigated hillslope farms. We anticipated that irrigated hillslope farms were likely to be associated with high rates of off-site pesticide migration due to their steeper slope combined with intensive farming practices (pesticide usage and irrigation).

The study area was located in Houn district, immediately north of the Sibounheuang village cluster, Oudomxay province, northern Laos. The study area was selected because it was the only site visited that had a small watershed dominated by banana farms and bordered by a similarly sized watershed dominated by other commercial crops (Figure 3). The two catchments had a combined area of 24.8 km^2 and were called NB and MC in this report because the dominant crop types were 'new banana' and 'mixed crops', respectively.

Figure 2. Farmworkers at a temporary packaging facility in Houn district, Oudomxay province, in February 2016. Blue plastic-wrapped banana racemes wait to be harvested in the background (*photo:* Touleelor Sotoukee).

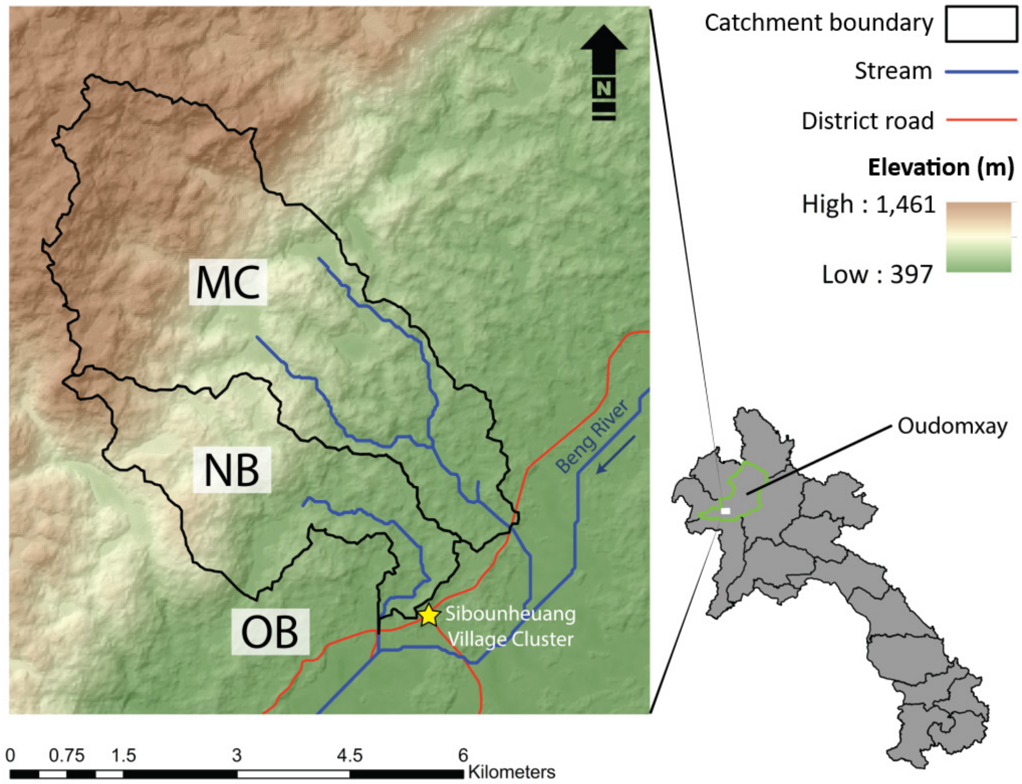

Figure 3. Map of the study area topography. Stream channel locations were estimated from a 10 m² digital elevation model.
Notes: MC - Mixed crops; NB - New banana; OB - Old banana.

Climate

Houn district has a tropical savanna climate with pronounced wet and dry seasons. The rainy season typically extends from late May to September, followed by a cool dry season from October to February, and a hot dry season from March to early May. The average annual rainfall was 1,415 mm over the period 1990–2004, as recorded by a weather station of the Department of Meteorology and Hydrology located in the provincial capital of Muang Xai (approximately 100 km to the northeast) (Figure 4). Although convection events cause considerable spatial and temporal variability in rainfall at the local scale, rainfall does not vary substantially across the area when observed at the monthly scale (Zveryaev and Aleksandrova 2004).

Topography and Geology

The study area consisted of two adjacent catchments situated within the Beng River sub-basin approximately 26 km upstream from the Beng River's confluence with the Mekong River. The Beng River valley has a southwest-northeast orientation and is bound on either side by steep mountains with interspersed valleys. A band of steeply sloped mountains consisting of Triassic marine limestone and Permian limestone karsts feature in the study area headwaters (Department of Geology and Department of Mines 2008). The mountains transition to extensive carboniferous sandstone hills and the valley floor, where unconsolidated Quaternary fluvial deposits form gently sloping rice paddy lands (Figure 5). Soils in the study area range from silt loams along ridgelines to heavy clays along ephemeral stream channels. Potential groundwater yield from karstic and alluvial aquifers in the study area is possibly high (as much as 10 liters per second [L/s]) (Viossanges et al. 2018). The village cluster of Sibounheuang contained two shallow wells for domestic use (i.e., cooking and washing). Sibounheuang's major drinking water source is listed as 'other' in the 2011 Agricultural Census, which means that it is neither river water nor well water (MAF 2014b). However, conversations with local residents revealed that people in the village who could not afford bottled water relied on the wells and springs for their domestic water supply.

Streamflow in the study area fluctuated substantially between the dry and wet seasons. The average daily streamflow recorded as part of this study increased from 0.2 m^3/s in May to 2.8 m^3/s in September (Appendix 3).

Land Use

The two catchments featured different crop types in the lower parts. The NB catchment (7.7 km^2) comprised predominantly of new banana plantations (since 2012), transitioning to maize and upland rice fields dotted with limestone outcrops, and eventually forest and scrubland in the headwaters. The MC catchment (17.1 km^2) supported a wider variety of crop types, including maize, rubber,

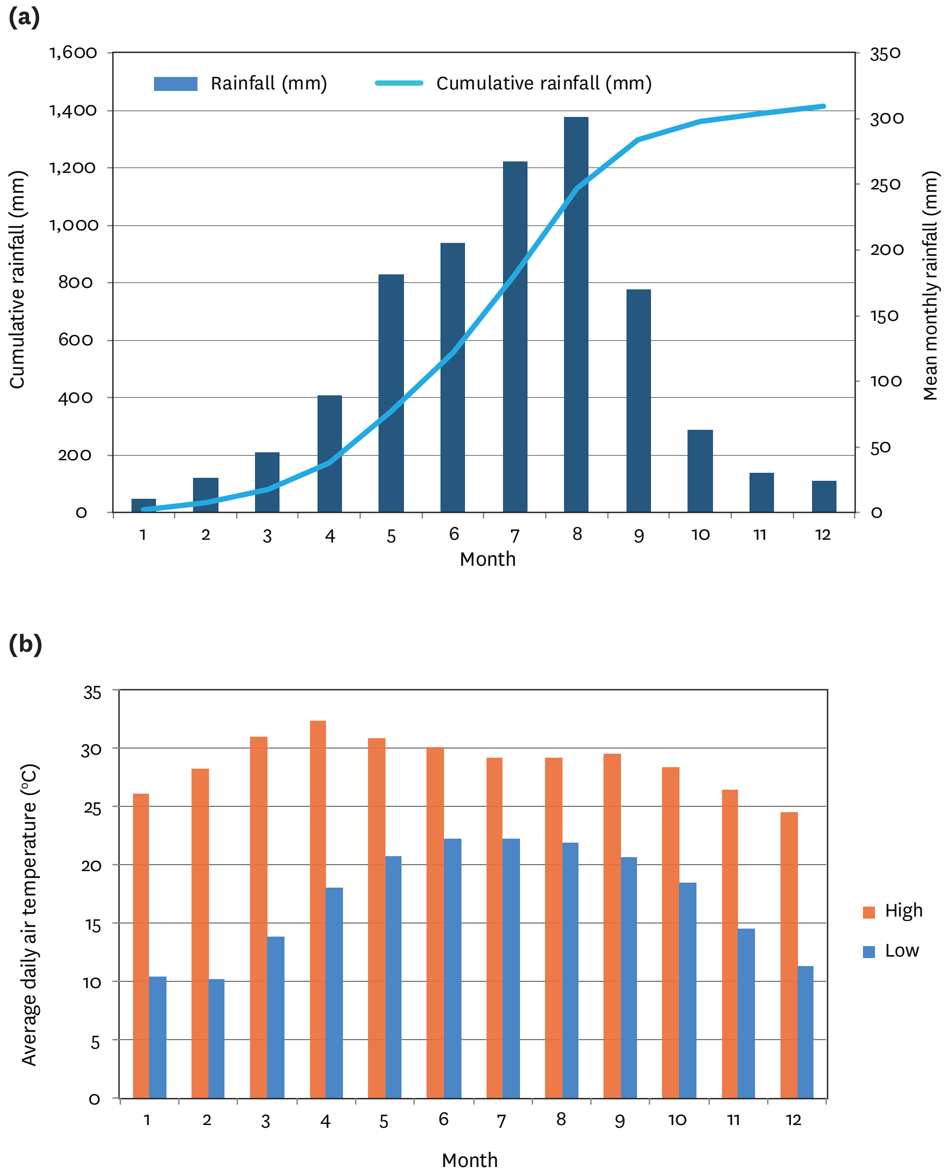

Figure 4. (a) Mean monthly rainfall, and (b) daily high and low temperatures recorded at the Muang Xai climate station over the period 1990–2004.
Source: Department of Meteorology and Hydrology.

upland rice, gourd and banana fields connected to the farm in the NB catchment near the outlet. The headwaters of the MC catchment were also predominantly covered in forest and scrubland.

An older banana farm, referred to as OB in this study, was located beyond the southwestern boundary of the NB catchment (Figure 3). This farm was the first commercial banana farm in the area according to the deputy village head, with the land being used for the cultivation of commercial bananas since 2010, and covering an area of approximately 60 ha.

Farming Practices

Water management in the two study area watersheds varied depending on crop type. All crops except for banana (and paddy rice) were under rain-fed cultivation. For the banana farms, water from the Beng River was pumped to a series of small- to medium-sized storage ponds located on ridges and hilltops. From the storage ponds, water was gravity fed through a network of polyvinyl chloride (PVC) pipes to fields, where it was delivered to crops via perforated flexible plastic tubing.

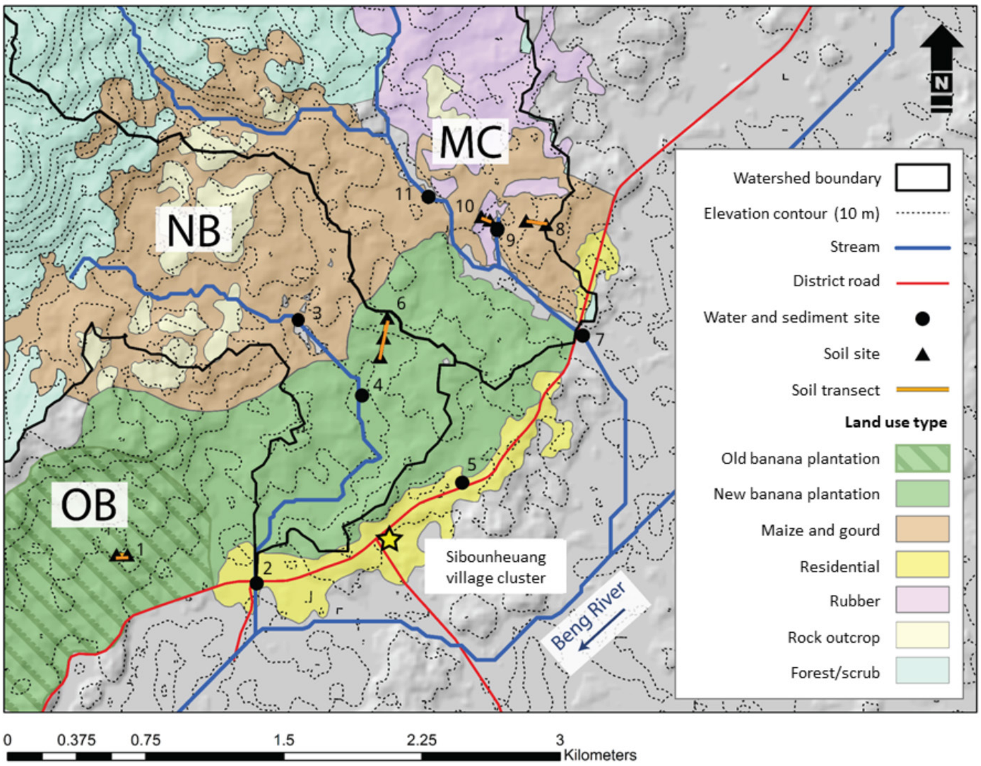

Figure 5. A map of the study area including soil and water sampling locations and land use types in the lower portions of the watersheds.

Notes: MC - Mixed crops; NB - New banana; OB - Old banana.

1 = OB_Soil transect, 2 = NB_SW3 and GW1, 3 = NB_SW1, 4 = NB_SW2, 5 = GW2, 6 = NB_Soil transect, 7 = MC_SW3, 8 = MC_Soil_Maize transect, 9 = MC_SW2, 10 = MC_Soil_Rubber transect, and 11 = MC_SW1.

Deep field tillage, lack of erosion controls, and fields' proximity to streams created conditions conducive to elevated soil erosion and transport to watercourses. For example, sedimentation, which occurred after a period of heavy rainfall in August 2016, raised the elevation of the stream beds in the NB and MC catchments by almost 0.5 meters (m). All crops grown in the lower portions of the study area closely abutted streams. Riparian vegetation buffers were small, ranging from 0 to 2 m in width.

Detailed information about pesticide application rates was highly uncertain for all crops in the study area, largely because the farmworkers interviewed applied compounds (stored in Chinese-labelled containers) in different amounts throughout the fields, often only where pests were observed. Banana farmers applied insecticides and fungicides approximately twice a month beginning one month before flowering and ending one month before the annual harvest (a total of 9–10 applications). Herbicides were usually applied three times per growing cycle. While the amount applied varied due to the type of chemical used and the degree of weed growth, it was approximately 2 kg/ha (~0.15 mg/plant, assuming 1 L = 1 kg) on average. Although application rates for maize and rubber farms were not available for the study area, previous research from rubber farms in China found that herbicides (10% glyphosate) were typically applied twice annually at a rate of 10 kg/ha, whereas pre-emergence herbicides are normally applied only once a year to maize fields in Thailand (Ekasingh et al. 2004; Liu et al. 2016). Understory growth in the rubber tree plantation was limited to sparse grasses, perhaps resulting from herbicide application typical in rubber tree plantations in Laos, but unconfirmed in the study area (Liu et al. 2016).

Field Sampling

Samples of surface water, groundwater, streambed sediment and soil were collected during two field missions—dry and wet season—to observe seasonal patterns (Table 1). Dry season sampling occurred during May 2016 while wet season sampling took place in September 2016. Three surface water and three sediment sampling locations were chosen in each of the two catchments to capture longitudinal patterns in pesticide residue concentration. Streambed sediment and surface water samples were also collected from the main stem of the Beng River to serve as a reference for water quality.

Streamflow

The research team installed staff gauges at the outlets of the two catchments on May 12, 2016, and staff from

Table 1. Number of samples collected during the two field missions by media type for each land-use type.

Media type	MC catchment (dry/wet)	NB catchment (dry/wet)	OB soil transect (dry/wet)	Beng River (dry/wet)
Groundwater	—	2 / 2	—	—
Surface water	1 / 3	3 / 3	—	1 / 1
Sediment	1 / 3	3 / 3	—	1 / 1
Soil	4 / 4	3 / 3	2 / 2	—

the District Agriculture and Forestry Office (DAFO) manually measured daily stream discharge from May 14 to September 22, 2016. However, the record had many gaps, and an intense storm, which occurred on August 19, 2016, washed away the staff gauge at the outlet of the NB catchment. The average flow velocity was calculated from three manual measurements of flow velocity that were taken when samples were collected. Discharge (*Q*) was calculated from equation (1):

$$Q = V \times A \tag{1}$$

Where: V is the velocity and *A* is the cross-sectional flow area. Velocity was measured by recording the average time it took a floating object (e.g., a small lime) to cover a known distance (e.g., 1 m). We calculated the cross-sectional flow area by multiplying the width of the channel by the average of three depth measurements.

Surface Water

Surface water grab samples were collected from streams at seven sites during the wet season (on May 12, 2016) and from only five sites during the dry season (September 25–26, 2016) due to extremely low or no-flow conditions. Samples were collected in 1 L amber glass jars following standard protocols for pesticide analysis (Shelton 1994).

In the NB catchment, one sampling point (NB_SW1) was located upstream of the banana farm to measure pesticide residue concentrations before being influenced by runoff from the banana fields (Figure 5). NB_SW2, NB_SW3 and MC_SW3 were all located at points in the stream that received runoff from banana fields. Surface water samples were not collected from the OB catchment, because the catchment was too small for any permanent stream channels to develop. We also measured the basic physiochemical properties of the surface water and groundwater samples (temperature, pH, electrical conductivity (EC) and total dissolved solids) in the field using a portable meter (Hanna Instruments - HI98129).

Groundwater

Groundwater samples were collected from two wells at downstream locations (Figure 5) during each sampling mission. Samples were collected from wells with a PVC bailer and were stored in the same type of 1 L amber glass jar used to transport surface water samples. Samples were collected from the wells without pumping beforehand to represent the water that would be used by nearby residents.

GW1 was located on the stream bank at the outlet of the NB catchment. Residents from the surrounding houses used water from the GW1 well for bathing and washing clothes. The well also served as a source of water for drinking and cooking for households unable to afford bottled water. The second groundwater sampling site, GW2, was a private well located in a small catchment between the outlets of NB and MC catchments (Figure 5). It is unknown how the water from the GW2 well was used, and whether it was only used privately or was also available for use by the community. The GW2 well site was modified between sampling missions. A mound of soil was piled behind the house by the owners, and the top of the casing was extended by approximately 2 m to match the new ground surface elevation. Depth to water at GW1 was 1.24 m below the ground surface during the dry season and 1.31 m during the wet season (it should be noted that the wet season measurement was taken approximately 30 minutes after villagers had drawn water from the well for bathing and washing clothes and the exact amount withdrawn was unknown). Depth to water in the dry season at GW2 was 6.93 m below the ground surface and 4.38 m in the wet season (approximately 2.38 m below the original ground surface elevation).

Sediment

Sediment samples were collected from depositional zones of stream beds within 50 m upstream of surface water sampling locations following standard procedures (Shelton and Capel 1994). After collection, samples were kept on ice to minimize pesticide residue degradation until they could be sent to the laboratory for analysis. Composite sediment samples were collected from wetted stream beds to a depth of 10 cm using a galvanized steel pipe. Sediment samples were not collected from the upper portions of the MC catchment due to no/low-flow conditions during the dry season.

Soil

Soil samples were collected along four transects; one in each of the most common commercial crop types, including new banana (three sampling points), old banana (two sampling points), maize (two sampling points), and rubber (two sampling points). Transects were located to follow the flow path of runoff through a field from higher to lower elevation and it varied in length and steepness depending on the fields' characteristics (Figure 6). This approach was chosen to determine whether pesticide residues had accumulated in downslope portions of the fields.

Composite samples were collected at each location along the sampling transect. Each composite sample consisted of nine individual soil cores taken to a depth of 20 cm with a galvanized steel pipe (Figure 6). Samples were taken from each square excluding the center square in the case of banana and rubber sites where the tree roots were very thick and obstructed sampling.

Sample Analysis

Laboratory Analysis of Soil Properties

Soil properties, including texture, pH, organic matter content, exchangeable potassium, available phosphorus and cation exchange capacity, were analyzed at the Khon Kaen University Agricultural Development Research Center, Thailand. Soil pH was measured from a 1:1 solution of soil and water. Ammonia and organically bound nitrogen were measured using the Kjeldahl method (Kirk 1950), organic matter (OM) percentage using the Walkley-Black method (Walkley and Black 1934), and exchangeable potassium (K) using atomic absorption spectrophotometry. Available phosphorus (P) was measured using the Bray number 2 extraction method and spectrophotometry, and cation exchange capacity (CEC) was measured as a function of ammonium saturation, leaching and distillation for ammonium.

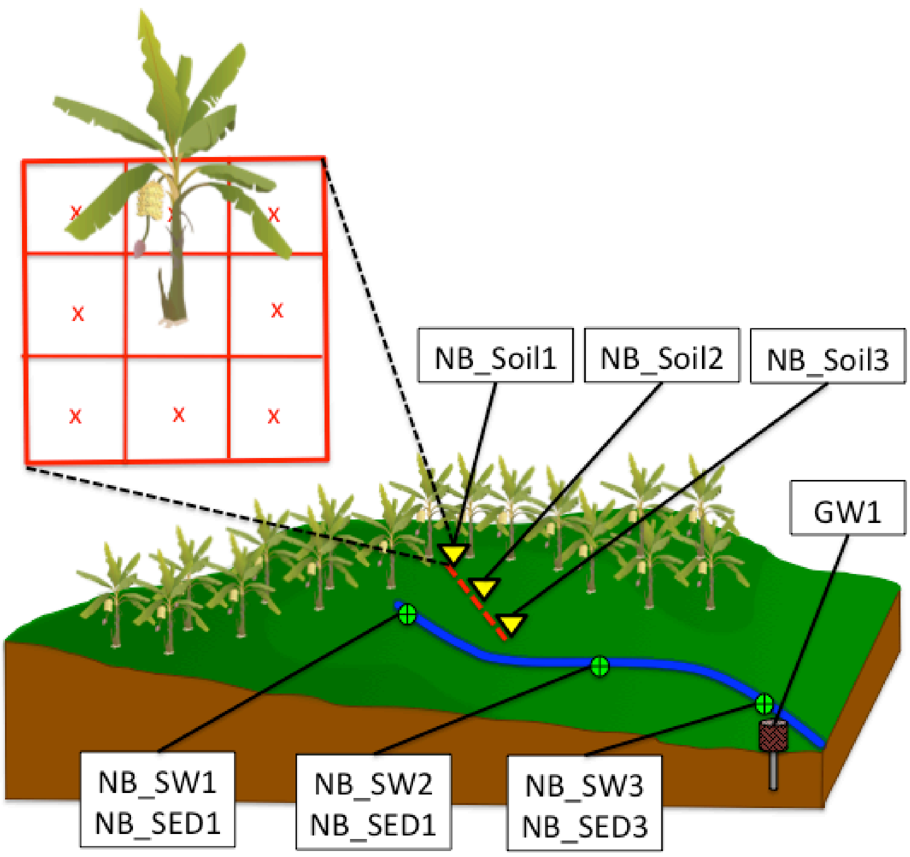

Figure 6. A conceptual diagram of surface water, groundwater, streambed sediment, and soil sampling protocol from the new banana catchment. The inset diagram shows the 2.25 m^2 grid used to guide soil sampling. Each smaller square was 0.5 m x 0.5 m.

Notes: NB – New banana, SED – sediment sampling location, SW – surface water sampling location, GW – groundwater sampling location.

Laboratory Analysis of Pesticide Residues

In total, residues from 40 compounds were analyzed, including pesticide active ingredients and their major (i.e., persistent) breakdown products (e.g., the insecticide DDT and its breakdown products Dichlorodiphenyldichloroethane [DDD] and Dichlorodiphenyldichloroethylene [DDE]). Twenty compounds referred to in this study as Currently Used (CU) compounds were selected because they were observed as being used in the field (usually as discarded containers or stored on the farm). Twenty highly persistent OC compounds were selected for two reasons. First, the National University of Laos (NUOL) Department of Chemistry could analyze their residue concentrations. Second, these compounds can pose a considerable threat to environmental and public health for many years after their use. We chose to analyze many OC compounds' breakdown products because they too are hazardous and can contribute significantly to the overall risk from pesticide residues over time. Table 2 lists the names of the compounds analyzed, their chemical class, World Health Organization (WHO) hazard class and the laboratory where the analyses were performed. The pesticides fell into the following hazard categories: II - Moderately hazardous, III - Slightly hazardous, U - Unlikely to be hazardous, and NL - Not listed (WHO 2010).

Samples were analyzed for pesticide residues at two laboratories: (i) National University of Laos, Department of Chemistry, Vientiane, Lao PDR (simply called NUOL; not International Organization for Standardization [ISO] accredited); and (ii) SGS Vietnam Ltd., Ho Chi Minh City, Vietnam (ISO 9001 accredited). The NUOL laboratory analyzed samples for OC compounds and chlorpyrifos residues, while SGS Vietnam Ltd. analyzed samples for the remaining 19 compounds listed in Table 2 and chlorpyrifos. Dry season samples were analyzed only at NUOL whereas wet season samples were analyzed at both NUOL and SGS.

At NUOL, samples were analyzed for residues from OC pesticides and chlorpyrifos using the QuEChERS (quick, easy, cheap, effective, rugged and safe) method (Carneiro et al. 2013). At the SGS Vietnam Ltd. laboratory, pesticide residues were analyzed using standard methods. The British Standards European Norm (BS EN) 15662:2008 method was used to analyze samples for acetamiprid, azoxystrobin, bifenthrin, carbosulfan, chlorothalonil, chlorpyrifos (-ethyl), fenbuconazole, fenpropathrin, imidacloprid, iprodione, kresoxim-methyl, prochloraz, pyridaben, tebuconazole, thiamethoxam, thiophanate-methyl and thiram. The European Union Reference Laboratory for Single Residue Methods (EURL-SRM) (version 2, 2009) was used to analyze samples for dithiocarbamate (expressed as CS2, including maneb, mancozeb, metiram, propineb, thiram and ziram). The EURL-SRM method[2] was used to analyze samples for propineb (as propylenediamine). The method by Kolberg et al. (2012) was used to analyze samples for paraquat.

Quality Assurance and Quality Control

Samples were kept in ice chests to minimize pesticide residue degradation during the trip from the study area to Vientiane, where they were either delivered to the NUOL laboratory or sent to the SGS laboratory in Vietnam.

Wet season samples sent to the SGS laboratory were delayed by Vietnam Customs and kept in ambient air temperature conditions for approximately two weeks, which likely resulted in the loss of CU pesticide residues due to degradation. We, therefore, expect that our assessment of the risks from pesticide residues will be inherently conservative.

To estimate the fraction of residues lost across all CU compounds, we compared the concentration of chlorpyrifos (the only compound analyzed in both laboratories) detected in wet season samples at the NUOL laboratory against the concentration of chlorpyrifos detected in the wet season samples sent to SGS. Since the wet season samples analyzed at NUOL had been kept cool from the time of collection, they provided a valuable comparison against the samples that were sent to SGS.

The percentage loss from other compounds besides chlorpyrifos was estimated using a first-order degradation kinetics model (Walker 1976; Dykaar and Kitanidis 1996). Residue concentration (C_t) was predicted as a function of the initial concentration (C_o), the compound-specific degradation rate constant (k), and time (t):

$$dC_t \, / \, d_t = -kC_o \qquad (2)$$

The degradation rate constant was calculated from values for half-life ($t_{1/2}$) reported in the literature:

$$k = (\ln 2) \, / \, t_{1/2} \qquad (3)$$

The estimated fraction lost for each compound is provided in Appendix 5.

Field Test Kit

Samples collected during the wet season field mission were kept refrigerated and analyzed using the GT test kit within 10 days of sampling. Each sample was prepared as per instructions provided with the GT test kit (G9 Company 1997). Five grams of soil and sediment samples were blended manually, solvent was used to extract OP and carbamate pesticide residues, and the excess water was evaporated at 32–36 °C. Sample extracts were then added to a test tube containing cholinesterase enzyme, which changed

[2] https://www.eurl-pesticides.eu/docs/public/home.asp?LabID=200&Lang=EN

Table 2. Pesticide compounds analyzed. Pesticide names listed in **bold** were observed as being used in the study area.

Intended use	Chemical class	Pesticide name (**bold** = **CU compound**)	Half-life in soil (days)	K_{oc} (L/kg)	WHO hazard class	Laboratory
Insecticide	Carbamate	**Carbosulfan**	13	8,500	II	SGS
	Neonicotinoid	**Imidacloprid**	40-124	262	NL	
		Acetamiprid	8.2	343		
		Thiamethoxam	8-44	68.4		
	Organochlorine	4,4'-DDT	730-5,475	151,000	II	NUOL
		Cis-Chlordane	3,650-7,300	20,000		
		Heptachlor	146-292	24,000		
		Trans-Chlordane	37-3,500	20,000		
		Methoxychlor	120	80,000	U	
		4,4'-DDD[a]	365	150,000	NL	
		4,4'-DDE[a]	2,920	50,000		
		Aldrin	365	17,500		
		Dieldrin	30-1,825	12,000		
		Endosulfan I[b]	35	11,500		
		Endosulfan II[b]	150	10,715		
		Endosulfan sulfate[b]	30-103	5,194		
		Endrin	4,380	10,000		
		Endrin aldehyde[c]	1,460	4,300		
		Endrin ketone[c]	--	173,780		
		Heptachlor epoxide[d]	183-1,278	22,485		
		Lindane (a-BHC)[e]	120	1,888		
		Lindane (b-BHC)[e]	120	3,715		
		Lindane (g-BHC)[e]	120	3,715		
		Lindane (d-BHC)[e]	120	6,309		
	Organophosphorus	**Chlorpyrifos**	7-141	9,930	II	SGS, NUOL
	Pyrethroid	**Bifenthrin**	97-250	237,000		SGS
		Fenpropathrin	34	5,000		
	Unclassified	**Pyridaben**	82	66,503	III	
Herbicide	Bipyridylium	**Paraquat**	426-4,745	15,473-1,000,000	II	
Fungicide	Azole	**Tebuconazole**	28-1,260	1,000		
		Prochloraz	11.4-61.7	2,225	III	
		Fenbuconazole	79-365	4,425	U	
	Benzimidazole	**Thiophanate methyl**	0.7-867	225		
	Dicarboximide	**Iprodione**	14	700		
	Dithiocarbamate	**Thiram**	< 1-77	9,629	III	
		Mancozeb	28-56	6,000	U	
		Propineb	2	18		
	Organochlorine	**Chlorothalonil**	10-60	1,790		
	Strobin	**Azoxystrobin**	14	581		
		Kresoxim-methyl	< 1-34	437	NL	

Sources: Kim et al. 2016; Kegley et al. 2016.
Notes: [a] DDT metabolite, [b] Endosulfan metabolite, [c] Endrin metabolite, [d] Heptachlor metabolite, [e] Lindane metabolite.
SGS = SGS Vietnam Ltd. analytical laboratory; K_{oc} = Sorption coefficient.

color according to the fraction of cholinesterase inhibited. Residue concentrations estimated with the GT test kit were approximated according to the percentage of cholinesterase enzyme that was inhibited after exposure to the sample.

According to GT test kit instructions provided by the G9 Company, the test classifies results into three categories: 'Non-Detection', 'Low-Detection', and 'High-Detection'. Samples are considered 'Non-Detection', if less than 50% of the cholinesterase was inhibited. Low-Detection corresponds with approximate cholinesterase inhibition levels equal to 50%, and High-Detection corresponds with approximate cholinesterase inhibition levels greater than 50%. This process was undertaken visually by comparing the color of the samples against a control which had no inhibition, and a 'spiked' sample with approximately 50% inhibition (Figure 7).

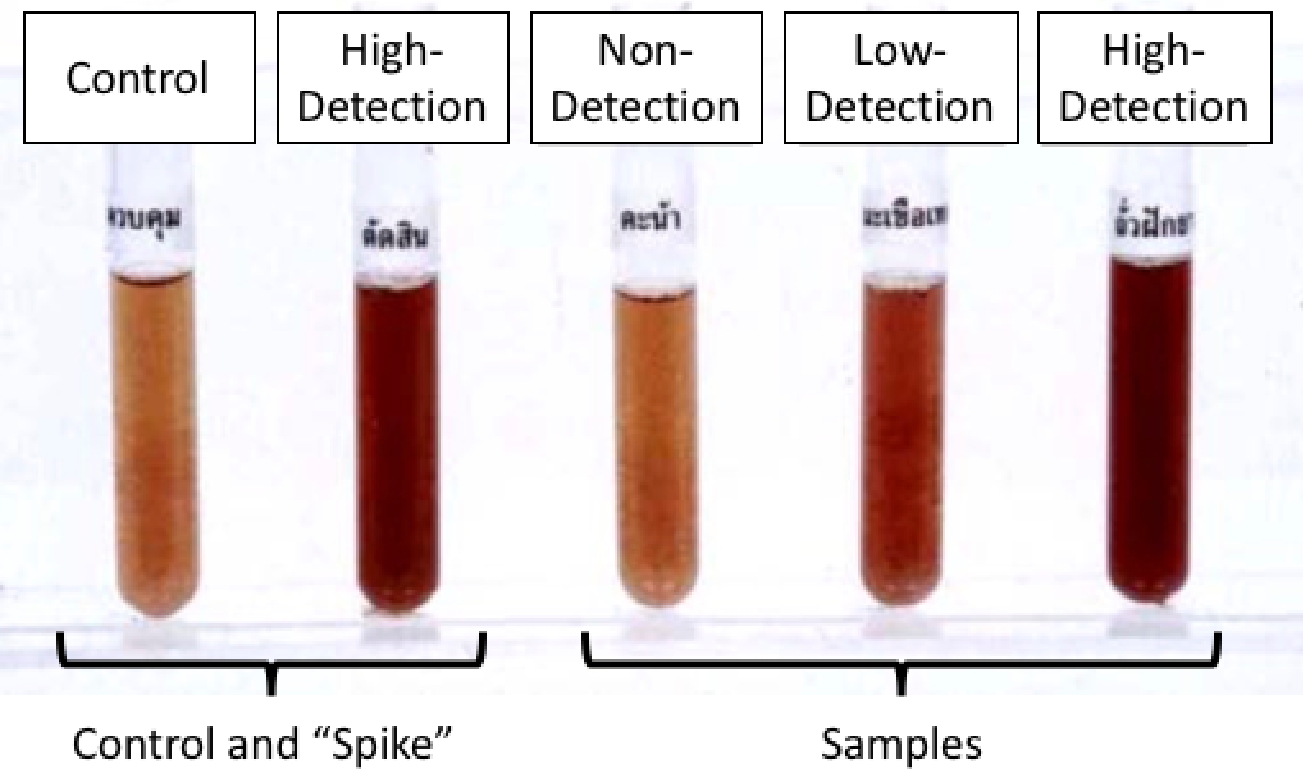

Figure 7. An example of the GT test kit results. Darker color indicates greater cholinesterase inhibition.
Source: G9 Company 1997.

Risk Assessment Modelling

The estimated degree of risk calculated using the PIRI model was compared against results from laboratory analysis to explore whether PIRI can be used to accurately identify pesticides that pose a higher risk to surface water quality. Risks to groundwater were not included in this study because geologic data required to estimate recharge were unavailable. Agreement between the results of the model (toxicity rating) and laboratory analysis was assessed by correlation, although no specific threshold was chosen as a cutoff for an acceptable versus an unacceptable degree of agreement.

PIRI's qualitative prediction of off-site migration potential includes representations of the major pathways through which pesticides are released into surface water and groundwater resources: runoff, erosion, aerial drift and leaching (Kookana et al. 2005). Each component is quantified using pesticide characteristics (i.e., half-life, sorption coefficient [K_{oc}], etc.) in addition to environmental and site-related characteristics (i.e., soil organic carbon content, water input, the slope of land, etc.). The description of pesticide characteristics, including the K_{oc}, can be found in Tables 2 and 3.

Fish were chosen as the target species for this application, because many farmers who were interviewed during the scoping mission expressed concern about the impacts of pesticides on fisheries in the area. Rainbow trout was considered an acceptable proxy species, because a study of the fish immune response to OP pesticide exposure observed toxic effects at similar orders of magnitude in rainbow trout as in two fish species (tilapia and carp) commonly farmed in the area (Díaz-Resendiz et al. 2015). The risk level is determined by the lethal concentration at which 50% of fish die after exposure (LC_{50}), typically within 96 hours.

Eleven of the pesticides that were observed on banana farms were available in the database of pesticide properties that comes built-in with the PIRI model (Table 3). Frequency and amount of pesticide applications were a major source of uncertainty in the modeling effort, because interviewees were unable to provide definitive information. As such, a combination of farmworkers' descriptions and manufacturer recommendations were used to estimate likely application rates and frequency.

Table 3. PIRI model inputs for pesticide properties (half-life and K_{OC}), and application rate and frequency deduced through information collected from farmers.

Pesticide name	Half-life (days)	K_{oc} (L/kg)	LC_{50}, fish (mg/l)	Application frequency (times/year)	Active ingredient application rate (L/ha/year)
Azoxystrobin	78	589	0.47	6	2.46
Bifenthrin	26	236,610	0.00026	2	0.65
Chlorothalonil	22	850	0.038	2	5
Chlorpyrifos	50	8,151	0.0013	3	2
Imidacloprid	191	225	211	5	0.56
Kresoxim-methyl	16	308	0.19	3	0.375
Metiram	1	500,000	0.33	6	4.5
Paraquat	3,000	1,000,000	19	1	3.2
Propineb	3	18	0.4	2	2
Tebuconazole	63	769	4.4	2	1
Thiophanate-methyl	0.6	40	11	1	1.68

Source: Heller et al. 1990.

Results

The concentration of pesticide residues for each catchment and media type are presented in two groups: currently used (CU) compounds and organochlorine compounds (OC). The CU compounds group consisted of 20 pesticides that were observed on farms in the study area during the field visits (Table 2). The OC group consisted of 20 pesticides and their breakdown products (e.g., DDT, DDD and DDE). None of the OC compounds listed in Table 2, excluding chlorothalonil, were observed as being used in the field. However, their tendency to persist in the environment at potentially harmful levels (evidenced by their long half-lives [Table 2]) was the reason for including them in the study (Colborn et al. 1993). We interpreted OC pesticide residue levels as representative of the legacy effects of historical pest management practices on environmental health. Assuming the FAO assessment that these OC compounds have not been used in Laos for some years is correct, it is likely that OC application preceded the establishment of commercial banana farms and perhaps rubber and maize cultivation as well. It is possible, although unproven, that OC compounds were used in Laos as part of public health programs to prevent malaria, as has been done elsewhere (van den Berg 2009).

The maximum residue concentrations observed for each compound are found in the following section. We presented the maximum concentrations observed because they provide a more conservative estimate of the environmental risk from each compound even though it obscures seasonal trends in residue concentrations. Nonetheless, the two sampling trips were unlikely to capture short duration peak residue concentrations from non-point source pollution that would be expected to follow pesticide application (Richards and Baker 1993). Because seasonality is an important consideration for understanding the results and eventually for designing an appropriate management strategy, analysis of wet versus dry season concentrations is covered later in this section.

Scoping Mission

Banana farm locations in the landscape varied across the three provinces; however, they tended to be located on flat or gently sloping land near perennial streams from which water could be diverted to supply dry season irrigation. Three distinct banana farm typologies were evident: (i) irrigated upland plain, (ii) irrigated hillslope, and (iii) rain-fed hillslope. Plantation size, water management and the level of chemical inputs varied noticeably across farm types. Distance to surface water appeared to be the key factor that determined whether farms were irrigated, with farms further than a few kilometers from water bodies not having access to irrigation water. Irrigated farms appeared to use agrochemicals more intensively and plant banana trees more densely than rain-fed farms. Both irrigated upland plain and irrigated hillslope farms relied on heavy chemical inputs to maximize yields, whereas rain-fed hillslope farms used much smaller amounts of fertilizer and pesticides.

Water management systems observed in northern Laos varied across farm types; with some farms using sophisticated irrigation technology, others having rudimentary irrigation systems, and some having no irrigation at all. Despite their large water requirements, waterlogging negatively impacts bananas. Therefore, banana farms on flatlands often featured drainage ditches to remove excess water from the root zone.

A variety of water sources were used to meet irrigation demands depending on the farm setting. Irrigated upland plain farms in Luang Namtha diverted water from small tributary streams for storage in unlined ponds. On the other hand, irrigated hillslope farms in Oudomxay pumped as much as 5,000 m^3 of water per day from the main stem of the Beng River and stored it in large plastic-lined ponds. Irrigation water was typically delivered to plants via perforated plastic tubing run between alternating rows of crops. One farm manager in Oudomxay claimed that 4,000 m^3/day of water was used during the dry season for his 120 ha farm, and this was applied to one of four quadrants on a rotating basis, so that each quadrant received water one out of four days (average 13 mm/day or approximately 2,300 mm in total over the dry season).

The type of crops being replaced by bananas also varied across farm types. On hillslope farms, bananas had typically replaced maize, whereas paddy rice and sugarcane had been substituted with bananas on upland plain farms.

In general, farmworkers did not know which pesticides they were using because the labels were mostly printed in Chinese. They also could not provide the details about the timing and amount of pesticides applied. However, a farm manager interviewed in Houn district, Oudomxay province, described that a wide variety of pesticides were used throughout the year, with some being used only for a brief period or in the event of certain pest or disease outbreaks. Generally, herbicides were used broadly three times during the year, whereas some insecticides were only used after flowering. The frequent herbicide usage and dense canopy that developed after the bananas reached their full height created nearly bare soil conditions underneath the banana canopy. Without a vegetative cover to protect the soil surface, raindrop impacts and other weathering processes can lead to severe soil erosion, creating a pathway for runoff enriched with sediment-bound pesticides to be transported off-site (Lacombe et al. 2016).

Streamflow and Basic Water Chemistry

Streamflow in the study area increased substantially from the dry season to the wet season at both catchment outlets (Table 4). From the data recorded, it can be inferred that both the NB and MC systems had regular flash flows (Figure 8), responding quickly to high-intensity rainfall events typical of the wet season in Laos (Yazid and Humphries 2015). Streamflow in the NB catchment increased from upstream to downstream, indicating that subsurface flow is a contributing source. The same can be said for the MC catchment. However, measurements from MC_SW1 to MC_SW2 and MC_SW3 were not directly comparable with those from NB_SW1, NB_SW2 and NB_SW3, because MC_SW2 was located on a smaller tributary to the main channel (Figure 5). MC_SW2 was located on a small tributary to the main stream because it was discovered that the lowermost reaches of the MC catchment were downslope from banana fields.

Field conditions changed considerably between dry and wet season field missions. Streamflow at the catchment outlets increased by an order of magnitude, with running water being observed in the upper reaches of the MC catchment, which had been dry in May. Sediment deposited at the NB_SW3 sampling site in between missions caused the channel to deviate by approximately 2 m from its previous course, and the staff gauge at the MC_SW3 sampling site was buried by 50 cm of sediment deposits.

Pesticide Residue Concentrations

Residue concentrations are shown by catchment and media type to illustrate trends across the study area. Relationships between crop type and concentration levels are included later. In interpreting Figures 9 to 14, it is important to note that the site names correspond to the catchment name and do not accurately reflect the crop type(s) present. For example, MC_SW3 was located at the outlet of the MC catchment, where it was affected by runoff from mixed commercial crops (maize, rubber and gourd) as well as banana fields in the lower portion of the MC catchment (Figure 5). On the other hand, NB_SW1 was located above the banana farm in the NB catchment and, therefore, did not receive runoff from banana fields.

Table 4. Streamflow at each surface water sampling site measured concurrently with sample collection.

Site name	Dry season streamflow (L/s)	Wet season streamflow (L/s)
MC_SW1	‘No flow’	13
MC_SW2	‘No flow’	13
MC_SW3	1	28
NB_SW1	‘Very low flow’	2
NB_SW2	‘Very low flow’	12
NB_SW3	2	42

Note: No flow = 0 L/s; Very low flow = < 1 L/s.

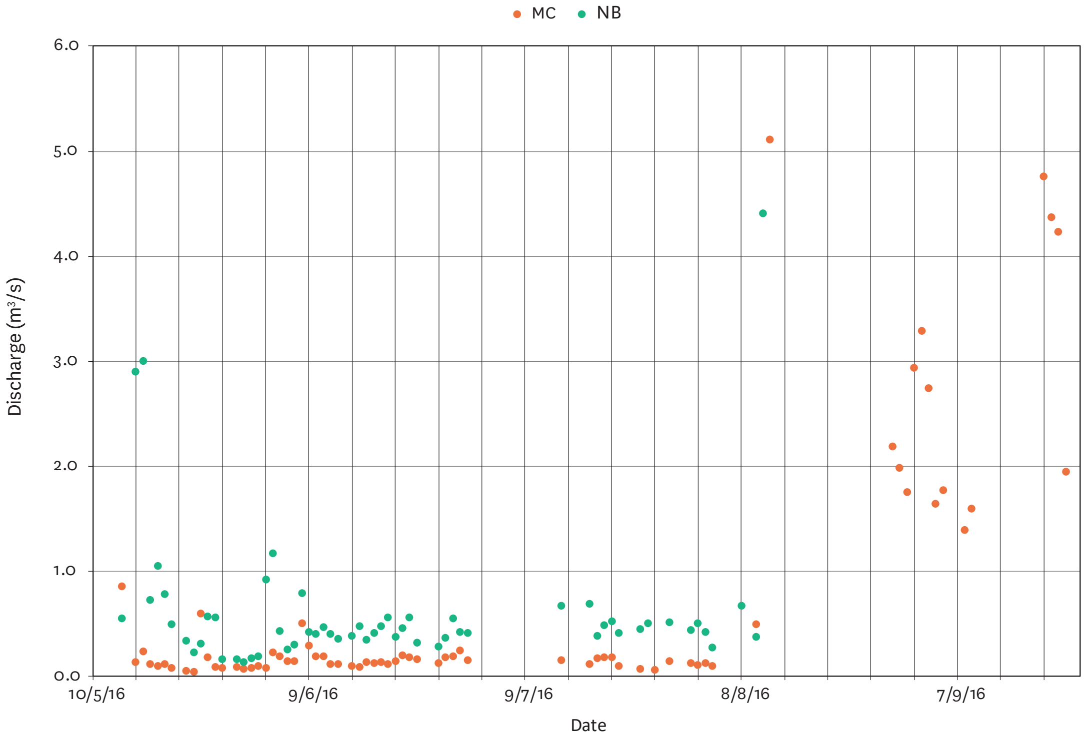

Figure 8. Streamflow observed at outlets from the NB and MC catchments. There were several gaps in the streamflow records, because the DAFO staff member responsible for taking measurements was unable to access the site due to conflicting work responsibilities and/or dangerous high-water conditions.

Quality Assurance and Quality Control

Reported values for chlorpyrifos residues were typically two times higher in the samples analyzed at the NUOL laboratory than those examined at the SGS laboratory. The degradation rate of chlorpyrifos is moderate (half-life = 7 to 144 days) compared to some of the other compounds included in this study. For example, paraquat breaks down at a much slower rate (half-life = 426 to 4,745 days) while kresoxim-methyl breaks down considerably faster (half-life = < 1 to 34 days).

From the first-order kinetics model, it would be expected that losses of some compounds such as endrin and paraquat would be 0–2%, whereas residues from other compounds such as propineb might be nearly fully degraded (Appendix 5, Table A5).

Surface Water Detections

For the CU pesticides, wet season surface water samples from both catchments (MC and NB) contained chlorpyrifos and imidacloprid residues, but paraquat was only detected in the MC catchment (Figure 9). Chlorpyrifos and imidacloprid were observed more frequently and at much higher concentrations in surface water samples from the NB catchment than the MC catchment. Small amounts of chlorpyrifos were detected at all three sites in the MC catchment. Chlorpyrifos levels at MC_SW1 and MC_SW2 were very low at 0.006 µg/L and 0.005 µg/L, respectively, and increased to 0.089 µg/L at MC_SW3. In the NB catchment, the concentration of imidacloprid increased from upstream to downstream. This occurred despite the diluting effects of increased streamflow along the same drainage line. On the other hand, chlorpyrifos residues increased from NB_SW1 to NB_SW2, but proceeded to decrease between NB_SW2 and NB_SW3. This finding suggests that chlorpyrifos was applied more heavily nearby NB_SW2, and then residue levels declined either due to dilution, chemical breakdown or adsorption to sediment particles as it moved through the system.

OC pesticide residues were also found in surface water samples from both NB and MC catchments (Figure 10). Of the 20 OC compounds analyzed, 18 were observed in NB surface water samples and 12 in MC surface water samples. The compounds that were observed in higher concentrations (DDT, dieldrin, heptachlor and lindane breakdown products) were similar across both catchments. However, there was no clear pattern in OC residue levels with respect to the position along the flow paths, except for the lindane breakdown products (a-, b-, g-, and d-BHC), which peaked at NB_SW1 and declined in the two downstream sites. DDT residues were greater than the related breakdown products (4,4'-DDD and 4,4'-DDE) across four of the six SW sites where it was detected.

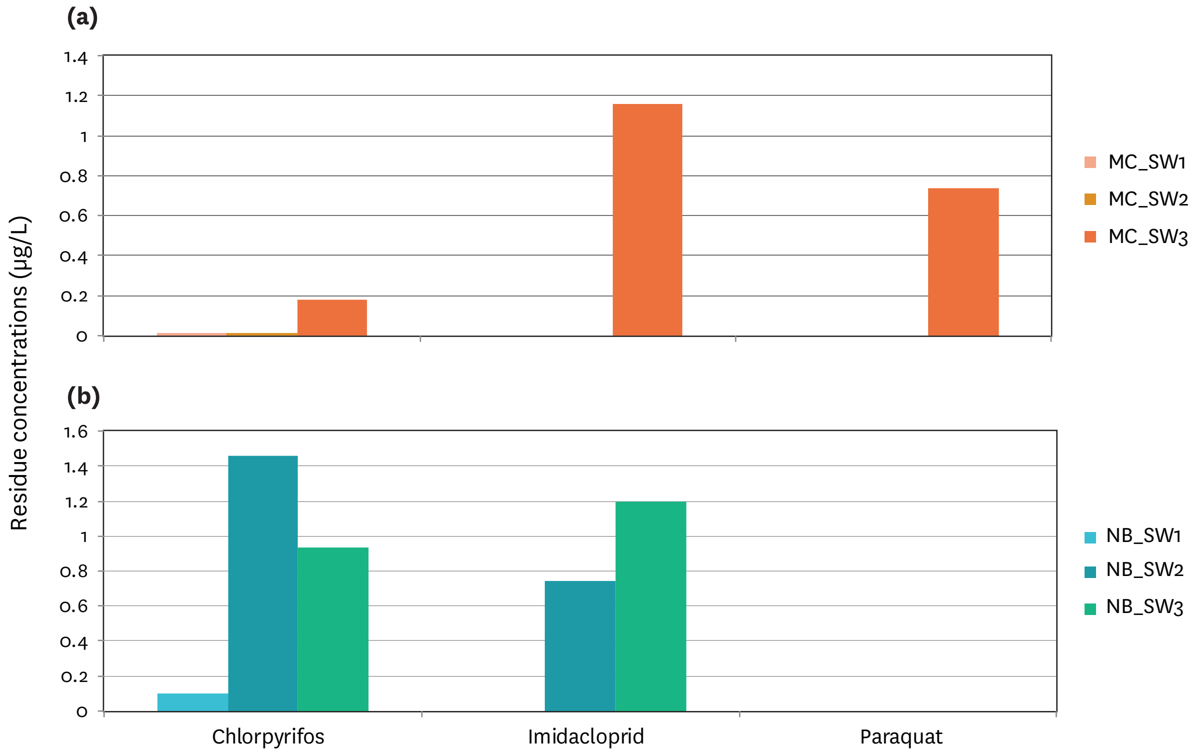

Figure 9. Maximum concentrations of CU pesticides in the wet season surface water samples in (a) MC, and (b) NB catchments. Compounds that were not detected were omitted from the chart.

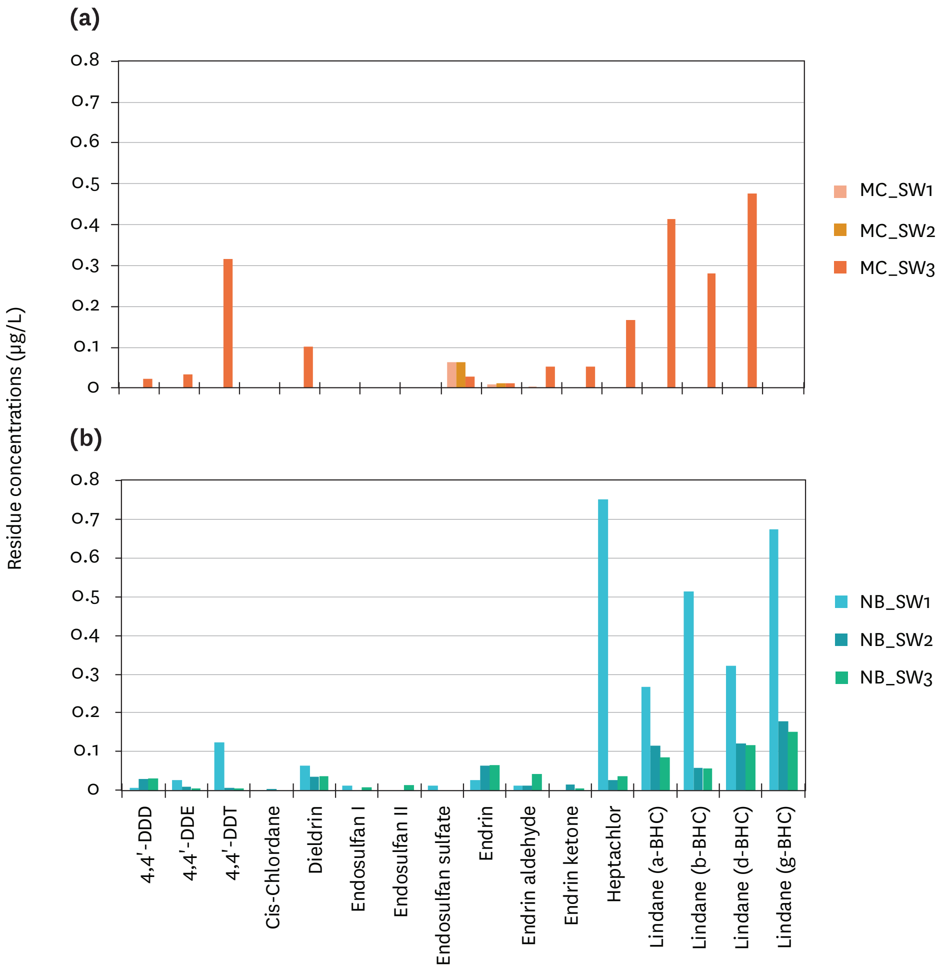

Figure 10. Maximum concentrations of OC compounds analyzed in surface water samples from both the wet and dry season sampling missions in the (a) MC, and (b) NB catchments.

Groundwater Detections

Of the pesticides analyzed, 14 OC compounds were detected in groundwater samples. Of the 20 CU compounds, only chlorpyrifos could be detected. OC pesticide residues were observed in samples from both wells (Figure 11). Residues of DDT were substantially higher in the groundwater sample from GW1 than the surface water sample from NB_SW3 despite being located within 20 m of each other. This finding suggests that the signal from DDT residues is stronger in groundwater than surface water, perhaps because of dilution by inputs from rainfall or longer groundwater flow paths, which might delay the arrival of the contaminant signal (Sophocleous 2002). Some possible dilution of OC residues was also observed in groundwater during the wet season, when OC residue levels decreased compared with the samples collected during the dry season (Appendix 6, Table A6.4).

Soil Detections

Residues from CU pesticides were most abundant in soil samples from the NB transect (Figure 12). Concentrations were much lower in samples from the OB transect, and most compounds were not detected in either transect from the MC catchment. There are two potential explanations for this finding: (i) the higher residue concentrations reflect a higher pesticide application load on the newer banana farm than the older farm and the maize and rubber fields in the MC catchment; and (ii) the difference in residue concentrations could result from the timing of pesticide applications. Higher residue concentrations would be expected at the OB transect if the new farm was applied with the same amount of pesticides as the old farm. No definite conclusions can be drawn from this finding, since we were unable to get detailed information from farmworkers about the timing and amount of pesticide application (Appendix 2).

In samples from the NB transect, residue levels of every compound excluding pyridaben increased from the transect top to the bottom. Considering the high sorption coefficient of many of the OC compounds and chlorpyrifos, the observed trend would suggest that the contaminated sediment had moved downslope faster than the compounds could break down, assuming pesticide application rates were uniform (Boyd et al. 2003; Selim et al. 2010; Weston et al. 2015). It should also be noted that the downslope transport of imidacloprid and similar compounds with lower sorption coefficients might have occurred via dissolution in the runoff. In the OB transect, most residue concentrations were approximately equivalent at upslope and downslope sampling locations, except for tebuconazole and thiamethoxam. This might indicate that sediment enrichment did not occur along the OB transect (except for tebuconazole and thiamethoxam), but it could also be explained by the relatively short length of the OB transect. Increased tebuconazole residues at the downslope location might have been the result of sediment enrichment, since the compound has a longer half-life (28–1,260 days) and a moderate sorption coefficient (1,000 L/kg). On the other hand, thiamethoxam was more likely transported by dissolution in the runoff, because it has a short half-life (8–44 days) and a low sorption coefficient (68.4 L/kg) (Table 2). More extensive sampling would be required to identify the dominant transport mechanisms with certainty.

OC pesticide residue concentrations in soil samples were low across all three catchments. Most residue levels did not substantially exceed the limit of quantification (Figure 13; Appendix 6). Residue levels tended to decrease from upslope to downslope sampling locations (Figure 13).

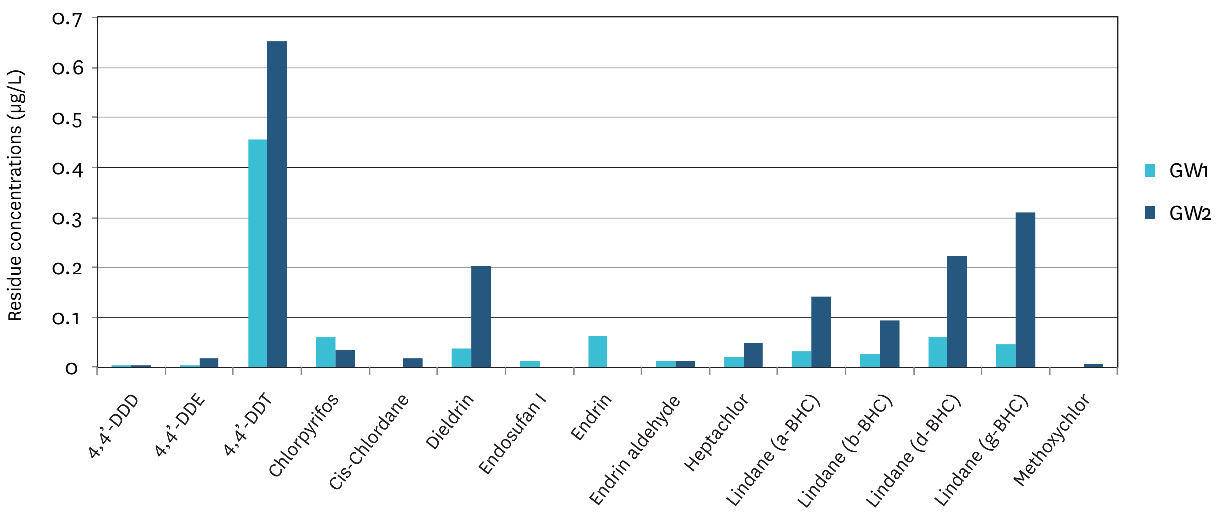

Figure 11. Maximum concentrations of OC compounds and chlorpyrifos in groundwater samples from both the wet and dry season sampling missions.

Heptachlor residues in the OB transect were 160 μg/L, which was an order of magnitude greater than all other compounds detected. The vast difference in heptachlor concentrations between OB_Soil1 and OB_Soil2 raises questions. Heptachlor, like many of the OC compounds observed in the study area, is persistent in the environment with a half-life between 180 to 1,280 days (WHO 2004). It is reasonable to expect that some measurable fraction of the soil-bound residues observed at OB_Soil1 would have migrated downslope and be detected at OB_Soil2, if heptachlor was applied/deposited uniformly over the field. Without additional samples collected from the OB field, it is impossible to identify the cause for such a localized spike with certainty.

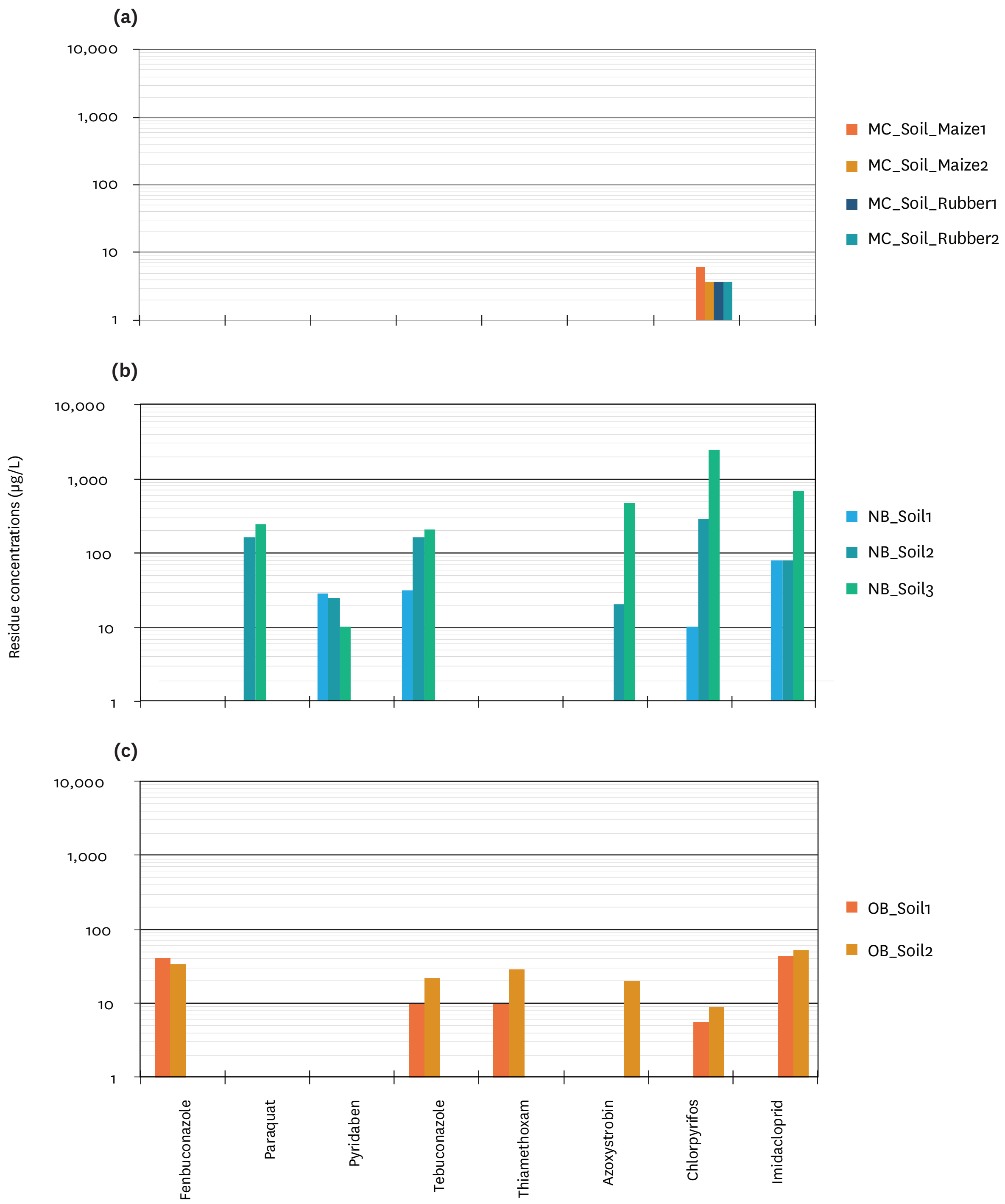

Figure 12. Maximum residue concentrations observed for CU pesticides from (a) MC, (b) NB, and (c) OB soil samples. Compounds that were not detected were omitted from the chart.

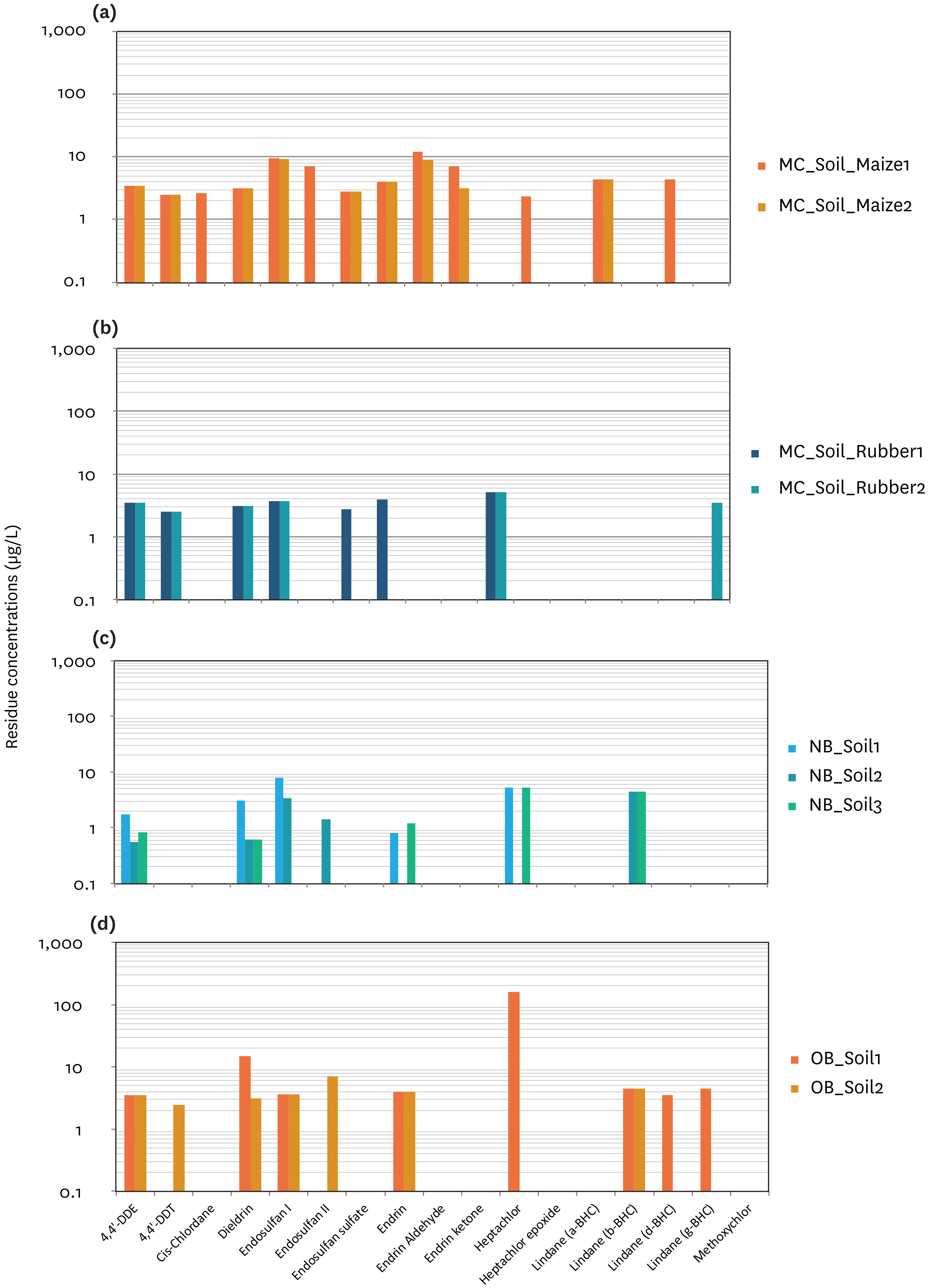

Figure 13. OC pesticide residue concentrations in soil samples from (a) maize, (b) rubber, (c) new banana, and (d) old banana fields. Most of the levels detected were near the limits of quantification. Compounds that were not detected were omitted from the chart.

Stream Sediment Detections

CU pesticide residue concentrations in sediment samples were higher in the NB catchment than the MC catchment, the latter of which were below the detection limit for all compounds except chlorpyrifos (Figure 14). Concentrations of pyridaben, imidacloprid and chlorpyrifos decreased from upstream to downstream sampling sites in the NB catchment, and substantial dithiocarbamate residues were detected above the banana farm at NB_SED1. These findings suggest that CU pesticide residues entering the NB stream were diluted.

Surprisingly, high concentrations of paraquat were observed at NB_SED2, but not at the downstream (NB_SED3) location. It is possible that paraquat-enriched sediment was deposited in the stream at NB_SED2 in the period between the last sediment-moving storm event and the time of the sample being collected. However, more frequent sampling would be required to evaluate this hypothesis.

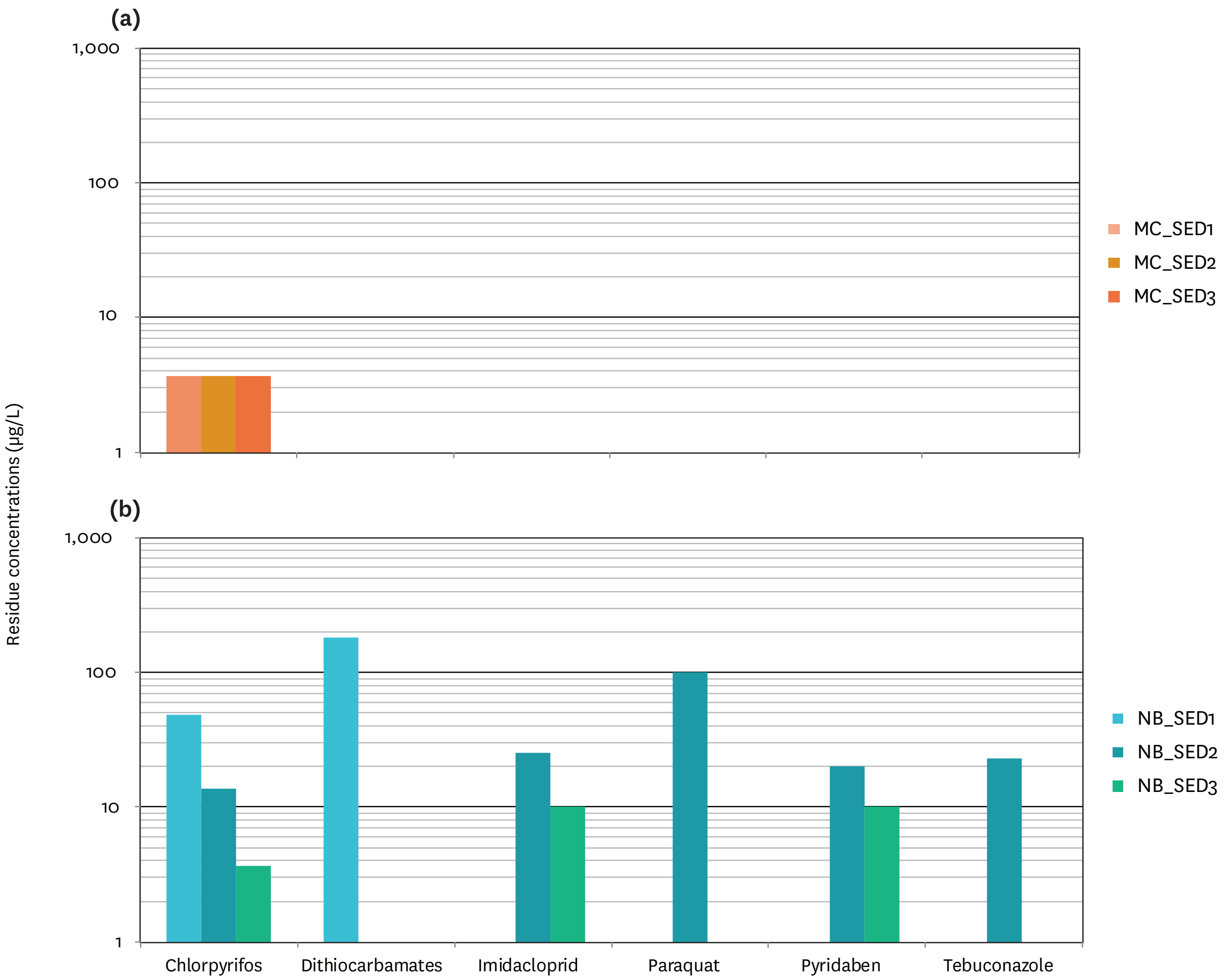

Figure 14. CU pesticide residue concentrations in sediment samples from the (a) MC, and (b) NB catchments. Dithiocarbamate compounds included propineb, mancozeb and thiram.

OC pesticide residue levels were low in sediment samples from both the NB and MC catchments. Detected residue levels were the same for lindane (b-BHC) across all six sampling sites (Figure 15). The lindane (b-BHC) breakdown product was found in every sample at a concentration equal to the limit of quantification (LOQ) of 4.5 µg/L.

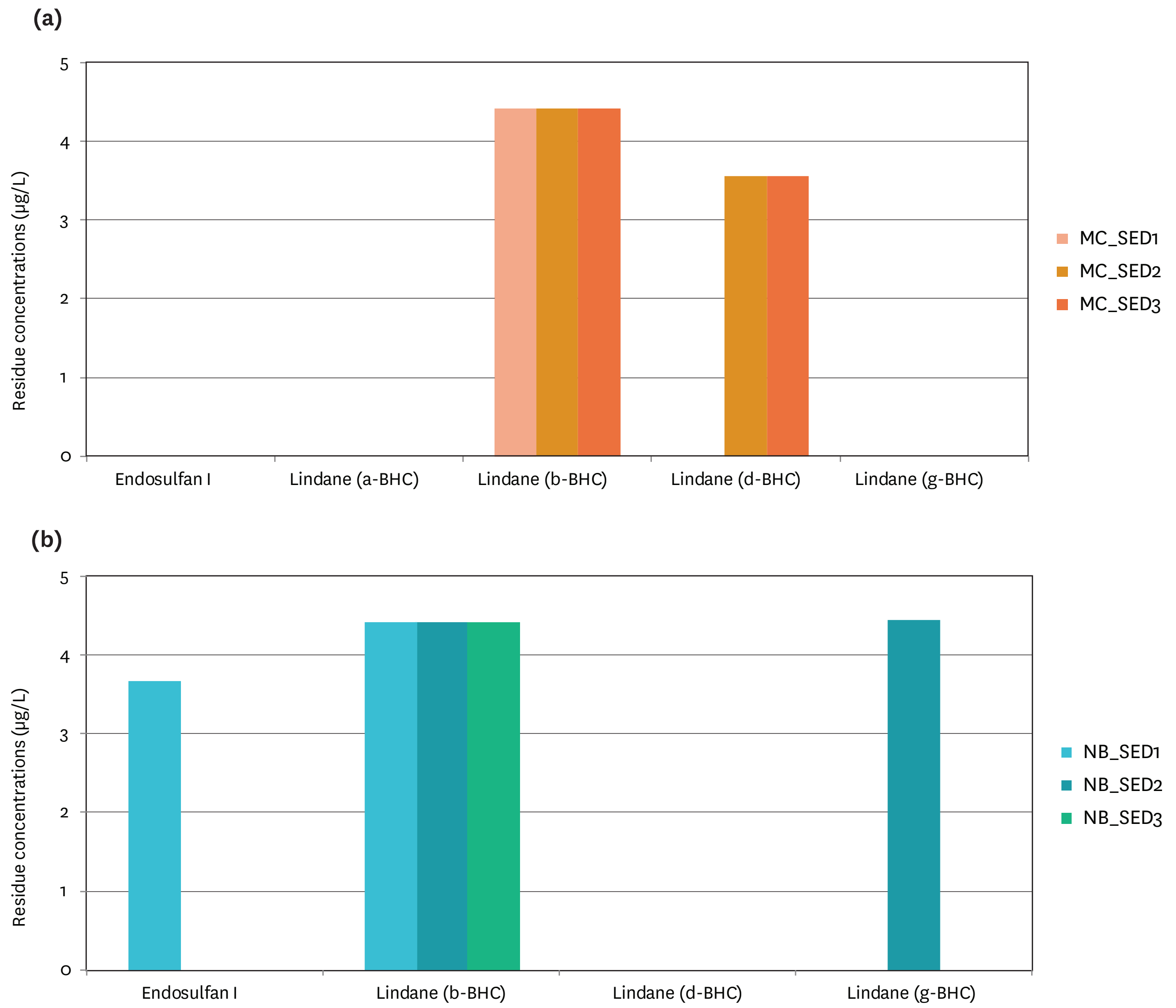

Figure 15. OC residue concentrations in sediment samples from the (a) MC, and (b) NB catchments.

Seasonal Variations in Frequency and Concentration of Pesticide Residue Detections

OC compounds and chlorpyrifos detections were compared across the two sampling missions to understand seasonal variations in the abundance of pesticide residues, because only these had been measured in both wet and dry season samples. The number of pesticide detections was lower in surface water, groundwater and soil samples during the wet season, but higher for sediment (Figure 16).

Lower concentrations in the wet season surface water samples did not match the pattern observed in an upland agricultural basin in northern Thailand, where pesticide levels peaked in surface waters during the wet season (Sangchan et al. 2014). Without more detailed information about application rates within our study area or a higher frequency of sampling and precipitation monitoring, it is uncertain whether the observed differences are due to pesticide application patterns or residue dilution in higher streamflow (Gilliom 2007; Lewis et al. 2016). Decreased detection frequency in soil samples is consistent with observations in previous research, where a finite stock of OC compounds was depleted by erosion-induced transport (Kookana et al. 1998). According to Kookana et al. (1998), eroded sediments have a much higher proportion of fine particles than their parent soils, which can lead to as much as a fivefold increase in pesticide residues. The higher wet season detection frequency in sediment was largely influenced by the increased presence of chlorpyrifos. Chlorpyrifos was detected in seven wet season samples compared with only three dry season samples. This was possibly due to the erosion of pesticide-enriched sediment from field surfaces, as had been observed in a previous study of chlorpyrifos' environmental behavior in the tropics (Dores et al. 2016).

Figure 17 provides a comparison of wet and dry season OC compound and chlorpyrifos residue concentrations in the various media. Residue concentrations expressed a similar pattern as detection frequency in surface water and groundwater (higher detection frequency and residue concentrations during the dry season), whereas soil samples had a higher detection frequency in the dry season, but higher residue concentration in the wet season (Figures 16 and 17). Sediment was the only media which had a higher detection frequency among wet season samples. Sediment samples were similar to soil in that wet season samples had higher residue concentrations.

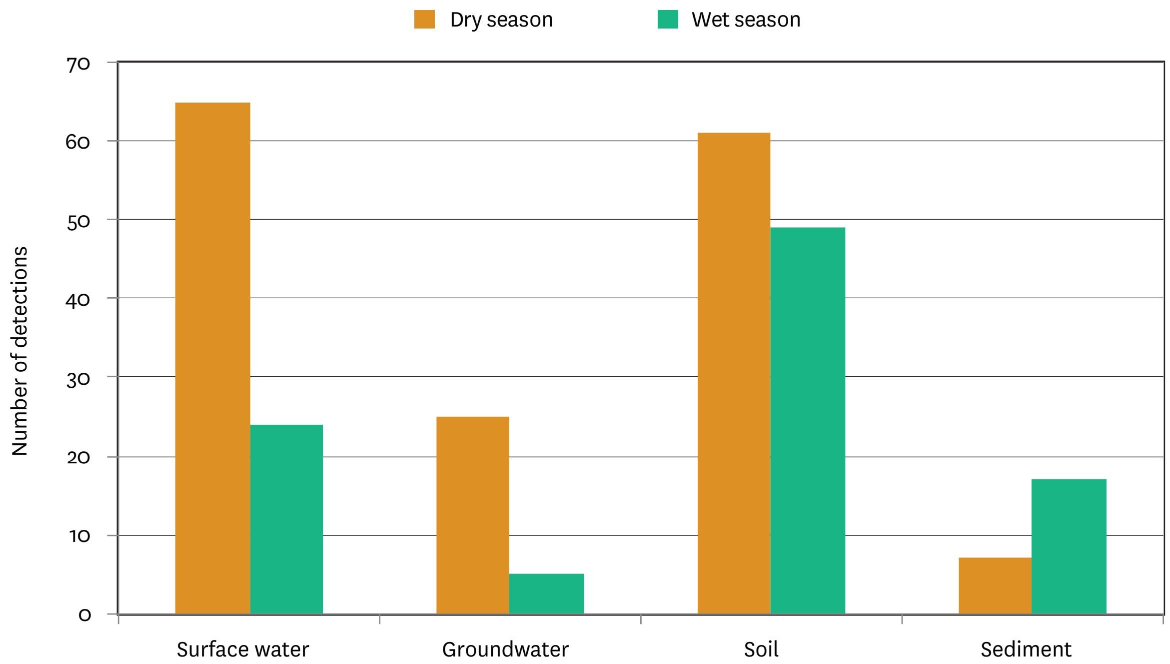

Figure 16. Frequency of detections for either OC or chlorpyrifos from the dry and wet season sampling missions.

Comparison of Pesticide Residues Across Crop Types

Residue concentrations for OC and CU compounds detected in surface water and sediment samples are shown as boxplots in Figures 18 and 19, respectively. We chose to show the soil residue concentrations on log-scale plots due to the wide range of results (Figure 19). We also assessed the statistical relationships between crop type and pesticide residue concentration for surface water, sediment and soil samples. We determined the statistical significance of the differences in mean residue concentrations using a two-tailed t-test. For surface water and sediment, we compared mean residue concentrations from the new banana plantation and mixed commercial crops. For soil, we undertook two comparisons: (i) mixed crops (rubber and maize) versus bananas (old and new plantations), and (ii) old versus new bananas.

In surface water samples, most compounds were detected at low levels in both crop types (new banana plantation and mixed commercial crops) (Figure 18). Median residue levels of three CU compounds (chlorpyrifos, imidacloprid and paraquat) were notably higher in the new banana samples, and two OC compounds (lindane [b-BHC] and heptachlor) were higher in surface water from mixed crops. Of the 21 compounds detected in surface water samples, only imidacloprid was found to be significantly higher in new bananas than mixed crops ($\alpha = 0.05$, $p = 0.046$).

Analysis of the basic water quality parameters measured during sample collection did not reveal any patterns explaining the observed differences in residue levels across crop types. The average surface water pH was 7.9 in both catchments, but the average temperature of the NB stream was 2 °C warmer than the MC stream. Average EC was nearly the same in both streams (EC_{NB} = 640 µS/cm and EC_{MC} = 644 µS/cm) (Appendix 3, Table A3.1).

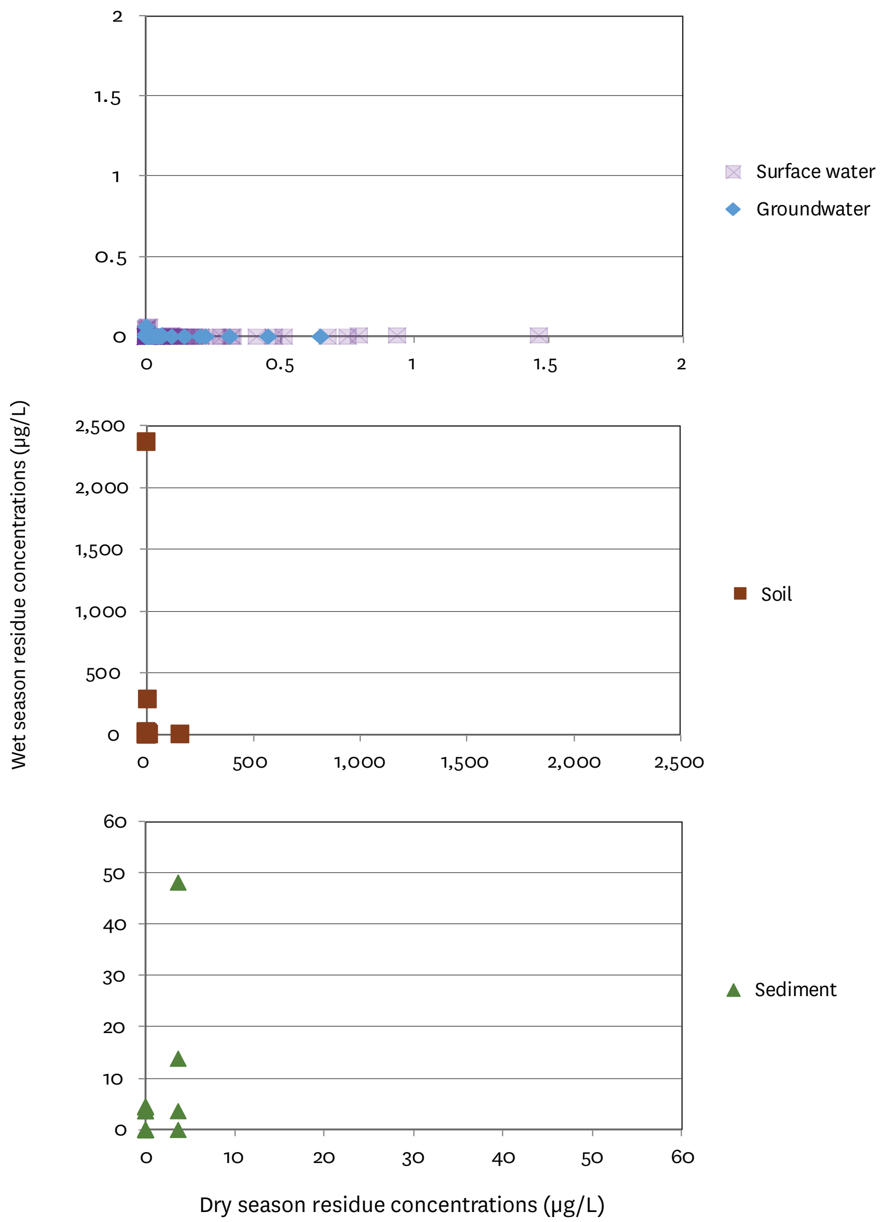

Figure 17. Difference in OC and chlorpyrifos pesticide residue concentrations between the wet and dry season samples. The high concentration wet season detection in soil was chlorpyrifos; in sediment, the detection was dithiocarbamate. Each point represents a single location.

Soils from new bananas contained higher levels of CU compound residues than other crop types, although the difference with old bananas was not as great as compared with the mixed crop types (Figure 19). New and old bananas both had considerably higher concentrations of CU compounds compared with mixed crops, especially chlorpyrifos, azoxystrobin, imidacloprid, methoxychlor, paraquat and tebuconazole.

Three OC compounds were significantly higher in mixed crops than bananas (combined old and new). Residues of 4,4'-DDE ($p = 0.017$), endosulfan sulfate ($p = 0.035$) and endrin aldehyde ($p = 0.037$) were significantly higher in mixed crop samples. Comparison of soils from old and new banana farms found that fenbuconazole ($p = 0.001$) and thiamethoxam ($p = 0.004$) residues were significantly higher in the old banana farm, whereas pyridaben ($p = 0.005$) was significantly higher in the new banana farm. These findings likely resulted from the small sample sizes collected for each media type coupled with a high degree of variation across the sites. While the residue levels of many compounds were not statistically significant, it was evident that bananas were associated with higher levels of contamination from CU pesticides, while OC pesticide residue concentrations were similar across both crop types.

Soil samples' physical characteristics varied somewhat by crop type, but it is unlikely that they strongly influenced pesticide detections. Organic matter content, which can have a significant effect on sorption, was nearly the same for both mixed crops (2.59%) and

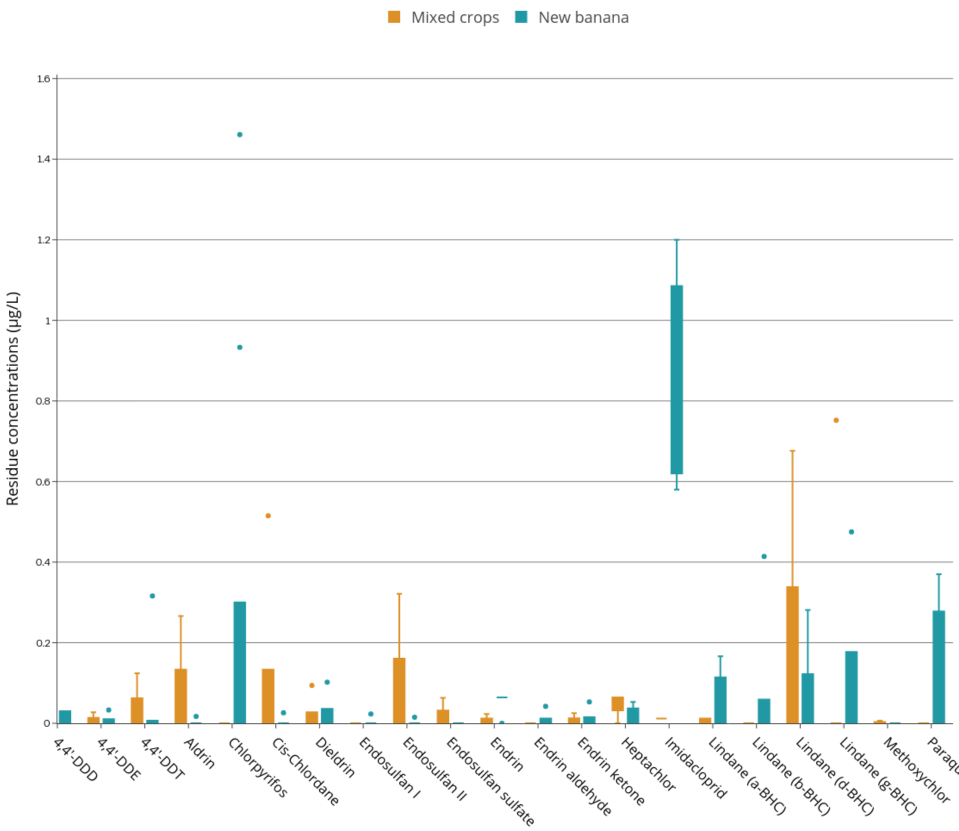

Figure 18. Comparison of pesticide OC and CU residue concentrations in surface water across seasons from mixed crops and new banana. The orange and blue dots on the plot represent observations that fell outside the interquartile range.

bananas (2.70%) (Appendix 3). Although pH was much lower in bananas (5.79) than in mixed crops (7.24), conditions in the mixed crop soils were not sufficiently alkaline to significantly affect breakdown rates of the weakly acidic pesticides (i.e., carbamates and OPs) analyzed (Tharp 2013).

Pesticide residues in sediment affected by new bananas were also typically higher than mixed crops in the MC and upper NB catchments (Figure 20). Residues of the CU compounds dithiocarbamate, imidacloprid, paraquat, pyridaben and tebuconazole had the largest difference between crops. Dithiocarbamate, a group of compounds that includes the commonly used fungicides mancozeb and propineb, were the only pesticides with a higher concentration in mixed crops than in new bananas. Dithiocarbamate had high residue levels in a single sediment sample from mixed crops above the new banana plantation (NB_SED1), but was not detected in sediments affected by the bananas. Most dithiocarbamates such as propineb and mancozeb have short half-lives (< 7 days), so the residues observed likely reflect recent pesticide application in the upper NB catchment (Geissen et al. 2010). However, differences between residues in sediment from mixed crops and new banana were not statistically significant for any of the pesticides observed.

GT Test Kit

The results from GT test kit analyses were compared against the sum of wet season OP and carbamate residues for each sampling site (Table 5). The three qualitative categories were given numerical codes to compare against pesticide residue concentrations. Samples from five of the total 23 sampling sites were classified as 'High-Detection', nine were 'Low-Detection', and nine were 'Non-Detection'. All three of the soil samples from the NB transect, along with OB_Soil2, and MC_SED2 comprised of the 'High-Detection' category.

In general, the test kit did not match laboratory results closely (Table 5). Its performance was somewhat better for soil media, as shown by the 'High-Detection' rating given to the NB_Soil samples with the highest concentrations (Figure 21). However, there was a considerable degree of inconsistency. NB_SED1 was rated 'Non-Detection' even though its residue levels were comparable to NB_Soil2, which was rated 'High-Detection'.

The findings from this study suggest that the GT test kit is not a viable replacement for laboratory analysis. Using the test kit for detecting residues in soil may hold some promise, but additional testing would be needed, especially considering multiple duplicate analyses for each sample. Since the GT test kit was not developed for environmental testing, this would help to evaluate the appropriate level of confidence that one should have in the results.

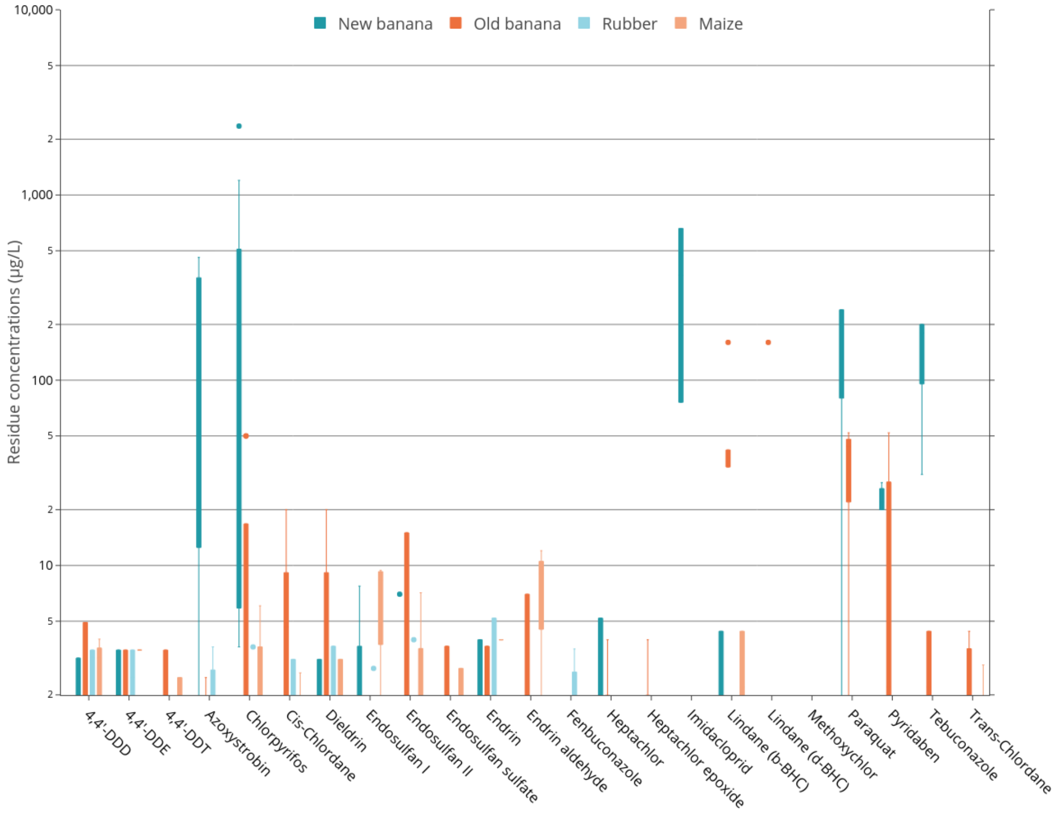

Figure 19. Comparison of residue concentrations of pesticide (all types) in the soil.
Note: The y-axis is on a log scale from 2 to 10,000 µg/L.

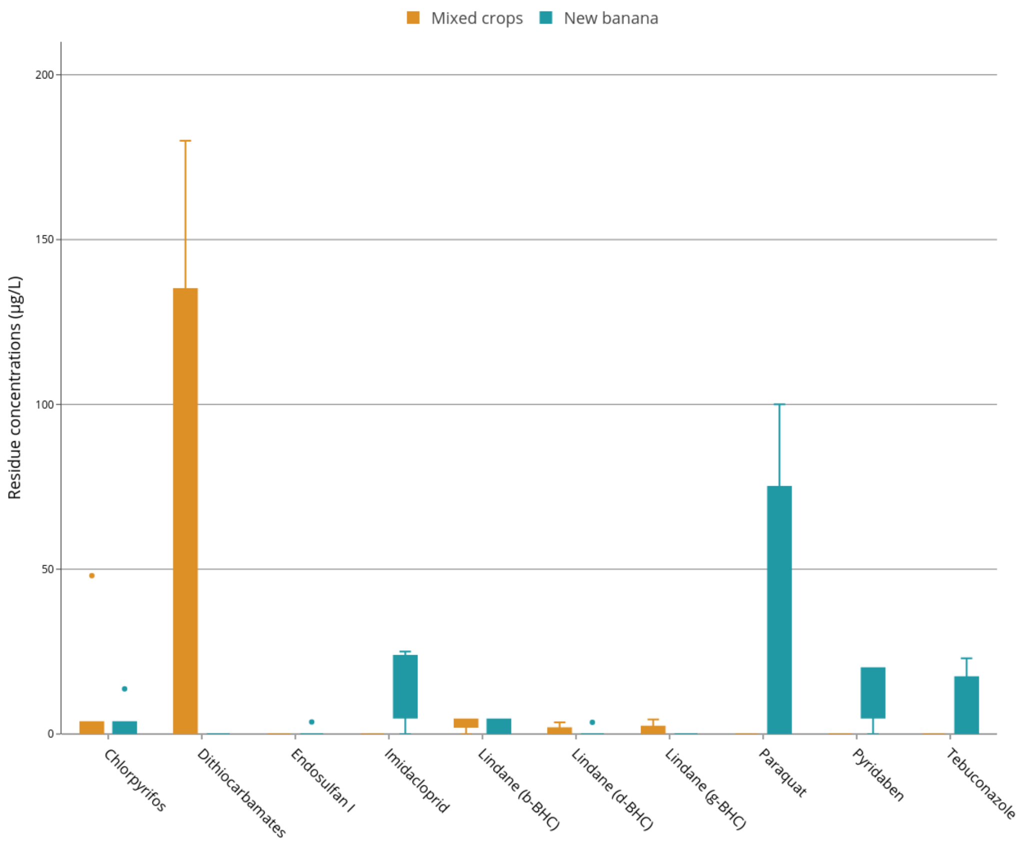

Figure 20. Comparison of pesticide (all types) residue concentrations in sediment samples from mixed crops and new banana. The orange and blue dots on the plot represent observations that fell outside the interquartile range.
Note: Dithiocarbamates include the compounds maneb, mancozeb, metiram, propineb, thiram and ziram.

Water Quality Risk Assessment Modelling

Model outputs for the degree of risk (toxicity) to the species of concern (fish) and the likelihood that a given pesticide will migrate off-site (mobility) are given for each of the 11 pesticides available in PIRI's built-in database (see Table 6). For the most part, compounds with high toxicity ratings also had high mobility ratings. This finding was unsurprising, because a compound's mobility strongly influences pesticide loading to the stream, and higher pesticide loading to streams results in higher toxicity to the target species. A notable exception was bifenthrin, which was identified as one of the highest toxicity risks, but had the lowest mobility score. Although its toxicity to fish would probably be high, we would expect a lower likelihood of detecting bifenthrin residues in surface water samples, because its chemical properties make it less likely to migrate off-site.

We compared the observed maximum residue concentrations across all surface water samples against PIRI mobility ratings (ranked on a scale of 1 to 6) and found that the two were not correlated (R^2 = 0.01). This suggests that PIRI is not well suited to predict residue concentrations in a small number of infrequently collected surface water samples. Since PIRI has been successfully implemented across a wide range of field conditions elsewhere in the world, it is possible that collecting samples more frequently and identifying actual pesticide application rates would help improve model performance.

Table 5. GT test kit scores and combined wet season organophosphate and carbamate pesticide residue concentrations for each site. GT test kit scores were color coded to facilitate interpretation. Green = 1 - 'Non-Detection', Yellow = 2 - 'Low-Detection', and Red = 3 - 'High-Detection'.

Crop	Media	Site name	Sum of OP and carbamate residues (µg/L)	GT test kit score
Banana (NB, OB)	Groundwater	GW1	0.1	2
		GW2	ND	2
	Sediment	MC_SED3	3.6	2
		NB_SED2	13.7	2
		NB_SED3	3.6	1
	Soil	NB_Soil1	10.0	3
		NB_Soil2	280.0	3
		NB_Soil3	2,355.0	3
		OB_Soil1	15.7	1
		OB_Soil2	39.0	3
	Surface water	MC_SW3	0.1	2
		NB_SW2	1.5	1
		NB_SW3	0.9	2
Mixed crops (MC)	Sediment	MC_SED1	3.6	1
		MC_SED2	3.6	3
		NB_SED1	228.1	1
	Soil	MC_Soil_Maize1	6.1	1
		MC_Soil_Maize2	3.6	1
		MC_Soil_Rubber1	3.6	1
		MC_Soil_Rubber2	3.6	1
	Surface water	MC_SW1	ND	2
		MC_SW2	ND	2
		NB_SW1	0.1	2

Note: ND - Not detected.

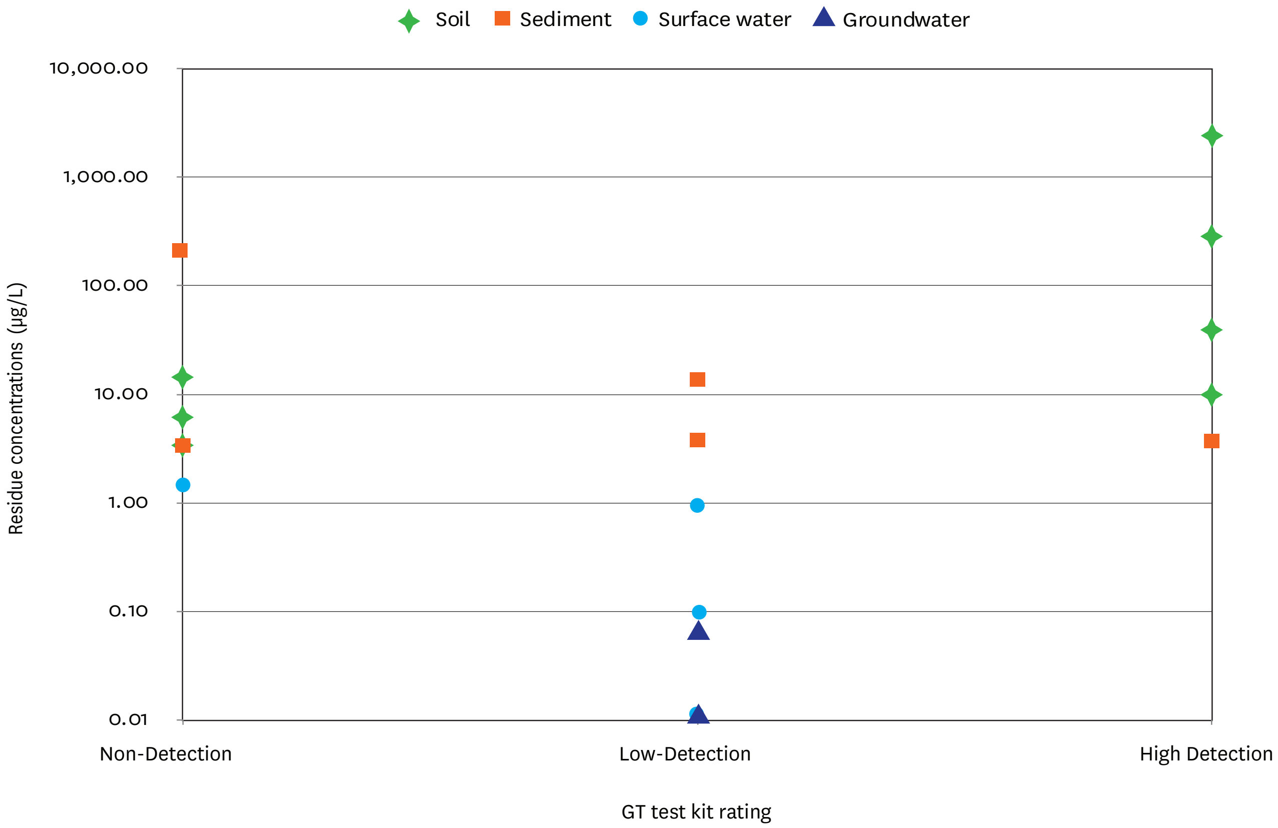

Figure 21. Comparison of GT test kit results and the sum of observed organophosphate and carbamate pesticide residues.

Table 6. Output from the PIRI model. All the compounds considered for the PIRI assessment were observed on farms, either in fields or storage sheds.

Pesticide name	Maximum surface water residue (µg/L)	Toxicity (fish)	Mobility
Chlorpyrifos	1.46	Exc. high	High
Thiram	ND	Exc. high	High
Chlorothalonil	ND	Exc. high	High
Bifenthrin	ND	Exc. high	Low
Propineb	ND	Very high	Very high
Azoxystrobin	ND	Very high	High
Kresoxim-methyl	ND	High	Medium
Thiophanate-methyl	ND	Medium	High
Tebuconazole	ND	Medium	Medium
Paraquat	0.37	Low	High
Imidacloprid	1.2	Very low	High

Notes: ND - Not detected, Exc. – exceptionally.

Discussion

Pesticide residues measured in the surface water and groundwater of the study area present a considerable risk to environmental and human health. CU pesticide residues were predominantly found in areas affected by banana farms, whereas OC residues were widespread across the study area. Both surface water and groundwater contained pesticide residue levels that exceeded WHO Drinking Water Guidelines (WHO 2008) for some OC compounds, but only surface water impacted by banana fields was contaminated with CU compounds above environmental guidelines (ANZECC and ARMCANZ 2000). Soils were also contaminated by OC and CU compounds as were streambed sediments, which contained high levels of CU compounds. However, it is difficult to determine the severity of risk posed by residues in soil and streambed sediments to human and environmental health, because regulatory guidelines for soil and sediments have not been developed for most of the compounds investigated in this study.

We observed a strong seasonal trend in chlorpyrifos and OC compound residues in surface water and groundwater, which peaked during the dry season and, in some cases, exceeded drinking water guidelines (Figure 17; Table 7). CU pesticides, with the exception of chlorpyrifos, were not analyzed for seasonal trends because CU pesticide residues were only measured in wet season samples. Although soils were contaminated by pesticide residues, none of the compounds for which environmental guidelines exist exceeded the maximum limit.

Determining the overall risk level from individual pesticides proved to be a difficult task. Only 15 of the 40 compounds included in this study (38%) had established water quality guidelines, and a large portion of the pesticides detected did not have WHO Acute Hazard Ratings (30%). Increasing the proportion of pesticides with established water quality guidelines would provide essential information for land managers to evaluate the degree of risk from pesticide usage in their areas.

Wet season CU pesticide concentrations only exceeded water quality guidelines in surface water samples from the banana farm (MC_SW3 was in the MC catchment, but downslope from a cluster of banana fields). With the small number of sampling locations and infrequent sample collection, it is difficult to say whether these findings are representative of typical conditions in the study area. Combined biogeochemical and hydrological processes may result in 'hot spots' and 'hot moments' in which high residue concentrations occur in a small area and/or for a short period of time (Vidon et al. 2010). Hot spots and hot moments can occur shortly after application and can pose acute risks to human and environmental health. A larger dataset would be required to more clearly indicate whether or not one of these hot spots and moments was captured in one or more of our samples.

The two OC compounds that exceeded drinking water guidelines in Table 7 were heptachlor and dieldrin. Dry season groundwater samples from both wells exceeded the 0.03 µg/L Maximum Residue Level (MRL) for combined aldrin and dieldrin (WHO 2008; Water Resources and Environment Administration 2009). The discovery of OC pesticides above MRLs was surprising, since it is our understanding that these pesticides have not been used for decades. While we expect the risk from these compounds to decrease over time, OC pesticides can persist in the environment for decades before degrading to safe levels, and steps should be taken to minimize exposure to polluted water. Also, fish ponds in the area may pose a considerable risk to public health, since many of the OC compounds detected in the study area have the potential to bioaccumulate (WHO 2008). The CU compounds that exceeded guidelines in Table 7 were imidacloprid and paraquat, which surpassed guidelines in surface water during the wet season (dry season samples were not analyzed for CU compounds). Although some compounds were within acceptable limits for drinking water, they still posed a significant threat to the aquatic ecosystem. For example, one surface water sample contained 1.46 µg/L of chlorpyrifos, which is far less than the 30 µg/L recommended by the WHO for safe drinking water, but exceeded the LC_{50} for fish, which is 1.3 µg/L (WHO 2008; Sangchan et al. 2014). Chlorpyrifos residue levels in surface water from the new banana plantation in this case were also higher compared with other similar agricultural settings, including a banana-producing region in Costa Rica and the Mae Sa agricultural watershed in northern Thailand (Castillo et al. 2000; Sangchan et al. 2014).

Table 7. Maximum observed pesticide residue levels (all types) in surface water and groundwater compared with maximum allowable residue levels. The values in red indicate measured concentrations that exceed guidelines.

		Chemical class	OC		CU	
		Compound name	Dieldrin (µg/L)	Heptachlor (µg/L)	Imidacloprid (µg/L)	Paraquat (µg/L)
		Maximum residue level (µg/L)	0.03*	0.03	0.23	> ND
Media type	Crop type	Site name				
Surface water	Mixed crops (MC)	MC_SW1	ND	ND	ND	ND
		MC_SW2	ND	ND	ND	ND
		NB_SW1	0.06	0.75	ND	ND
	New banana (NB)	MC_SW3	0.10	0.05	0.58	ND
		NB_SW2	0.04	0.03	0.74	ND
		NB_SW3	0.04	0.04	1.20	0.37
Groundwater	--	GW1	0.04	0.16	ND	ND
		GW2	0.20	0.77	ND	ND

Sources: Canadian Environmental Quality Guidelines - Canadian Council of Ministers of the Environment 2007; WHO Drinking Water Guidelines - WHO 2008.
Notes: ND - Not detected.
* Combined maximum residue level for dieldrin and aldrin.

Conclusions

This study represents an important step in establishing data and understanding conditions to inform pesticide management in Laos. The scoping mission and subsequent pesticide residue analysis built on existing work from elsewhere in the region to improve our understanding of pesticide risks in upland agricultural systems.

The main findings from the scoping mission were as follows: (i) banana plantations typically replaced other crops on fields already being farmed rather than uncultivated forest; (ii) farming techniques varied depending on topographic conditions, farm size and access to surface water for irrigation; and (iii) chemical inputs were higher where proximity to surface water allowed for irrigation. Although further study is required to assess pesticide risks from each banana farm type, we would expect that large, irrigated farms on sloping land present the greatest risk due to higher intensity farming practices conjoined with favorable conditions for off-site transport of pesticide residues.

Our assessment of environmental samples from banana plantations found high levels of currently used (CU) pesticide residues, especially chlorpyrifos, paraquat and imidacloprid. While CU residue levels were highest in banana farm soil, they only exceeded environmental guidelines in surface water samples. Our sampling was not purposely timed with rainfall/flooding events, which typically give rise to spikes in concentrations, especially if such events occur shortly after application. Thus, the acute risk from pesticides was possibly even greater over short periods between sampling missions. On the other hand, we may have detected high pesticide concentrations by chance, if sampling happened just after application or if the samples were inadvertently collected nearby pesticide handling (storing, mixing, washing/cleaning and disposal) sites. While CU pesticide residue issues were mostly limited to the banana farms, considerable OC pesticide residues were present in samples from all crop types, and are thus also likely present across an unknown portion of the agricultural landscape cultivated on a permanent basis. Dry season surface water and groundwater samples exceeded water quality guidelines for the OC pesticides dieldrin and heptachlor. In summary, CU pesticide pollution from banana farms presents a serious threat to aquatic ecosystems, and legacy OC pesticide pollution poses an additional health risk to humans consuming contaminated water.

Given the limited understanding of pesticide application, the PIRI model was not a useful tool for evaluating risks to water quality. Similarly, the GT test kit did not provide sufficiently accurate results when compared with the laboratory analysis to be reliable for assessing environmental risks from pesticides. One possible exception was the usage of the GT test kit to detect high residue levels in soils. However, given the small size of our dataset, it is also possible that this was an anomalous result. Hence, we cannot recommend the test kit as a substitute for laboratory analysis. A larger study would be required to provide more definitive results about the test kit's accuracy, and such a study would benefit from conducting duplicate analyses to quantify the degree of uncertainty for the test kit's results. Finally, as mentioned earlier, the GT test kit can only detect a small subset of commonly used pesticides, so its use would be warranted only when OP and carbamate pesticides are the specific compounds of concern.

Recommendations

Our findings indicate that pesticide usage in commercial banana production in northern Laos poses a potentially serious risk to humans and aquatic species adjacent to and downstream from banana fields, and this should be further investigated to prevent a host of possible negative outcomes to human health and biodiversity. The greatest pesticide risk to the environment from banana farms was from CU compounds, which tend to break down quickly and do not build up over time. Therefore, adoption of practices that delay the movement of contaminated runoff and sediments to streams, as encouraged in the 2017 Decree on Pesticide Management, could mitigate certain environmental risks from banana plantations (Government of Lao PDR 2017). Some low-tech methods have been shown to reduce pesticide loading to streams, including vegetated drainage ditches and sediment trapping basins (Long et al. 2010).

Environmental and public health risks from hazardous pesticides can be addressed and minimized in several ways:

- Greater vigilance towards eliminating the import and use of the most hazardous and persistent pesticides.

- Targeted education programs for managers and workers of banana companies on the hazards of pesticide exposure, including ensuring that farmworkers have access to Lao translations of labels on pesticides imported from China; judicious selection and use of pesticides; and the implementation of best practices, including the use of IPM techniques such as ensuring that vegetated buffers and sediment traps are maintained around farms to detain farm runoff long enough for CU pesticides to degrade to safe levels.

- Conduct environmental monitoring programs in major commercial banana-growing areas to assess the levels of risk from pesticides and identify appropriate mitigation measures.

Future monitoring of CU pesticide residues would be greatly improved by tracking pesticide application rates and timing to better understand the relationship between specific practices and environmental risks. This would also serve to inform and refine existing agriculture and trade-related policies. In addition to studying the risks from CU compounds, the extent and degree of OC pesticide pollution should be studied to determine an appropriate response. At present, it is unknown whether the findings from this study represent a local issue or a broader hazard. We recommend a survey of OC residues in groundwater from drinking water and domestic wells in agricultural areas as the first step to quantify the risks from OC pesticide contamination. In the short term, water from contaminated wells and streams, including those in the study area, should not be consumed or used for domestic purposes, especially during the dry season. As a broader recommendation, an appropriate method for remediating OC-contaminated water should be deployed. There are significant hurdles to overcome to remediate contaminated water, including high costs and technical expertise required to successfully implement an effective remediation technique (Zhang 2003; Centofanti et al. 2016). To achieve these goals, the Government of Lao PDR should take active steps to provide appropriate training to provincial- and local-level staff in natural resource management and/or agriculture. This can allow them to monitor and report on pesticide residues as per international standards. Once the first step of understanding the problem is completed, the next step would be to improve existing policies wherever necessary and ensure compliance to protect communities and the environment from pesticide pollution.

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Appendix 1. Environmental Fate of Pesticides: General Concepts.

A pesticide is a substance intended to destroy, repel or mitigate a pest, and includes herbicides, insecticides, fungicides and nematicides. Pesticides have been the subject of considerable study worldwide for many decades, because of their toxicity to non-target species and the potential to be transported from the fields where they are applied (Carson et al. 1962; Wauchope 1978). Pesticide risk assessments are difficult and expensive to conduct, because many different chemicals are used in agriculture and pesticides vary in their toxicity to different organisms, and behavior in the environment depends on their individual chemical properties (Cox 2002).

Three characteristics that play an important role in determining the likelihood and manner in which a pesticide will be transported from the application site are half-life, soil sorption coefficient and water solubility (Wauchope et al. 1992). Half-life, the time in which natural degradation processes reduce the original concentration by half, is a standardized measure of a pesticide's persistence in soil or water. Pesticides are considered non-persistent if their half-life is greater than 30 days, moderately persistent if it is 30–100 days, or persistent if it is greater than 100 days (Vogue et al. 1994). A pesticide's half-life is a dynamic characteristic that can be shortened or increased depending on environmental factors such as temperature, soil properties (e.g., clay content and organic matter content), and soil moisture content. The soil sorption coefficient (K_{oc}) describes a pesticide's tendency to bind on the surface of a soil particle (Vogue et al. 1994). Higher sorption slows a pesticide's movement; however, it can also slow degradation, in turn increasing persistence. The sorption coefficient is strongly affected by soil organic carbon content, with higher carbon content resulting in higher sorption coefficients. Finally, water solubility describes the amount of pesticide that will dissolve in a known amount of water at room temperature (20 °C or 25 °C) (Vogue et al. 1994). Pesticides with solubility greater than 10 mg/L are more likely to be transported from fields in the water phase of runoff or by leaching into groundwater (Wauchope 1978). Since pesticides break down in the environment at different rates, factors such as the frequency, rate and time passed since application also play a vital role in determining the risk of pollution.

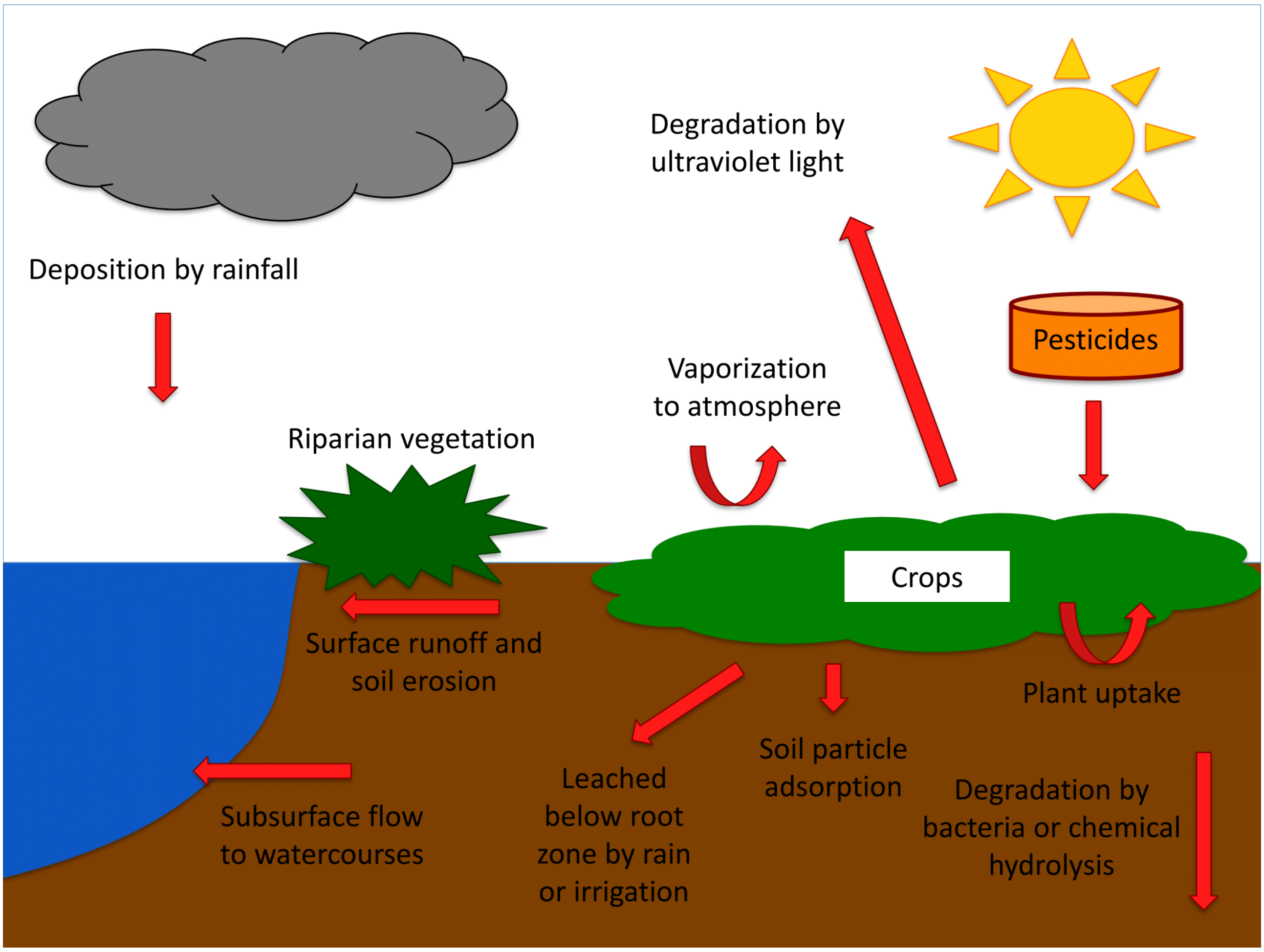

Figure A1. The pesticide cycle.

Appendix 2. Complete Scoping Mission Report.

In 2015, the Lao National Agriculture and Forestry Research Institute (NAFRI) initiated an assessment of the sustainability of commercial banana production led by Dr. Vongphapane Manivong. The first phase of the study, completed in March 2016, focused on the socioeconomic aspects of commercial banana farming. This appendix details the findings from the second phase of the study, which began in January 2016 to evaluate the environmental health risks from pesticide use in banana production. The research team included members from the International Water Management Institute (IWMI), the National University of Laos (NUOL) Department of Chemistry and NAFRI. This study is the first of its kind in the region to monitor the environmental impacts of commercial banana farming.

In February 2016, the research team from IWMI and NAFRI traveled to three banana-producing provinces in northern Laos on a scoping mission to inform the study's environmental monitoring efforts. The information gathered during the scoping mission was used to design a focused assessment of environmental impacts at the catchment scale that was conducted through December 2016.

Before the scoping mission, a few things about the banana farming sector were known: the approximate area of production within each province, the common usage of banned pesticides imported from neighboring countries, details about the different investment practices, and the driving factors for foreign investment, particularly for Chinese companies. The scoping mission helped to enhance the existing body of knowledge with a more detailed understanding of banana plantation typologies, as well as a list of pesticide active ingredients found in shops and farms.

Previous Work

In addition to regular agricultural surveys, commercial farming in northern Laos has been the focus of a number of studies in recent years. Previous research has also addressed the sociopolitical drivers of land-use change, illegal pesticide trade and the effects of Chinese banana investment on Lao farmers' access to land.

Land use in northern Laos has undergone substantial changes since the 1970s according to a study of aerial and satellite imagery from Oudomxay province (Saphangthong and Kono 2009). A large portion of the uplands that were home to shifting cultivation (slash and burn) practices transitioned to permanent commercial crops, such as maize and soybean. In places where shifting cultivation remained, average fallow periods were shortened from 10 years to 2–3 years. The discontinuity of changes from the 1970s to the late 1990s indicates that land-use change was not driven by population growth, which was steady over the study period, but by a combination of changing economic opportunities and the enforced resettlement of remote mountain villages in lowland areas closer to roads (Saphangthong and Kono 2009).

Northern Laos is a favorable location for Chinese investment in banana plantation for various reasons: the climate allows for year-round farming, the land is inexpensive to lease, the fungus that causes plant-killing Panama Disease is less prevalent in the region than in southern China, and there is less risk of damage to the crop from typhoon winds (Friis 2015). According to NAFRI (2016), the majority of banana farms in northern Laos are operated under the '1+4' contract farming business model, in which landowners lease their land to a company, which then provides the required technology, labor, agrochemicals and seedlings. Other business models for banana farming include '2+3' contract farming, in which landowners also contribute their labor and receive concessions. Concessions are granted in cases where activities are assumed to use resources more intensively. Thus, the investing company is required to pay a fee to the government as compensation, in addition to the fee for leasing the land paid to the landowner (Friis 2015). In Long district, Luang Namtha, Friis (2015) found that small-scale contract arrangements, unlike concessions, typically had little or no initial involvement from government institutions. Instead, land leases were coordinated by local middlemen mediating between the investors and landowners.

Increased foreign investment in commercial agriculture has raised concerns about social and environmental conflicts. Although the average number of hectares leased in Long district was smaller than many land concessions elsewhere in Laos, landowners still experienced the same consequences of dispossession, displacement, and environmental or social conflicts on site (Friis 2015). For example, rice farmers adjacent to banana plantations lost access to water for irrigation after banana farmers removed or altered the sluices they relied on to route water to their paddies. Farmers were also deeply concerned about land degradation due to agrochemical pollution. Nonetheless, many agreed to lease their land for banana farming, typically earning more income than was usually possible from selling surplus rice (Friis 2015).

MAF (2010) introduced the *Regulation on the Control of Pesticides in Lao PDR* in 2010 to ban certain active ingredients, and improve the safety of pesticide transportation, import and storage. However, a 2011 survey of available pesticides in the provinces of Luang Namtha, Xiengkhouang and Vientiane Capital found that illegal pesticides were still widely available (Vázquez 2013). Under the law, the Provincial Agriculture and Forestry Office (PAFO) is responsible for regulating pesticide imports, distribution and licensing, while the District Agriculture and Forestry Office (DAFO) is responsible for inspecting pesticide shops to ensure compliance with the law at the district level. Regulatory actions such as confiscation of banned pesticides create additional problems, because Laos does not have the required facilities to safely dispose of hazardous chemicals. The 2011 survey found that herbicides comprised the largest share of pesticides (70%) available in Luang Namtha and Sing districts, mostly for use in sugarcane and rubber cultivation.

The overuse of pesticides is common among upland farmers, because they fear losing large portions of their crops in the event of a pest outbreak (Lamers et al. 2013). In one study, training programs intended to reduce pesticide usage through techniques such as Integrated Pest Management (IPM) and Good Agricultural Practices (GAP) did not result in any significantly different behavior between farmers who received training and those who did not. Pesticide usage, as measured by the volume of active ingredient used per hectare, was not significantly different between the two groups. While GAP-trained farmers used fewer highly hazardous pesticides (WHO classes Ia, Ib, or II) on one crop (bell peppers), they used a higher share of highly hazardous pesticides on two others (lettuce and Chinese cabbage) (Lamers et al. 2013). Lamers et al. (2013) concluded that the observed patterns were the result of poor implementation of a farm auditing framework, lack of understanding among farmers of the logic of control points, and a lack of alternatives to pest management given to farmers.

Methods

The scoping mission was conducted during the period February 3–15, 2016. The scoping team spent four days in Luang Namtha, three days in Phongsaly, and three days in Oudomxay. Across the three provinces visited, the team toured 11 farms; interviewed 4 farmers, 4 farmworkers, 1 pesticide shop owner, 2 village heads, and staff members of a Chinese banana company working in Oudomxay (Table A2).

Table A2. A summary of scoping team actions across the three provinces visited.

Province name	Farms visited	Farmer owners/managers interviewed	Farmworkers interviewed	Other interviewees
Luang Namtha	4	2	2	Pesticide shop owner
Phongsaly	4	2		Village head
Oudomxay	3	1	2	Village deputy head

In each province, the IWMI team first met government officials from PAFO before traveling to a focal district (selected by NAFRI based on their preliminary survey work in 2015). Prior to visiting banana plantations, the team interviewed staff from DAFO and the District Office of Natural Resources and Environment (DONRE). The team asked whether the local government staff were aware of any reported environmental hazards associated with commercial banana production, which crops were being replaced by banana, and recommendations for any sites in their district that had good potential for in-depth study. Following consultation with government staff members, interviews were conducted with banana farm managers/owners and banana farmworkers. Interviews typically lasted 15–60 minutes and followed a list of questions prepared in advance to learn about banana farming practices, suspected environmental impacts and the crops being replaced by bananas.

There were a number of difficulties associated with acquiring information about pesticide management practices: (i) all but a few of the chemical labels were in Chinese and had to be translated after the scoping mission; (ii) farmers, who mostly do not read or speak Chinese, did not know which chemicals they were using and instead relied on company or pesticide shop workers to recommend the appropriate chemicals; and (iii) the timing of our trip corresponded with the Chinese New Year festival with most of the Chinese pesticide shop owners and technicians visiting family in China. During our trip, we could not reach the relevant technicians from the Chinese companies to inquire about pest management practices on banana plantations in their area (i.e., the specific chemicals they used, how often they applied pesticides, in what amount, and at what times throughout the year). Instead, we photographed the chemical containers found in shops and in banana fields to be translated later, and asked plantation workers to describe chemical usage on their farms to the best of their ability.

Interviews and farm visits revealed that many different chemicals are used on plantations (almost exclusively sold in Chinese-labeled packages), farmworkers know very little about the chemicals they are applying, and in many cases, workers and their families live among the banana fields. In total, 61 different active ingredients were found in pesticide shops and banana fields across the three provinces. Although the list of chemicals is not likely to be entirely comprehensive, it provides a useful starting point for this assessment, especially when considering the study's analytical constraints, as described in the section *Methodology*.

Results

Farming practices varied considerably across the three provinces, but there were also key similarities. For instance, every commercial farm grew the same variety of banana - the Cavendish. The Cavendish is grown on a 10-month cycle beginning with field preparation from March to April, followed by planting to coincide with the onset of the wet season in May and harvest in February. Banana trees continually produce new stems, but only one is allowed to develop at a time to maximize fruit yields. At the end of each season, the main stalk of a banana tree is cut down to allow a new stem to grow for the next season. A single banana plant is typically replaced after three seasons when fruit yields decline substantially.

Farm Types

Banana farming practices and plantation characteristics fell into three broad categories across the provinces depending on the availability of surface water and the investment model. The three banana farm types were: (i) irrigated upland plain farms, (ii) rain-fed hillslope farms, and (iii) irrigated hillslope farms. Plantation size, crop types being replaced, water management and the level of chemical inputs varied considerably across farm types. Conditions that determined irrigation and chemical application rates included distance to surface water and investment type.

Irrigated upland plain farms were the dominant form of banana farming in the broad, gently sloping valley of Sing district, Luang Namtha. These farms were typically situated on flat or gently sloping land close to perennial streams (Figure A2.1). Farms ranged in age from 1.5 to 4 years and in area from 2 to 38 ha. Three of the four farmers interviewed had previously grown paddy rice and switched to bananas because they did not have sufficient water to irrigate rice for the entire season. The prevailing investment model among irrigated upland plain farms was '2+3' contracting between Lao landowners and Chinese investors.

Figure A2.1. A typical lowland contract farm photographed from an adjacent hillside in Sing district, Luang Namtha. A stream, unable to be seen due to the perspective of the photograph, runs between the two fields.

Irrigated hillslope farms, predominantly found in Houn district, Oudomxay, were on average the largest farms observed during the scoping mission. They tended to be located on moderately sloped hillsides nearby the main stem of the Beng River (Figure A2.2). The concession investment model was the most common management scheme among upland irrigated farms in Houn district. Farms in Houn district ranged in size from 60 to 1,000+ ha. The first banana farm in the district was 6 years old, while the newest farms were beginning their first year of operation. Upland irrigated farms had replaced maize in some cases, but satellite imagery also indicated that some fallow swiddens might have been replaced by banana cultivation.

Figure A2.2. An upland concession farm managed by the Chinese company, Jin Xui, in Houn district, Oudomxay. The cleared hillslope on the left side of the photograph was converted from maize to banana cultivation during the next growing season.

Rain-fed hillslope farms were the most common farm type in Boun Neua district, Phongsaly. These farms were typically located on hillslopes far from perennial streams and ponds. Of the three farm types, rain-fed hillslope farms were located farthest from surface water resources (Figure A2.3). Upland contract farms in the Boun Neua district ranged in size from 4.5 to 76 ha and in age from 3 to 6 years.

Figure A2.3. A typical upland contract farm in Boun Neua district, Phongsaly.

Water Management

Commercial banana plantations require substantial water inputs over the 10-month growing season. According to the handbook on banana production by the Food and Agriculture Organization of the United Nations (FAO), annual water requirements range from 1,200 mm in the humid tropics to 2,200 mm in the dry tropics (Brouwer and Heibloem 1986). Water management systems observed in northern Laos varied across farm types; some farms used sophisticated irrigation technology while others had no irrigation at all. Despite their large water requirements, bananas suffer if they receive excess water, which causes their roots to remain saturated for extended periods of time. Therefore, banana farms on flatlands often feature drainage ditches to remove excess water following rainfall and irrigation.

Farms used different sources of water to meet irrigation demands. Irrigated upland plain farms in Luang Namtha diverted water from small tributary streams for storage in unlined ponds, whereas irrigated hillslope farms in Oudomxay pumped as much as 5,000 m^3 of water per day from the main stem of the Beng River to store in large plastic-lined ponds. Rain-fed hillslope farms relied on rainfall to satisfy crop water requirements.

Irrigation water was typically delivered to plants via perforated plastic tubing run between alternating rows of crops. One farm manager in Oudomxay stated that his 120 ha farm used 4,000 m^3 of water per day, which was applied to one of four quadrants on a rotating basis so that each quadrant received water one out of four days.

Field modifications to manage runoff were common across the three farm types. In irrigated upland plain farms, drainage ditches were located in between rows of bananas to drain excess irrigation and rainwater. In contrast, furrows and rows of crops overlapped in rain-fed hillslope farms to maximize the amount of rainwater delivered to plants.

Fertilizer Inputs

Banana plants require large amounts of the nutrients nitrogen (N), phosphorus (P) and potassium (K). FAO recommends fertilizer inputs of 200–400 kg/ha N, 45–60 kg/ha P and 240–480 kg/ha K per year (FAO 2015). FAO also recommends short intervals between fertilizer applications, especially nitrogen, to reduce losses from runoff, volatilization and denitrification.

Detailed information about chemical usage on banana farms in Laos was difficult to obtain. While farmers were forthcoming about the timing of fertilizer applications, they often did not know the chemical names because they were printed in Chinese. The fertilizers most commonly observed were mixtures of potassium, nitrogen and phosphorous.

Irrigated upland plain farms and irrigated hillslope farms had very similar fertilizer application regimes. Most farmers applied fertilizer twice a month. Both farm types used a practice called 'fertigation', in which fertilizers were added to irrigation water and applied together.

Fertilizer usage among rain-fed hillslope farms varied widely. In one case, fertilizers were only applied once during planting at the onset of the wet season, whereas another farmer reported applying fertilizer four to six times. In all cases, fertilizers were only applied during the wet season when rainfall would transport nutrients to the plant roots. One farmer also reported that banana yields tended to decrease after the third year of production and that more fertilizer was required.

Pesticide Inputs

Commercially grown bananas are vulnerable to a host of insect, bacterial and fungal pests. In order to protect their crop and maximize yields, farmers utilize a wide variety of pesticides before and throughout the growing season.

Irrigated upland plain farms in Sing district used herbicides three times per growing cycle and other pesticides as recommended by pesticide shop technicians, who were consulted when a problem occurred.

In Boun Neua district, rain-fed hillslope farms applied insecticides once a month as needed and fungicide up to three times after the fruit had emerged. District staff from the Ministry of Natural Resources and Environment (MONRE) mentioned that most of the pesticide shops in the area were small and contracting companies supplied the majority of chemicals. DAFO staff reported that banana farms used fewer herbicides than maize and rubber farms, but more insecticides and fungicides.

According to one farm manager in Houn district, irrigated hillslope farms applied insecticides and fungicides twice a month beginning one month before flowering and ending one month before harvest (with a total of 9–10 applications). Herbicides were usually applied three times per growing cycle, with the amount applied varying according to the type of chemical and the degree of weed growth, but an average amount was approximately 2 L/ha (~6–8 mL pesticide/20 L water is used on ~50 plants).

Waste Management

Agricultural waste from banana plantations included empty pesticide containers, plastic fruit covers and raceme stems (Figure A2.4). The law requires companies and farmers to either burn or bury the waste. Burning was the most commonly observed method of waste disposal, usually occurring in the banana fields or along drainage ditches. Although the potential impacts on air quality are greater from burning, the burial of used pesticide containers could pose a considerable threat to groundwater resources. In a few cases, there was a large amount of garbage that had been discarded or washed into streams. The largest of the irrigated hillslope farms was the best at removing garbage from fields.

Figure A2.4. Rubbish pile in an irrigated hillslope farm, including raceme stems and plastic fruit coverings. This photograph was taken in early May 2016; however, the rubbish pile was present at this location during the previous visit.

Crops Being Replaced by Banana

According to district-level government staff and farmers, irrigated upland plain farms in Sing district had primarily replaced paddy rice, maize and sugarcane, as well as a few rubber gardens on the hillsides bordering the valley floor. Three of the four farmers interviewed in Sing district reported that they had switched from growing paddy rice to bananas because they did not have sufficient water to keep their paddies inundated. Farmers and district government staff claimed that bananas do not require as much water as rice. According to FAO estimates of crop water requirements, paddy rice requires 450–700 mm/growing period (not including water to maintain saturated field conditions) compared with 1,200–2,200 mm/growing period for bananas (Brouwer and Heibloem 1986). Farmers in Sing district also reported that banana farming required less hard labor than sugarcane.

In Houn district, farmers and DAFO staff stated that irrigated hillslope farms had almost exclusively replaced maize. The largest farm in the district, which spanned over 1,000 ha, had recently ploughed a large swathe of adjacent farmland, previously under maize production, to prepare for banana planting in the upcoming season.

Rain-fed hillslope farmers in Boun Neua district reported switching from fallow upland rice (called 'hay' in government land-use maps) to sugarcane, maize and Job's tears. One farmer mentioned that it was common for a farm that had been growing 'hay' for many years to switch to sugarcane and then quickly to bananas.

Perceptions of Environmental and Public Health Impacts

Field conditions in every farm showed signs of nutrient pollution. The soil surface in many plantations was covered in a layer of green algae and adjacent streams were choked with algae floating on the water surface or growing on rocks. In one irrigated upland plain farm, a group of families' domestic water supply came from a shallow well located within 5 m of an irrigation pond that was littered with empty pesticide containers and showed evidence of extreme nutrient pollution.

Despite rumors of farmworkers becoming ill after applying pesticides, interviewees across the three farm types reported that neither they nor anyone they knew had experienced any negative health effects from working on banana farms.

Across the three provinces, PAFO staff members expressed interest in developing evidence-based guidelines for responsible fertilizer and pesticide usage in order to protect the environment and workers' health. However, they felt that they lacked the technical capacity to assess soil quality and pesticide contamination levels.

District-level government staff and village leaders (*naibans*) tended to be the most knowledgeable about environmental and public health issues in their respective areas. DAFO staff in every district expressed concerns about possible impacts on domestic water supply and soil fertility as a result of banana production as well as other commercial crops (i.e., sugarcane, maize, rubber and cassava).

District-level government staff in each of the three provinces cited fish die-offs; two of which occurred during the previous 12 months. DONRE in Sing district mentioned that a large number of fish had died along a 500 m reach of the Nam Dai River (January 22–23, 2016); however, it is unclear what caused the die-off since it occurred during an unusually cold period (fish in the region are accustomed to warm water conditions and can die if the water becomes too cold). In Sibounheuang, a large fish die-off occurred at the beginning of the 2015 wet season in Nam Beng River. The coincidence of the Sibounheuang die-off with warmer wet season temperatures would suggest low temperature was not the cause of death.

DONRE staff in Houn district were also concerned about the impacts of pesticide usage on local food sources. For example, staff mentioned problems of reduced yield in the rice paddies, which received runoff from commercial fields, as well as fears of pesticide poisoning due to villagers eating rats that live in the banana fields.

In Sing district, DONRE reported that some farmworkers had experienced symptoms of pesticide poisoning (skin rashes, headaches and respiratory problems) that forced them to breach their 3-year work contract with the banana company. DONRE described that it was common among farmers to store pesticides in their homes to prevent theft.

DONRE staff in Boun Neua district suggested that one way to reduce environmental hazards from commercial agriculture would be to prohibit the cultivation of certain crops in watersheds that are used for drinking water.

Conclusions

- Banana farming techniques varied depending on slope conditions and access to surface water for irrigation.
- Chemical inputs were higher where irrigation allowed for more profitable, high-density farming.
- Widespread rumors about negative public and environmental health impacts in banana farming areas did not match the narratives of banana farm managers and workers. This is either the result of the rumors being incorrect or interviewees' reluctance to tell the truth about the negative impacts of banana farming practices.

Appendix 3. Surface Water and Soil Properties.

Table A3.1. Water quality parameters measured in the field during sample collection.

Location ID	Season	Crop type	Location type	Temperature (°C)	pH -	EC (µS/cm)
MC_SW3	Dry	MC	SW	26.7	7.35	842
NB_SW1		NB	SW	30.9	7.55	748
NB_SW2		NB	SW	31.2	7.21	628
NB_SW3		NB	SW	28	7.79	747
BENG_SW		Beng	SW	29.6	8.52	386
MC_SW1	Wet	MC	SW	27.2	8.21	483
MC_SW2		MC	SW	25.9	7.95	182
MC_SW3		MC	SW	28.8	8.09	673
NB_SW1		NB	SW	28.6	8.29	413
NB_SW2		NB	SW	27.3	8.2	541
NB_SW3		NB	SW	28.2	8.49	760

Table A3.2. Physical properties of soil samples.

Site name	Sand (%)	Silt (%)	Clay (%)	Soil texture
MC_Soil_Maize1	8.38	40.49	51.13	Silty clay
MC_Soil_Maize2	15.87	38.94	45.19	Clay
MC_Soil_Rubber1	35.91	41.17	22.92	Loam
MC_Soil_Rubber2	51.16	31.74	17.1	Loam
OB_Soil1	38.5	26.19	35.31	Clay loam
OB_Soil2	42.72	27.43	29.85	Clay loam
NB_Soil1	29.24	36.26	34.5	Clay loam
NB_Soil2	33.85	35.26	30.89	Clay loam
NB_Soil3	36.54	33.04	30.42	Clay loam

Table A3.3. Chemical properties of soil samples.

Site name	pH_w (1:1)	Total N (%)	OM (%)	P (mg/kg)	K (mg/kg)	CEC (c mol/kg)
MC_Soil_Maize1	8.26	0.108	2.81	16.19	336.66	30.3
MC_Soil_Maize2	7.17	0.148	3	3.78	221.23	23
MC_Soil_Rubber1	7.24	0.107	2.48	2.39	238.31	10.8
MC_Soil_Rubber2	6.3	0.101	2.05	2.2	161.01	7.7
OB_Soil1	7.2	0.124	2.53	103.78	2,044.47	14
OB_Soil2	5.76	0.12	2.19	94.53	815.84	11.9
NB_Soil1	4.72	0.1	2.81	223.46	897.85	15.7
NB_Soil2	5.81	0.13	2.71	190.22	888.31	16
NB_Soil3	5.44	0.123	3.24	179.81	458.99	16.7

Appendix 4. PIRI Model Description and Inputs.

Table A4. PIRI model inputs for physical site characteristics.

Land use information	Input value
Land use and land cover	Bananas
Soil type of land use	Clay loam
Start month	May
End month	February
Toxicity target species	LC_{50}, fish (mg/l)
Field cover	Bare ground
Indication of the severity of soil loss	Sediment very evident
Usual soil moisture content during the period of interest	Wet
Organic matter (%)	5
Total rainfall during the period of interest (mm)	1,279
Total irrigation during the period of interest (mm)	550
Soil pH	6.75
Average minimum air temperature (°C)	18
Average maximum air temperature (°C)	28.7
Width of nearest water body (m)	3
Slope of land to water body (degrees)	5.14
Distance from edge of the crop to water body (m)	0.5
Width of the buffer zone (m)	0
Minimum number of days from application to the first rainfall	0

Appendix 5. Pesticide Degradation Estimation.

Table A5. Estimated decrease in pesticide residue concentrations during a 14-day delay at the customs office in Ho Chi Minh City. Minimum and maximum reported half-life values were used to capture the range of expected residue loss due to degradation.

Pesticide name	Half-life minimum (days)	Half-life maximum (days)	Residue loss maximum (%)	Residue loss minimum (%)
Endrin	4,380	4,380	0	0
Cis-Chlordane	3,650	7,300	0	0
4,4'-DDE	2,920	2,920	0	0
Endrin aldehyde	1,460	1,460	1	1
4,4'-DDT	730	5,475	1	0
Paraquat	426	4,745	2	0
4,4'-DDD	365	365	3	3
Aldrin	365	365	3	3
Heptachlor epoxide	183	1,278	5	1
Endosulfan II	150	150	6	6
Heptachlor	146	292	7	3
Lindane (a-BHC)	120	120	8	8
Lindane (b-BHC)	120	120	8	8
Lindane (d-BHC)	120	120	8	8
Lindane (g-BHC)	120	120	8	8
Methoxychlor	120	120	8	8
Bifenthrin	97	250	10	4
Pyridaben	82	82	12	12
Fenbuconazole	79	365	12	3
Imidacloprid	40	124	24	8
Trans-Chlordane	37	3,500	26	0
Endosulfan I	35	35	28	28
Fenpropathrin	34	34	29	29
Dieldrin	30	1,825	32	1
Endosulfan sulfate	30	103	32	9
Tebuconazole	28	1,260	35	1
Azoxystrobin	14	14	69	69
Iprodione	14	14	69	69
Carbosulfan	13	13	75	75
Prochloraz	11.4	61.7	85	16
Chlorothalonil	10	60	97	16
Acetamiprid	8.2	8.2	118	118
Thiamethoxam	8	44	121	22
Chlorpyrifos	7	141	139	7
Propineb	2	2	485	485
Kresoxim-methyl	1	34	970	29
Thiram	1	77	970	13
Thiophanate methyl	0.7	867	1,386	1

Note: Residue losses of > 100% indicate complete degradation of the pesticide residue.

Appendix 6. Pesticide Residue Concentrations.

Table A6.1. CU pesticide residue concentrations in wet season surface water and groundwater samples collected on September 25, 2016.

Compound name	Unit	LOD	NB_SW1	NB_SW2	NB_SW3	MC_SW1	MC_SW2	MC_SW3	BENG_SW	GW1	GW2
Acetamiprid	µg/L	0.1	ND	ND	ND	ND	ND	ND	ND	ND	ND
Azoxystrobin	µg/L	0.1	ND	ND	ND	ND	ND	ND	ND	ND	ND
Bifenthrin	µg/L	0.1	ND	ND	ND	ND	ND	ND	ND	ND	ND
Carbosulfan	µg/L	0.1	ND	ND	ND	ND	ND	ND	ND	ND	ND
Chlorothalonil	µg/L	0.1	ND	ND	ND	ND	ND	ND	ND	ND	ND
Chlorpyrifos(-ethyl)	µg/L	0.1	ND	ND	ND	ND	ND	ND	ND	ND	ND
Fenbuconazole	µg/L	0.1	ND	ND	ND	ND	ND	ND	ND	ND	ND
Fenpropathrin	µg/L	0.1	ND	ND	ND	ND	ND	ND	ND	ND	ND
Imidacloprid	µg/L	0.1	ND	0.74	1.2	ND	ND	0.58	ND	ND	ND
Iprodione	µg/L	0.1	ND	ND	ND	ND	ND	ND	ND	ND	ND
Kresoxim-methyl	µg/L	0.1	ND	ND	ND	ND	ND	ND	ND	ND	ND
Prochloraz	µg/L	0.1	ND	ND	ND	ND	ND	ND	ND	ND	ND
Pyridaben	µg/L	0.1	ND	ND	ND	ND	ND	ND	ND	ND	ND
Tebuconazole	µg/L	0.1	ND	ND	ND	ND	ND	ND	ND	ND	ND
Thiamethoxam	µg/L	0.1	ND	ND	ND	ND	ND	ND	ND	ND	ND
Thiophanate-methyl	µg/L	0.1	ND	ND	ND	ND	ND	ND	ND	ND	ND
Thiram	µg/L	0.1	ND	ND	ND	ND	ND	ND	ND	ND	ND
Dithiocarbamate (maneb, mancozeb, metiram, propineb, thiram and ziram)	mg/L	0.02	ND	ND	ND	ND	ND	ND	ND	ND	ND
Propineb (as propylenediamine)	mg/L	0.02	ND	ND	ND	ND	ND	ND	ND	ND	ND
Paraquat	µg/L	0.1	ND	ND	ND	ND	ND	0.37	ND	ND	ND

Note: ND - Not detected.

Table A6.2. CU pesticide residue concentrations in wet season sediment samples collected on September 25, 2016.

Compound name	Unit	LOD	MC_SED1	MC_SED2	MC_SED3	NB_SED1	NB_SED2	NB_SED3	BENG_SED
Acetamiprid	mg/kg	0.01	ND	ND	ND	ND	ND	ND	ND
Azoxystrobin	mg/kg	0.02	ND	ND	ND	ND	ND	ND	ND
Bifenthrin	mg/kg	0.01	ND	ND	ND	ND	ND	ND	ND
Carbosulfan	mg/kg	0.01	ND	ND	ND	ND	ND	ND	ND
Chlorothalonil	mg/kg	0.01	ND	ND	ND	ND	ND	ND	ND
Chlorpyrifos(-ethyl)	mg/kg	0.01	ND	ND	ND	ND	ND	ND	ND
Fenbuconazole	mg/kg	0.01	ND	ND	ND	ND	ND	ND	ND
Fenpropathrin	mg/kg	0.01	ND	ND	ND	ND	ND	ND	ND
Imidacloprid	mg/kg	0.01	ND	ND	ND	ND	0.025	Detected (< 0.02)	ND
Iprodione	mg/kg	0.01	ND	ND	ND	ND	ND	ND	ND
Kresoxim-methyl	mg/kg	0.01	ND	ND	ND	ND	ND	ND	ND
Prochloraz	mg/kg	0.01	ND	ND	ND	ND	ND	ND	ND
Pyridaben	mg/kg	0.01	ND	ND	ND	ND	0.02	Detected (< 0.02)	ND
Tebuconazole	mg/kg	0.01	ND	ND	ND	ND	0.023	ND	ND
Thiamethoxam	mg/kg	0.01	ND	ND	ND	ND	ND	ND	ND
Thiophanate-methyl	mg/kg	0.01	ND	ND	ND	ND	ND	ND	ND
Thiram	mg/kg	0.01	ND	ND	ND	ND	ND	ND	ND
Dithiocarbamate (maneb, mancozeb, metiram, propineb, thiram and ziram)	mg/kg	0.02	ND	ND	ND	0.18	ND	ND	ND
Propineb (as propylenediamine)	mg/kg	0.02	ND	ND	ND	ND	ND	ND	ND
Paraquat	mg/kg	0.05	ND	ND	ND	ND	Detected (< 0.10)	ND	ND

Note: ND - Not detected.

Table A6.3. CU pesticide residue concentrations in wet season soil samples collected on September 23–24, 2016.

Compound name	Unit	LOD	MC_Soil_ Maize1	MC_Soil_ Maize2	MC_Soil_ Rubber1	MC_Soil_ Rubber2	OB_Soil1	OB_Soil2	NB_Soil1	NB_Soil2	NB_Soil3
Acetamiprid	mg/kg	0.01	ND	ND	ND	ND	ND	ND	ND	ND	ND
Azoxystrobin	mg/kg	0.02	ND	ND	ND	ND	ND	Detected (< 0.05)	ND	Detected (< 0.05)	0.46
Bifenthrin	mg/kg	0.01	ND	ND	ND	ND	ND	ND	ND	ND	ND
Carbosulfan	mg/kg	0.01	ND	ND	ND	ND	ND	ND	ND	ND	ND
Chlorothalonil	mg/kg	0.01	ND	ND	ND	ND	ND	ND	ND	ND	ND
Chlorpyrifos(-ethyl)	mg/kg	0.01	ND	ND	ND	ND	ND	Detected (< 0.02)	Detected (< 0.02)	0.28	1.2
Fenbuconazole	mg/kg	0.01	ND	ND	ND	ND	0.042	0.034	ND	ND	ND
Fenpropathrin	mg/kg	0.01	ND	ND	ND	ND	ND	ND	ND	ND	ND
Imidacloprid	mg/kg	0.01	ND	ND	ND	ND	0.044	0.052	0.076	0.076	0.66
Iprodione	mg/kg	0.01	ND	ND	ND	ND	ND	ND	ND	ND	ND
Kresoxim-methyl	mg/kg	0.01	ND	ND	ND	ND	ND	ND	ND	ND	ND
Prochloraz	mg/kg	0.01	ND	ND	ND	ND	ND	ND	ND	ND	ND
Pyridaben	mg/kg	0.01	ND	ND	ND	ND	ND	ND	0.028	0.024	Detected (< 0.02)
Tebuconazole	mg/kg	0.01	ND	ND	ND	ND	Detected (< 0.02)	0.022	0.031	0.16	0.2
Thiamethoxam	mg/kg	0.01	ND	ND	ND	ND	Detected (< 0.02)	0.029	ND	ND	ND
Thiophanate-methyl	mg/kg	0.01	ND	ND	ND	ND	ND	ND	ND	ND	ND
Thiram	mg/kg	0.01	ND	ND	ND	ND	ND	ND	ND	ND	ND
Dithiocarbamate (maneb, mancozeb, metiram, propineb, thiram and ziram)	mg/kg	0.02	ND	ND	ND	ND	ND	ND	ND	ND	ND
Propineb (as propylenediamine)	mg/kg	0.02	ND	ND	ND	ND	ND	ND	ND	ND	ND
Paraquat	mg/kg	0.05	ND	ND	ND	ND	ND	ND	ND	0.16	0.24

Note: ND - Not detected.

Table A6.4. Results from the NUOL analysis of pesticide residues in surface water and groundwater samples.

Compound name	Field mission	LOQ (ng/L)	NB_SW1	NB_SW2	NB_SW3	GW1	GW2 (ng/L)	MC_SW1	MC_SW2	MC_SW3	BENG_SW
Lindane (a-BHC)	Wet	5.92	ND	ND	ND	ND	ND	ND	ND	ND	ND
Lindane (g-BHC)	Wet	9.09	ND	ND	ND	ND	ND	ND	ND	ND	ND
Lindane (b-BHC)	Wet	8.1	ND	ND	ND	ND	ND	ND	ND	ND	ND
Lindane (d-BHC)	Wet	10	ND	ND	ND	ND	ND	ND	ND	ND	ND
Heptachlor	Wet	26	ND	ND	ND	ND	ND	ND	ND	ND	ND
Chlorpyrifos	Wet	5.23	< 5.23	5.81	5.35	< 5.23	< 5.23	5.72	< 5.23	6.59	< 5.23
Aldrin	Wet	17	ND	ND	ND	ND	ND	ND	ND	ND	ND
Heptachlor epoxide (Isomer B)	Wet	23	ND	ND	ND	ND	ND	ND	ND	ND	ND
Trans-Chlordane	Wet	32	ND	ND	ND	ND	ND	ND	ND	ND	ND
Cis-Chlordane	Wet	26	ND	ND	ND	ND	ND	ND	ND	ND	ND
4,4'-DDE	Wet	9.03	ND	ND	ND	ND	ND	ND	ND	ND	ND
Dieldrin	Wet	26.1	ND	ND	ND	ND	ND	ND	ND	ND	ND
Endosulfan I	Wet	23	11	ND	ND	ND	ND	ND	ND	ND	ND
Endrin	Wet	6.39	ND	< 6.3	< 6.39	< 6.39	ND	< 6.39	< 6.39	ND	ND
Endosulfan II	Wet	15	ND	ND	13	ND	ND	ND	ND	ND	ND
4,4'-DDD	Wet	5	ND	ND	ND	ND	ND	ND	ND	ND	ND
Endrin aldehyde	Wet	12	< 12	12	42	< 12	< 12	10	< 12	< 12	< 12
Endosulfan sulfate	Wet	25	ND	ND	ND	ND	ND	ND	ND	ND	ND
4,4'-DDT	Wet	6.3	ND	ND	ND	ND	ND	ND	ND	ND	ND
Endrin ketone	Wet	4.67	ND	15	< 4.67	ND	ND	< 4.67	ND	53	ND
Methoxychlor	Wet	6.56	ND	ND	ND	ND	ND	ND	ND	ND	ND
Lindane (a-BHC)	Dry	5.92	266	114	85	32	142	--	--	166	93
Lindane (g-BHC)	Dry	9.09	676	177	150	47	311	--	--	475	192
Lindane (b-BHC)	Dry	8.1	515	59	56	26	93	--	--	414	69
Lindane (d-BHC)	Dry	10	321	122	118	59	223	--	--	281	180
Heptachlor	Dry	26	752	27	37	21	49	--	--	53	39
Chlorpyrifos	Dry	5.23	94	1,461	933	61	35	--	--	89	793
Aldrin	Dry	17	ND	ND	0.94	ND	ND	--	--	ND	ND
Heptachlor epoxide (Isomer B)	Dry	23	ND	ND	ND	ND	ND	--	--	ND	ND
Trans-Chlordane	Dry	32	ND	ND	ND	ND	ND	--	--	ND	ND
Cis-Chlordane	Dry	26	ND	2.74	ND	ND	17	--	--	ND	ND
4,4'-DDE	Dry	9.03	27	10	5.98	4.23	17	--	--	33	23
Dieldrin	Dry	26.1	63	34	36	38	202	--	--	102	78

(Continued)

Table A6.4. Results from the NUOL analysis of pesticide residues in surface water and groundwater samples. (Continued)

Compound name	Field mission	LOQ (ng/L)	NB_SW1	NB_SW2	NB_SW3	GW1	GW2 (ng/L)	MC_SW1	MC_SW2	MC_SW3	BENG_SW
Endosulfan I	Dry	23	ND	ND	8.91	12	ND	--	--	ND	ND
Endrin	Dry	6.39	27	11	7.48	ND	ND	--	--	29	29
Endosulfan II	Dry	15	ND	ND	ND	ND	ND	--	--	ND	ND
4,4'-DDD	Dry	5	6.16	30	30	< 5	< 5	--	--	23	< 5
Endrin aldehyde	Dry	12	ND	ND	ND	ND	ND	--	--	ND	ND
Endosulfan sulfate	Dry	25	12	ND	ND	ND	ND	--	--	ND	ND
4,4'-DDT	Dry	6.3	124	< 6.30	3.86	456	651	--	--	316	201
Endrin ketone	Dry	4.67	ND	ND	ND	ND	ND	--	--	ND	ND
Methoxychlor	Dry	6.56	< 6.56	ND	ND	ND	< 6.56	--	--	ND	ND

Note: ND - Not detected.

Table A6.5. Results from the NUOL analysis of pesticide residues in sediment samples.

Compound name	Field mission	LOQ (µg/kg)	NB_SED1	NB_SED2	NB_SED3 (µg/kg)	MC_SED1	MC_SED2	MC_SED3	BENG_SED
Lindane (a-BHC)	Dry	3.25	ND	ND	ND	--	--	ND	ND
Lindane (g-BHC)	Dry	4.44	ND	ND	ND	--	--	ND	ND
Lindane (b-BHC)	Dry	4.41	ND	ND	ND	--	--	ND	ND
Lindane (d-BHC)	Dry	3.55	ND	ND	ND	--	--	ND	ND
Heptachlor	Dry	5.19	ND	ND	ND	--	--	ND	ND
Chlorpyrifos	Dry	3.63	< 3.63	< 3.63	ND	--	--	ND	< 3.63
Aldrin	Dry	3.7	ND	ND	ND	--	--	ND	ND
Heptachlor epoxide (Isomer B)	Dry	2.33	ND	ND	ND	--	--	ND	ND
Trans-Chlordane	Dry	2.9	ND	ND	ND	--	--	ND	ND
Cis-Chlordane	Dry	2.63	ND	ND	ND	--	--	ND	ND
4,4'-DDE	Dry	3.49	ND	ND	ND	--	--	ND	ND
Dieldrin	Dry	3.11	ND	ND	ND	--	--	ND	ND
Endosulfan I	Dry	3.66	ND	< 3.66	ND	--	--	ND	ND
Endrin	Dry	3.97	ND	ND	ND	--	--	ND	ND
Endosulfan II	Dry	6.99	ND	ND	ND	--	--	ND	ND
4,4'-DDD	Dry	3.16	ND	ND	ND	--	--	ND	ND
Endrin aldehyde	Dry	9.04	ND	ND	ND	--	--	ND	ND
Endosulfan sulfate	Dry	2.78	ND	ND	ND	--	--	ND	ND
4,4'-DDT	Dry	2.48	ND	ND	ND	--	--	ND	ND
Endrin ketone	Dry	3.19	ND	ND	ND	--	--	ND	ND
Methoxychlor	Dry	3.54	ND	ND	ND	--	--	ND	ND
Lindane (a-BHC)	Wet	3.25	ND	ND	ND	ND	ND	ND	ND
Lindane (g-BHC)	Wet	4.44	< 4.44	ND	ND	ND	ND	ND	ND
Lindane (b-BHC)	Wet	4.41	< 4.41	< 4.41	< 4.41	< 4.41	< 4.41	< 4.41	< 4.41
Lindane (d-BHC)	Wet	3.55	ND	ND	ND	ND	< 3.55	< 3.55	ND
Heptachlor	Wet	5.19	ND	ND	ND	ND	ND	ND	ND
Chlorpyrifos	Wet	3.63	48.05	13.7	< 3.63	< 3.63	< 3.63	< 3.63	< 3.63
Aldrin	Wet	3.7	ND	ND	ND	ND	ND	ND	ND
Heptachlor epoxide (Isomer B)	Wet	2.33	ND	ND	ND	ND	ND	ND	ND
Trans-Chlordane	Wet	2.9	ND	ND	ND	ND	ND	ND	ND
Cis-Chlordane	Wet	2.63	ND	ND	ND	ND	ND	ND	ND
4,4'-DDE	Wet	3.49	ND	ND	ND	ND	ND	ND	ND
Dieldrin	Wet	3.11	ND	ND	ND	ND	ND	ND	ND

(Continued)

Table A6.5. Results from the NUOL analysis of pesticide residues in sediment samples. (Continued)

Compound name	Field mission	LOQ (µg/kg)	NB_SED1	NB_SED2	NB_SED3	MC_SED1 (µg/kg)	MC_SED2	MC_SED3	BENG_SED
Endosulfan I	Wet	3.66	ND	ND	ND	ND	ND	ND	ND
Endrin	Wet	3.97	ND	ND	ND	ND	ND	ND	ND
Endosulfan II	Wet	6.99	ND	ND	ND	ND	ND	ND	ND
4,4'-DDD	Wet	3.16	ND	ND	ND	ND	ND	ND	ND
Endrin aldehyde	Wet	9.04	ND	ND	ND	ND	ND	ND	ND
Endosulfan sulfate	Wet	2.78	ND	ND	ND	ND	ND	ND	ND
4,4'-DDT	Wet	2.48	ND	ND	ND	ND	ND	ND	ND
Endrin ketone	Wet	3.19	ND	ND	ND	ND	ND	ND	ND
Methoxychlor	Wet	3.54	ND	ND	ND	ND	ND	ND	ND

Note: ND - Not detected.

Table A6.6. Results from the NUOL analysis of pesticide residues in dry season soil samples from the NB transect.

Compound name	LOQ (µg/kg)	NB_Soil1a	NB_Soil1b	NB_Soil1c	NB_Soil2a	NB_Soil2b (µg/kg)	NB_Soil2c	NB_Soil3a	NB_Soil3b	NB_Soil3c
Lindane (a-BHC)	3.25	ND	ND	ND	ND	ND	ND	ND	ND	ND
Lindane (g-BHC)	4.44	ND	ND	ND	ND	ND	ND	ND	ND	ND
Lindane (b-BHC)	4.41	ND	ND	ND	ND	ND	ND	ND	ND	ND
Lindane (d-BHC)	3.55	ND	ND	ND	ND	ND	ND	ND	ND	ND
Heptachlor	5.19	< 5.19	< 5.19	< 5.19	ND	ND	ND	ND	ND	ND
Chlorpyrifos	3.63	ND	14	ND	ND	5.86	13	ND	9.36	< 3.63
Aldrin	3.7	ND	ND	ND	ND	ND	ND	ND	ND	ND
Heptachlor epoxide (Isomer B)	2.33	ND	ND	ND	ND	ND	ND	ND	ND	ND
Trans-Chlordane	2.9	ND	ND	ND	ND	ND	ND	ND	ND	ND
Cis-Chlordane	2.63	ND	ND	ND	ND	ND	ND	ND	ND	ND
4,4'-DDE	2.39	< 2.39	3.51	< 2.39	< 2.39	ND	< 2.39	< 2.39	< 2.39	< 2.39
Dieldrin	3.11	< 3.11	< 3.11	< 3.11	< 3.11	ND	< 3.11	ND	< 3.11	< 3.11
Endosulfan I	3.66	< 3.66	21	< 3.66	ND	8.94	< 3.66	ND	ND	ND
Endrin	4	ND	< 4	< 4	ND	ND	ND	< 4	< 4	< 4
Endosulfan II	7	ND	ND	ND	ND	< 7	< 7	ND	ND	ND
4,4'-DDD	2.45	< 2.45	< 2.45	< 2.45	ND	ND	ND	< 2.45	ND	< 2.45
Endrin aldehyde	9.04	ND	ND	ND	ND	ND	ND	ND	ND	ND
Endosulfan sulfate	2.78	ND	ND	ND	ND	ND	ND	ND	ND	ND
4,4'-DDT	2.48	ND	ND	ND	ND	ND	ND	ND	ND	ND
Endrin ketone	3.19	ND	ND	ND	ND	ND	ND	ND	ND	ND
Methoxychlor	3.54	ND	ND	ND	ND	ND	ND	ND	ND	ND

Note: ND - Not detected.

Table A6.7. Results from the NUOL analysis of pesticide residues in dry season soil samples from the OB, MC_Maize and MC_Rubber transects.

Compound name	LOQ (µg/kg)	OB_Soil1	OB_Soil2	MC_Maize1	MC_Maize2 (µg/kg)	MC_Rubber1	MC_Rubber2
Lindane (a-BHC)	3.25	ND	ND	ND	ND	ND	ND
Lindane (g-BHC)	4.44	< 4.44	ND	ND	ND	ND	ND
Lindane (b-BHC)	4.41	ND	ND	ND	ND	ND	ND
Lindane (d-BHC)	3.55	< 3.55	ND	ND	ND	ND	ND
Heptachlor	5.19	160	ND	ND	ND	< 5.19	< 5.19
Chlorpyrifos	3.63	ND	< 3.63	< 3.63	< 3.63	ND	ND
Aldrin	3.7	ND	ND	ND	ND	ND	ND
Heptachlor epoxide (Isomer B)	2.33	ND	ND	ND	ND	ND	ND
Trans-Chlordane	2.9	ND	ND	ND	ND	ND	ND
Cis-Chlordane	2.63	ND	ND	ND	ND	ND	ND
4,4'-DDE	2.39	< 2.39	< 2.39	< 2.39	< 2.39	< 2.39	< 2.39
Dieldrin	3.11	15	< 3.11	ND	ND	ND	< 3.11
Endosulfan I	3.66	< 3.66	< 3.66	9.4	9.11	< 3.66	< 3.66
Endrin	4	< 4	< 4	< 4	< 4	< 4	ND
Endosulfan II	7	ND	< 7	ND	ND	ND	ND
4,4'-DDD	2.45	4.92	< 2.45	ND	< 2.45	< 2.45	< 2.45
Endrin aldehyde	9.04	ND	ND	ND	< 9.04	ND	ND
Endosulfan sulfate	2.78	ND	ND	ND	ND	ND	ND
4,4'-DDT	2.48	ND	< 2.48	ND	ND	ND	ND
Endrin ketone	3.19	ND	ND	ND	< 3.19	ND	ND
Methoxychlor	3.54	ND	ND	ND	ND	ND	< 3.54

Note: ND - Not detected.

Table A6.8. Results from the NUOL analysis of pesticide residues in wet season soil samples from the OB, MC_Maize and MC_Rubber transects.

Compound name	LOQ (µg/kg)	NB_Soil1	NB_Soil2	NB_Soil3	OB_Soil1	OB_Soil2	MC_Soil_Maize1	MC_Soil_Maize2	MC_Soil_Rubber1	MC_Soil_Rubber2
		(µg/kg)								
Lindane (a-BHC)	3.25	ND	ND	ND	ND	ND	ND	ND	ND	ND
Lindane (g-BHC)	4.44	ND	ND	ND	ND	ND	< 4.44	ND	ND	ND
Lindane (b-BHC)	4.41	ND	< 4.41	< 4.41	< 4.41	< 4.41	< 4.41	< 4.41	ND	ND
Lindane (d-BHC)	3.55	ND	ND	ND	ND	ND	ND	ND	ND	ND
Heptachlor	5.19	ND	ND	< 5.19	ND	ND	ND	ND	ND	ND
Chlorpyrifos	3.63	7.26	197	2,355	5.68	9.14	6.05	2.79	< 3.63	< 3.63
Aldrin	3.7	ND	ND	ND	ND	ND	ND	ND	ND	ND
Heptachlor epoxide (Isomer B)	2.33	ND	ND	ND	ND	ND	< 2.33	ND	ND	ND
Trans-Chlordane	2.9	ND	ND	ND	ND	ND	< 2.63	ND	ND	ND
Cis-Chlordane	2.63	ND	ND	ND	ND	ND	< 2.63	ND	ND	ND
4,4'-DDE	2.39	ND	ND	ND	ND	ND	< 2.39	< 2.39	< 2.39	< 2.39
Dieldrin	3.11	ND	ND	ND	ND	ND	< 3.11	< 3.11	< 3.11	< 3.11
Endosulfan I	3.66	ND	ND	ND	ND	ND	7.48	ND	ND	ND
Endrin	3.97	ND	ND	ND	ND	ND	< 3.97	< 3.97	ND	ND
Endosulfan II	6.99	ND	ND	ND	ND	ND	7.12	ND	ND	ND
4,4'-DDD	2.45	ND	ND	ND	ND	ND	4	< 2.45	ND	ND
Endrin aldehyde	9.04	ND	ND	ND	ND	ND	12	< 9.04	ND	ND
Endosulfan sulfate	2.78	ND	ND	ND	ND	ND	< 2.78	< 2.78	< 2.78	ND
4,4'-DDT	2.48	ND	ND	ND	ND	ND	< 2.48	< 2.48	< 2.48	< 2.48
Endrin ketone	3.19	ND	ND	ND	ND	ND	7	< 3.19	ND	ND
Methoxychlor	3.54	ND	ND	ND	ND	ND	ND	ND	ND	ND

Note: ND = Not detected.

Appendix 7. QuEChERS Method for Organochlorine Pesticide Residue Quantification.

Ten grams of either soil or sediment samples were extracted with 10 mL of acetonitrile in a 50 mL centrifuge tube. Sediment samples were centrifuged to remove excess water before extraction. The mixture was manually shaken for 5 minutes followed by ultrasonication for 30 minutes. Citrate salt was added to each centrifuge tube, following which the tubes were shaken by hand for 5 minutes and centrifuged for 5 minutes at ≥ 3,000 RCF (relative centrifugal force).

In the clean-up step, an aliquot (5 mL) of supernatant was transferred to 15 mL dSPE tubes ($MgSO_4$, PAS and C18). The tubes were shaken manually for 1 minute and then centrifuged for 5 minutes at ≥ 3,000 RCF. The supernatant was then directly transferred into a sample vial for analysis with a gas chromatograph (GC System 6890 Series, Agilent, USA) and mass selective detector (5973 Network, Agilent, USA), and autosampler with injector (7683 Series, Agilent, USA). The standards used for calibration were ordered from Restek: SOM01.0 Organochlorine Pesticides Resolution Check Mix (P/N 32454).

The limit of detection (LOD) (the lowest concentration of a substance that can be reliably detected with a given analytical method) and limit of quantification (LOQ) (the lowest concentration that can be detected within some predefined limits for total error) were determined by conducting recovery tests on samples of soil, water and sediment spiked with known pesticide residue concentrations (10–50 µg/kg depending on the compound). Results from the spiked sample analysis were compared against the known concentration to determine the percentage recovered.

Pesticide extraction from water samples was conducted using solid-phase extraction (SPE) using ISOLUTE multi-layer SPE cartridges (C2/C18 EC, Biotage, Japan). The cartridge condition was carried out with 5 mL of methanol followed with 5 mL of deionized water. Each 1,000 mL water sample was loaded into individual SPE cartridges through Teflon tubing at a flow rate of 10 mL/minute. The cartridges were then cleaned with 5 mL of deionized water and air-dried for 30 minutes. Pesticide elution from the cartridges was rinsed twice with 1 mL acetone and then transferred into a sample vial for analysis with gas chromatography/mass spectrometry (GC/MS; Agilent 7890).

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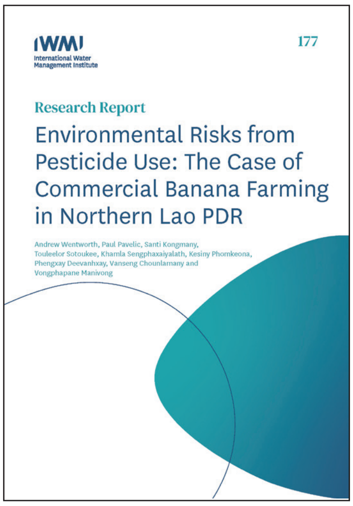

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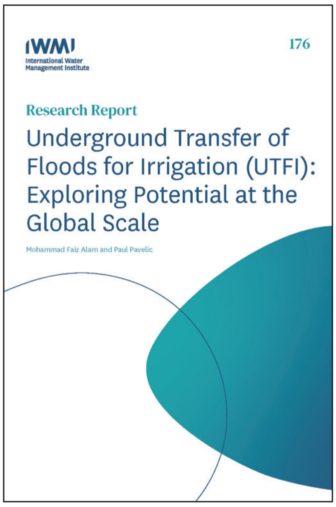

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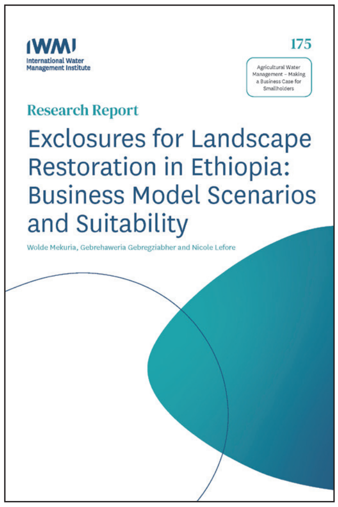

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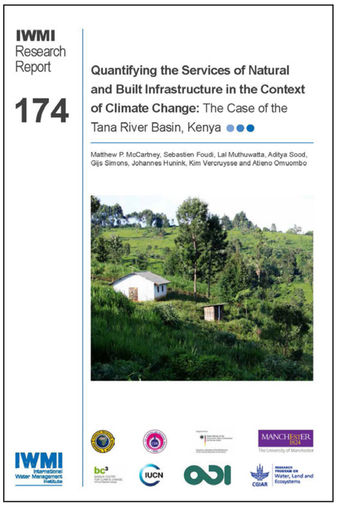

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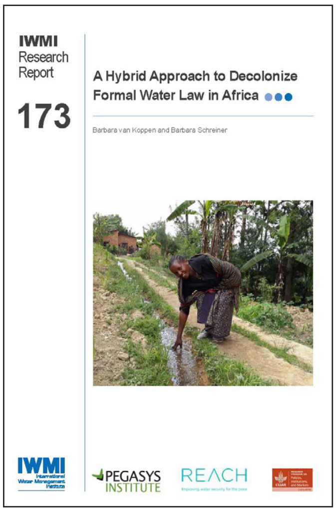

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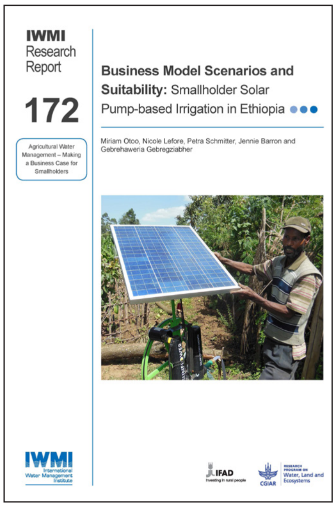

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