WORKING PAPER

Environmental exposures, health effects and institutional determinants of pesticide use in two tropical settings

Short title: PESTROP (Pesticide use in tropical settings)

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Preliminary remark

This working paper provides a summary of the main findings of the SNIS-funded PESTROP project as they are available in March 2019. At this stage, it cannot be an exhaustive presentation of our results; first because of the width of the study and second because many important data analyses are still on-going while preparing this final project report. In order to ensure consistent communication of our findings, we have included results that are considered robust and are highly improbable to change with later data analysis and leave out tentative results. Accordingly, this working paper is complementary to and not a substitute for the peer-reviewed papers that are going to follow from this project. This holds true also for the description of the various methods used within PESTROP. This document provides an overview about what was done and how, but the necessary disciplinary details will be described in the peer-reviewed articles. With the publication of these papers we will also make the respective data available to the scientific community through the data repositories commonly used by our institutions.

Background

Pesticides are intensively used in agriculture across the globe and data suggest that their use in the agricultural sector will continue to grow (Zhang, Jiang et al. 2011). According to the Food and Agriculture Organization (FAO), low- and middle-income countries (LMICs) located in tropical regions have the highest annual average application rates of pesticides (FAO 2013).

A particular characteristic of pesticides is that they are designed to impact living organisms (van den Berg, Zaim et al. 2012). Consequently, for a long time already, there have been concerns about negative impacts on the environment and human health due to the widespread use of these chemicals (Carson 1962, Chakraborty, Mukherjee et al. 2009, Azandjeme, Bouchard et al. 2013, Tago, Andersson et al. 2014). In LMICs, where there is insufficient regulation, less enforcement, lack of surveillance systems, and inadequate application of pesticides, negative side effects of pesticide use are expected to be larger than in high-income countries (Thundiyil, Stober et al. 2008). However, data based on a proper assessment of human and environmental exposure are generally very limited in LMICs (Prüss-Ustün, Vickers et al. 2011). Overall, there is also a lack of studies that jointly assess human and environmental health effects of pesticide use and how use practices are influenced by the institutional context. This poses a serious problem in how to best improve on the situation and may lead to inconsistent or even conflicting actions that get implemented.

A general strategy for counteracting pesticide-related risks is integrated pest management (IPM). IPM aims at implementing appropriate measures that keep pesticides and other interventions to levels that are economically justified and reduce or minimise risks to human health and the environment. Parsa et al. (2014) identified the following three most important obstacles to adaptation of IPM in LMICs: (i) low levels of education and literacy in farmers; (ii) insufficient training and technical support to farmers; and (iii) lack of favourable government policies. The study concluded that it was crucial to situate the debate within specific regional contexts and to have a broad stakeholder involvement.

Studying both the environmental and socio-behavioural dimensions within one research project allows to fill important data gaps related to pesticide exposure routes and health effects in tropical settings.

Goal of the project

Against the background described above, the central objective of this research project was to assess the misfits between pesticide use-related environmental exposure, human health effects, and institutional determinants in two tropical agricultural settings and to identify what changes in pesticide application and policy were needed to efficiently reduce human and environmental exposure to pesticides.

We investigated this overarching question in a comparative approach in two study areas located in Costa Rica and Uganda by addressing the following specific problems:

- To what degree are water resources in agricultural settings contaminated with pesticides and which types of pesticides contribute the most?
- Which are the main exposure pathways, risk determinants, and cumulative factors resulting in health effects due to pesticide use?
- What are the differences in pesticide-related health effects in small-scale farm workers with different levels of exposure?
- What policy design, competence allocation, and user right definitions are needed for the creation of an integrated IRR that efficiently reduces human and environmental exposure to pesticides?
- What interventions for reducing environmental and human exposure to pesticides at the local level are needed and how can national regulation support these?

Study areas

Costa Rica, Rio Tapezco catchment

The Rio Tapezco (RTZ) catchment is located in the central valley plateau in the province of Alajuela in the Zarcero County. It has a surface of 53.9 km^2 and ranges from 493 to 2039 meters above sea level (m a.s.l.) (Figure 1). Farmers intensively grow potatoes and other vegetables for the national market and rely heavily on synthetic pesticides to protect their crops. Fields are mostly situated on steep slopes (Figure 2).

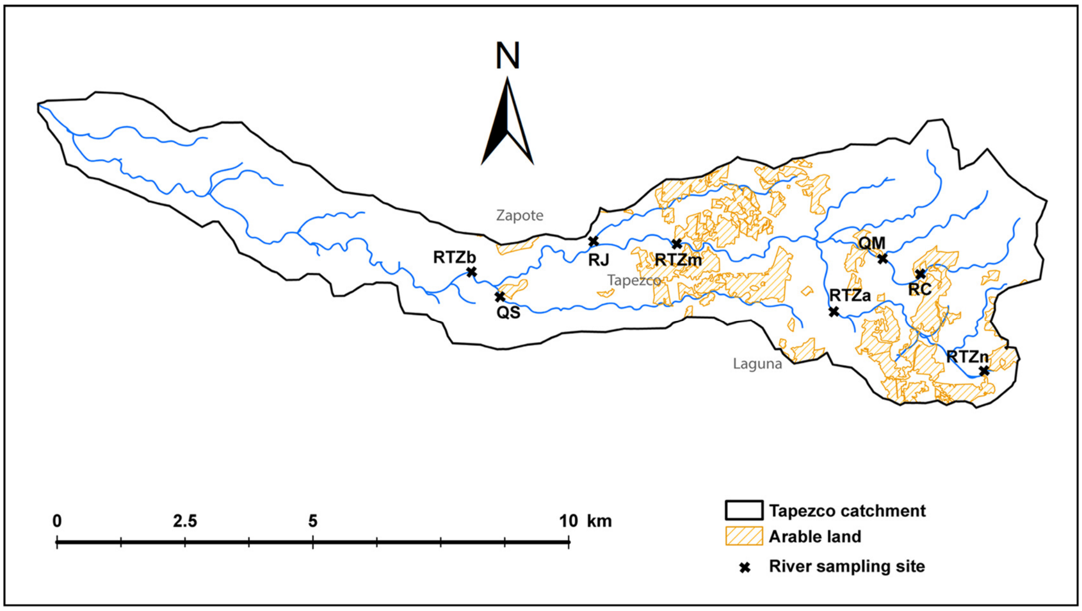

Figure 1: Map of the Rio Tapezco catchment with sampling sites, areas of arable land (brownish shaded areas) and village names (grey) (modified map from Moraga G., Universidad Nacional, Heredia, Costa Rica).

Figure 2: Pictures illustrating typical features of the landscape in the Río Tapezco catchment, Zarcero County, Costa Rica (pictures: Fred Weiss).

The environmental monitoring was conducted during the rainy season in 2015 (end of July to the beginning of October) and in 2016 (end of May to mid-October) by sampling the stream network at 5 and 8 locations, respectively in 2015 and 2016. Additionally, four drinking water tanks were studied.

From June to August 2016 farmer interviews and health assessments were conducted. For the institutional assessment, the document analysis and the expert interviews were conducted during May and June 2016. The restitution activities took place in November and December 2018.

Uganda, sub-catchment of river Mayanja (Wakiso district)

The study area of 72 km^2 covers part of the Mayanja river catchment in the Wakiso district (Figure 3). The altitude ranges from 1100 to 1300 m a.s.l. Major crops are beans, maize, (sweet) potato, banana, cassava, coffee, tomatoes, and groundnuts. They are planted on small plots mainly for subsistence use and the regional market (Figure 4). A growing number of farmers are cultivating horticultural products for commercial purposes. Both groups apply pesticides for crop protection. In addition, pesticides are used to protect livestock and for vector control. The topography of the study area in Wakiso district is rolling to slightly hilly.

All study components were conducted during the rainy season in 2017 (end of September to end of November). The restitution activities took place in January and February 2019.

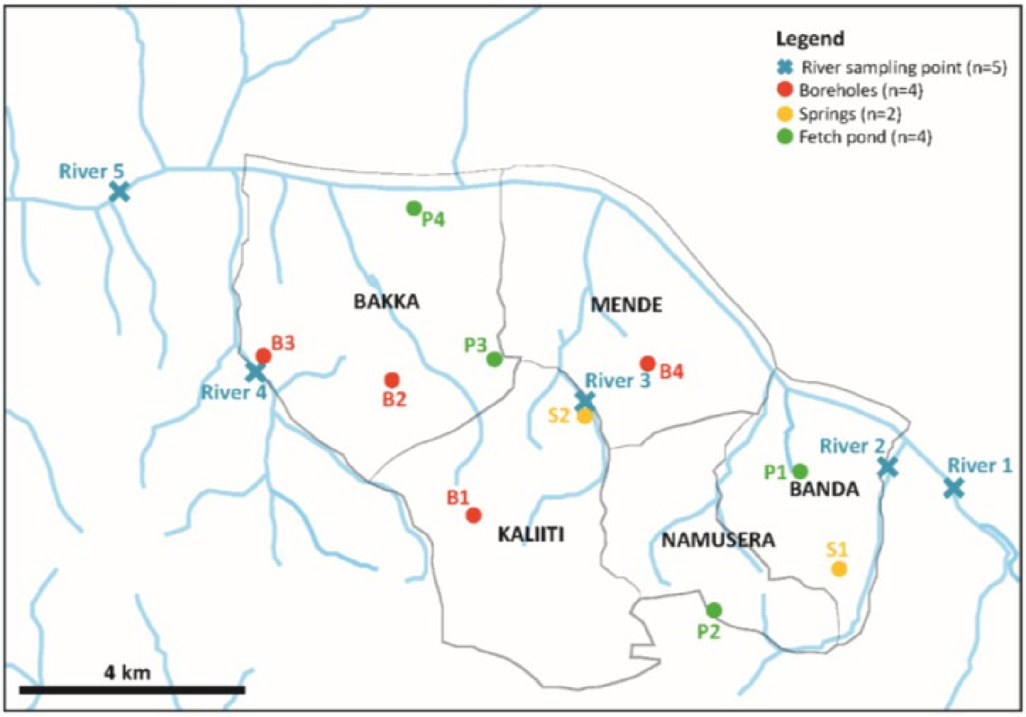

Figure 3: Map of the monitored sub-catchment of the Mayanja river in the Wakiso district, Uganda, with its five river sampling sites (blue crosses, two main rivers, three tributary streams), boreholes (red dots), springs (yellow dots) and fetch ponds (green dots) and the names of the different tribes (black) (original map from google maps, vectorised with Adobe Illustrator).

Figure 4: Pictures illustrating the landscape in the Mayanja catchment and pesticide use in the Wakiso district, Uganda (pictures: PESTROP team).

Methods

Farmer knowledge, attitude, and practices (KAP)

Participant Selection

In both areas, we planned to recruit a sample size of 300, equally distributed between conventional farmers (using synthetic pesticides) and organic farmers (not using synthetic pesticides). The detailed sample size calculation can be found in Fuhrimann et al. (2019). Due to an unexpected recent decrease in the number of certified organic farms in the Zarcero County, Costa Rica, we had to enrol in our study more farmers from conventional farms than from organic farms. This was not an issue in the Wakiso district, Uganda.

Farmers working within the study areas and aged 18 years or older were eligible for participation. The sampling strategy was different for the two study areas:

- Costa Rica: Random GPS points were generated using known farmland based on 2015 data to identify the farms and corresponding farmers using conventional techniques. Organic farmers were identified using a list from the local organic farmer association.
- Uganda: Community leaders from villages within the study area provided lists of farmers willing to participate. Random sampling of 50% of the provided farmers was used to select conventional farmers. Organic farmers were contacted through the local organic farming association, from where an initial list was used for snowball selection.

Standardised Interviews

In Costa Rica, interviews occurred at the farmers home or workplace. In Uganda, we invited farmers to meet us in rented offices. After an initial interview, we interviewed farmers again after 3-5 weeks and 2-4 weeks and in Costa Rica and Uganda, respectively. Standardised structured questionnaires in Spanish or Luganda were administered by trained interviewers and using Open Data Kit (http://opendatakit.org).

Questionnaire Structure

The interviews included questions on socio-demographics, health and work history, pesticide exposure, and application practices of the 15 active ingredients most frequently used in the study areas. In Costa Rica we assessed six fungicides, one herbicide and eight insecticides. The selection of these active ingredients was based on a study previously conducted in the Zarcero County by Ramírez et al. (2015). In Uganda, UNACOH, an NGO that has vast experience in the field of pesticide use in Uganda, advised on the most commonly used pesticides in Wakiso district. The final selection included one fungicide, three herbicides, and eleven insecticides.

Ethical considerations

All Study materials were approved by the human subjects committee of the Universidad Nacional in Costa Rica (UNA-CECUNA-ACUE-04-2016), the Higher Degrees, Research and Ethics Committee (HDREC) of Makerere University in Uganda (HDREC 522), and Ethical Board of the Ethikkommission Nordwest- und Zentralschweiz in Switzerland (EKNZ-UBE 2016-00771). At enrollment, each participant gave written informed consent.

Water quality

During both sampling campaigns, three passive sampling devices (water-level proportional sampler (WLP), styrene-divinylbenzene reverse phase sulfonated (SDB) disks, and polydimethylsiloxan (PDMS) sheets) were used to collect biweekly composite samples for the sampling locations in the rivers (5 locations both in Uganda and Costa Rica (2015), 8 locations in Costa Rica (2016)). Additional grab samples were obtained from 4 drinking water reservoirs in Costa Rica and 10 fetch ponds, boreholes, and springs in Uganda.

A target screening of total 276 organic pollutants was conducted according to Moschet et al. (Moschet, Wittmer et al. 2014, Moschet, Vermeirssen et al. 2015)). The list of analytes mainly consisted of pesticides plus some few additional organic micropollutants (55 fungicides, 7 fungicide transformation products: 56 insecticides, 11 insecticide transformation products, 97 herbicides, 41 herbicide transformation products, and 9 substances from various substance classes (pharmaceuticals, germicides, wood protection agents, phyto regulators, molluscicide, and preservatives). The extracts of the SDB disks and the WLP samples were analysed via offline liquid chromatography high-resolution tandem mass spectrometry (LC-HR MS/MS) (Moschet, Wittmer et al. 2014). The PDMS extracts were measured via gas chromatography via atmospheric-pressure chemical ionisation and tandem mass spectrometry (GC-APCI-MS/MS) by using an Agilent GC7890B gas chromatograph with backflush option and an Agilent MS/MS 6495 according to Rösch et al. (accepted).

Human health

In addition to all health-relevant information collected in the questionnaire survey (e.g. health history, pesticide use practices, and protective equipment use), clinical assessments were carried out (Figure 5, Figure 6 and Figure 7), covering the following parameters (Fuhrimann, Winkler et al. 2019):

- Neurobehavioral assessment: A neurobehavioral test battery that included an array of tests such as digit span test, digit symbol test, single reaction time test, finger tapping test, and Brief Symptom Inventory, was administered. The composition of the neurobehavioral test battery was determined by the types of pesticides applied in the study settings and, thus, was not the same in Uganda and Costa Rica (Manfioletti 2018).
- Acetylcholinesterase (AChE) activity: The activity of erythrocyte AChE and haemoglobin (Hb) levels were measured in a capillary blood sample with the Test-mate ChE Cholinesterase Test System (Model 400; EQM Research Inc., Cincinnati, OH). Erythrocyte AChE activity adjusted for Hb was analysed both as an independent variable and as a dependent variable (Staudacher 2016).
- Blood pressure: Systolic and diastolic pressures (BP) were measured with an automatic sphygmomanometer (Advantage 6021N) on two separate occasions: at the beginning and end of the visit. Average systolic and diastolic BP were calculated for each participant.
- Anthropometric measures: The height of the participants was measured using a portable stadiometer and weight with a digital scale (Tanita BC533, Arlington Heights, IL). The body mass index (BMI) was calculated as (weight/height^2) (kg/m^2), applying World Health Organization (WHO) cut-offs. Abdominal circumference was measured using a tape (Hoechstmass Balzer GmbH, Sulzbach, Germany).
- Functional neuroimaging: in a sub-sample of 50 farmers in Costa Rica, functional near-infrared spectrometry (fNIRS) was used to collect functional brain imagining (Baker, Rojas-Valverde et al. 2017).
- Analysis of pesticides in urine: Urine samples were collected (at baseline and follow-up) and analysed for multiple pesticide metabolites, including ethylenethiourea (ETU, metabolite of mancozeb), propylenethiourea (PTU, metabolite of propineb), 3-phenoxybenzoic acid (3-PBA, metabolite of pyrethroids), 3,5,6-trichloropyridinol (TCP, metabolite of chlorpyrifos), hydroxy pyrimethanil (OH-P, metabolite of pyrimethanil), and glyphosate (parent compound). Urine samples were analysed by tandem mass spectrometry and high performance liquid chromatography (Lindh, Littorin et al. 2008, Ekman, Maxe et al. 2013).
- Analysis of manganese in hair and toenails: at the second visit in Costa Rica, hair and toenail samples were collected and analysed for manganese (Mn), a biomarker of exposure to Mn-containing fungicides. Samples were digested by acid and reference material was analysed using electrothermal atomic spectroscopy with Zeeman background correction (Palzes, Sagiv et al. under review).

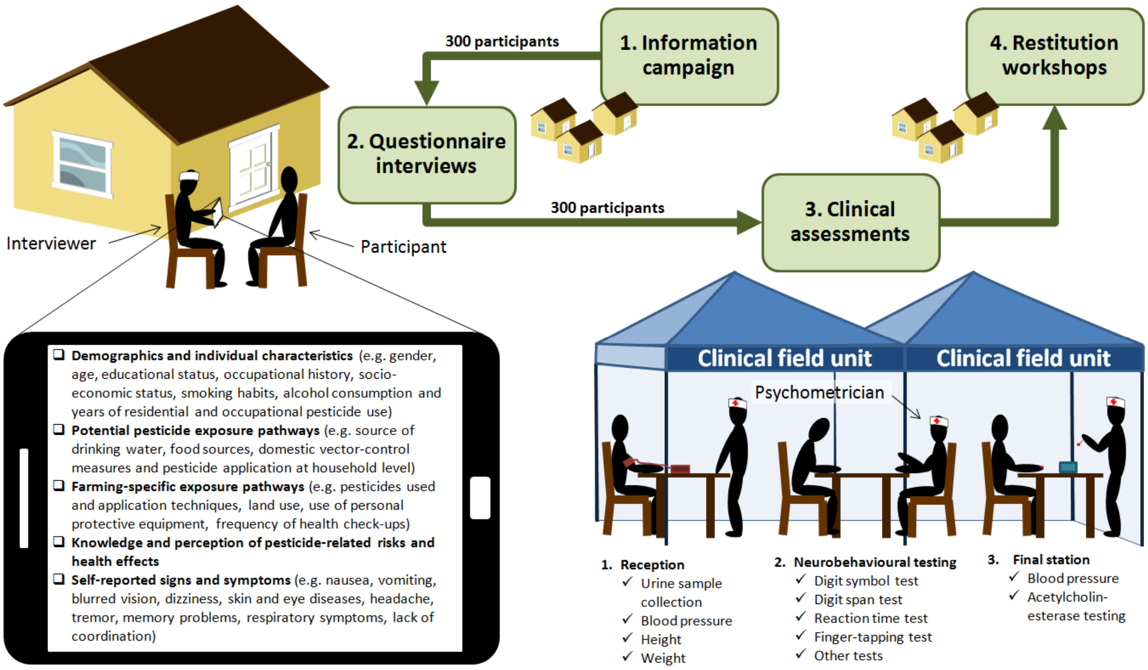

Figure 5. Field setup of the cross-sectional survey conducted both in Costa Rica and Uganda.

Figure 6. Clinical assessment station in in the Río Tapezco catchment area, Zarcero County, Costa Rica (pictures: Philipp Staudacher).

Figure 7. Clinical assessment station of the clinical assessments in the Mayanja catchment area in Wakiso district, Uganda (pictures: PESTROP team).

Linear and logistic mixed-effects regression models were applied for examining exposure-outcome associations. This was done in combination with exposure intensity scores that were developed using self-reported pesticide exposure data (Fuhrimann, Winkler et al. 2019, Fuhrimann, Staudacher et al. submitted).

Institutional analysis

Institutions are defined as the rules and guiding principles for policymaking in general, and for the actors involved in the political process in particular (Mayntz and Scharpf 1995). Policymaking involves a wide number of public and private organisations that have direct or indirect access to the final policy decision (Kenis and Schneider 1991). Besides politicians and representatives of administrative entities, this typically involves interest groups, organisations representing potential target groups of a policy (e.g. substance ban) or victims of a problem (e.g. farm workers), non-governmental and civil societal associations, science and many more. This so-called governance arrangement of different actions somehow involved in policymaking is steered by institutions (e.g. the rules that define whom can when participate in the political process and in what role) (Heikkila and Gerlak 2005).

Following the Institutional Resource Regime (IRR) framework (Gerber, Knoepfel et al. 2009), institutions include laws and regulations that steer a certain sector of policy subsystem; and property and user rights related to the concrete resource studied. In this project, we aimed for a non-traditional IRR approach. More specifically, we did not focus on one single (natural) resource but the public policies (laws and regulations) and property rights that regulate this resource. We focused on pesticide use and identified three (regulatory) conflicts: pesticide use conflicting with drinking water protection, with the protection of the aquatic ecosystem, and with human health.

We identified an exhaustive list of legal documents that regulate drinking water, protection of the aquatic ecosystem, and human health issues to the three key conflicts. A total of 30 legal texts for Costa Rica and 29 for Uganda were coded and then analysed. The codebook was divided in four dimensions to be measured: A) internal coherence of private law regulations; B) internal coherence of public policies; C) external coherence (between the private law regulations and public policy); and D) intensity of obligation. Indicators for these dimensions were: the clear definition of property titles, and use and disposal rights (for A), definition of the collective problem, causal hypothesis and target group, intervention hypothesis and policy instruments, and institutional coordination (for B), correspondence between target groups of the public policies and the holders of the property rights (for C). We added the fourth dimension (intensity of obligation) to understand whether existing policy instruments are sufficiently binding and coercive to foster compliance. Therefore, in a last step, we assessed the coerciveness of existing policy instruments to determine the intensity of obligation (for D). After the measurement of all four dimensions based on the afore mentioned indicators, we defined the institutional regime regulating pesticide use in the context of drinking water, the protection of the aquatic ecosystem, and human health.

The above assessment on how pesticide use is regulated was thereafter validated in interviews with selected key representatives of the public and private sector. These people also provided potential explanations when policy design gaps and implementation failures were identified through the text coding.

In Costa Rica, we also conducted a standardised survey and social network analysis in order to assess the implementation of organic farming at the regional level. Environmental policy processes are characterised by collaborative modes that include different sectors and actors working on different levels (global, national, and local). One promising approach to investigate collaborative, multi-level, and cross-sectional governance settings is social network analysis (SNA) (Kenis and Schneider 1991). SNA is based on the assumption that relationships among different interacting actors matter for policy outputs and outcomes. Applied to policy implementation and analysis, SNA focuses on structural patterns between actors (Lienert, Schnetzer et al. 2013), informal decision-making arrangements, and the integration of non-state actors are central components (Adam and Kriesi 2007). For this part of the institutional analysis, we focused on the County of Zarcero, where we surveyed actors about the governance structure and its influence on the implementation. We identified 38 actors of whom 9 local, 24 national, and 5 global. 30 actors (79%) participated in the survey and answered the questionnaire. We analysed the data with SNA to investigate how actors from different levels and sectors are positioned in the implementation process and who the most important stakeholders are.

<u>*Restitution activities*</u>

Restitution activities: In both countries, we relied on traditional ways of presenting and discussing the findings (workshops, conferences) that were specifically adapted to the target audiences. Additionally, we conducted a two-day design-thinking workshop in Uganda to let important stakeholders (agro-input dealers, extension officers, farmers, researchers, non-governmental organisations, local government, and industry representatives) identify key problems and develop specific solutions in an interactive process. The Design Thinking Technique allows participants to empathise with and observe the needs of the end user (in this case farmers). In different group formations, participants discussed their problem perceptions, the issues they are facing in their daily lives with pesticide management, and defined key problems. In a second step, they brainstormed solutions and developed one solution on a storyboard. Intermittently, ideas were exposed in plenum to all participants and consolidated after feedback implementation. In a last step, participants were invited to commit for implementation of the developed solutions.

Main findings

Disciplinary results

<u>*Farmer knowledge, attitude, and practices (KAP)*</u>

Costa Rica

Almost all farm workers (99%) considered that pesticides could be dangerous to their health. The majority of farmers (68%) said that family members wash the clothes used for applying pesticides, which could expose their relatives to pesticides and health risks that come with them.

The majority of farmers (more than 95%) said they use gumboots, long pants and hats, but only few (30% or less) reported to use gloves, masks with or without filter or a rubber apron.

Only about half of the farmers (48%) have received training in pesticide use, such as proper application techniques, storage, or safety procedures. Training is provided by the Ministry of Agriculture, commercial supply houses or local cooperatives.

Uganda

Most farmers (90%) considered that pesticides could be dangerous to their health. The majority of farmers (56%) said that family members wash the clothes used for applying pesticides, which could expose their relatives to pesticides and health risks that come with them.

Gumboots, long-sleeved pants and shirts are commonly available among farmers (65-80%) but not always used when applying pesticides (30-65%). Eyes, airways, and hands are rarely protected when applying pesticides. Overall, access and use of personal protective equipment (PPE) is considered low

Only one in four (23%) farmers has received training in pesticide use, such as proper application techniques, storage, or safety procedures. Among the users of synthetic pesticides, the numbers are even lower (14%). Training is provided by NGOs or governmental agencies, but rarely by commercial suppliers.

Comparison between study areas

As expected, in both countries a vast majority of pesticide users was aware that pesticides can have a negative effect on the health. The low numbers in training and PPE use correspondingly, show that this knowledge and awareness does not translate into action.

Farmers in Costa Rica state to apply a more diverse and more specific spectrum of pesticides. Most likely, due to their larger fields, they also apply these pesticides for longer hours than Ugandan farmers. Longer spraying hours indicate a more intense exposure of pesticides for human and environmental health.

<u>*Environmental health*</u>

Costa Rica

In the stream network, a total of 43 and 73 pesticides were detected across the different sampling sites during the field campaigns of 2015 and 2016, respectively. These numbers include similar shares of fungicides (18 and 29 compounds in the two years), insecticides (12 and 22 compounds) and herbicides (13 and 22 substances). Most of the flow-weighted concentrations over two weeks ranged between 1 and 100 ng/L. However, five pesticides were found in high (> 1000 ng/L) to very high concentrations (up to 10'000 ng/L for carbendazim). In the drinking water reservoirs, only five compounds were detected with concentrations below 100 ng/L.

Uganda

In the streams, 15 different pesticides (3 fungicides, 1 insecticides, and 4 herbicides) plus 8 transformation products were detected with one herbicide at concentrations > 100 ng/L. In the fetch ponds and boreholes used for domestic purposes, the number of detects were larger (Figure 8) and some concentrations were higher (two pesticides > 1000 ng/L).

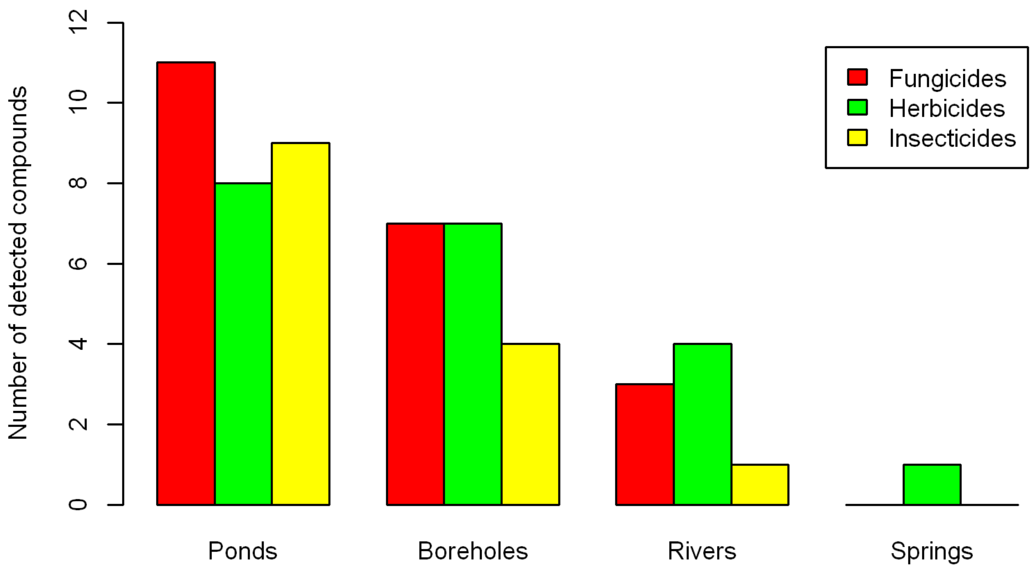

Figure 8: Comparison of number of compounds found in different types of water bodies in the Wakiso district (Uganda).

Comparison between study areas

The comparison between the two study areas reveals that more intensive pesticide use in Costa Rica is also reflected in higher pesticide pollution in its rivers (more compounds and (much) higher concentrations). However, in Uganda in water bodies potentially used for domestic purposes show higher pesticides levels and more pesticide detects than in Costa Rica (Figure 9).

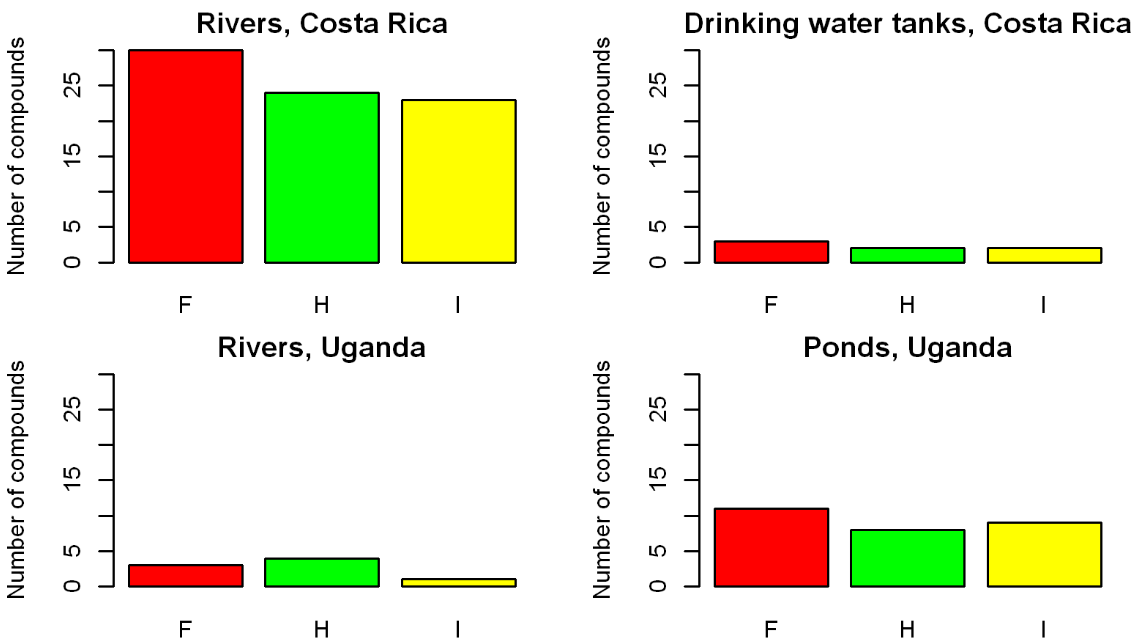

Figure 9: Comparison of the number of compounds detected in streams (left) and in ponds/boreholes/springs/drinking water tanks (right) in Costa Rica (top panel) and Uganda (lower panel).

Human health

Costa Rica

Based on the workers' responses to questions about their use of pesticides, we found that conventional farms (unrestricted use of synthetic pesticides) and sustainable farms (controlled use of synthetic pesticides and implementation of good agricultural practices) had greater contact with pesticides over time than workers from organic farms (limited use of synthetic pesticides, but implementation of biological pest management strategies) (Fuhrimann, Staudacher et al. submitted). More specifically, we observed a high within- and between-worker variability in weekly pesticide exposure scores (up to 180 and 70-fold differences in average weekly exposures between weeks and between average exposure among workers, respectively). Weekly pesticide exposure scores were reduced by a third in workers who have received training on pesticide use. Increasing work experience with pesticides also resulted in lower exposure scores (10% decrease in exposure for every 10 years of experience).

About 14% of farm workers reported having at least one pesticide poisoning in their life. This percentage was similar among workers from conventional, sustainable, and organic farms. However, workers from conventional farms reported a greater number of poisonings per person than workers from other farms. In addition to such acute effects, our results show that lingering health effects, such as fainting, problems sleeping, accelerated heart rate, numb hands and feet, and irritability in the last 12 months, are associated with having had a pesticide poisoning. Years of working with pesticides were associated with an increased risk of allergic rhinitis, but not with a higher risk of asthma, eczema, or chronic bronchitis.

No significant differences in mean acetylcholinesterase levels were found among the different study groups: 29.8 U/g for organic, 29.7 U/g for sustainable, and 29.6 U/g for conventional farming. Only five farmers (1.7%) had particularly low acetylcholinesterase values (i.e. ≤ 70% of quotient normal).

The urine sample analysis found higher levels of metabolites of several important pesticides ETU (metabolite of mancozeb), PTU (metabolite of propineb), TCP (metabolite of chlorpyrifos), 3-PBA (pyrethroid metabolite), DCCA (2,2-dimethylcyclopropane carboxylic acid; pyrethroid metabolite) and CFCA (3-(2-chloro-3,3,3-trifluoro-1-propenyl)-2,2-dimethylcyclopropanecarboxylic acid; metabolite of bifenthrin)) in workers from conventional farms compared to workers from organic farms (Figure 10). Interestingly, higher levels of glyphosate were found in urine samples of organic farm workers than in workers from conventional farms.

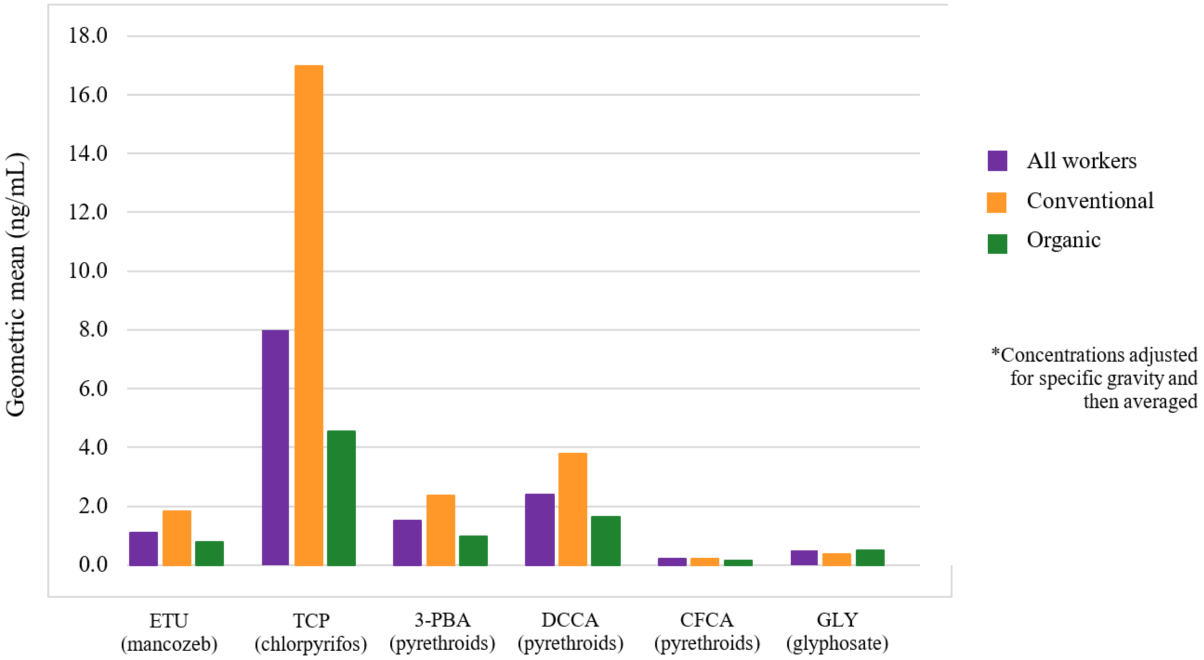

Figure 10: Geometric mean urinary concentrations of pesticide metabolites in Costa Rican farm workers (n=48).

In terms of Mn exposure, higher concentrations in toenail in workers from organic farms were observed (geometric mean (GM)=0.56; p=0.04) than those from conventional farms (GM=0.24) (Palzes, Sagiv et al. under review). In hair, Mn concentrations were similar in both groups. Higher toenail Mn concentrations in workers from organic farms could be due to the fact that it is common in organic farms to mix Mn and fertiliser when there is a Mn deficiency in the soil.

With regards to brain activity of farm workers, data showed that the higher the urinary concentrations of TCP, 3-PBA, and DCCA, the lower the activation of the prefrontal cortex while conducting working memory and executive function tests. This finding suggests that exposure to these pesticides may have altered the overall neural response, including the ability of a region or network to marshal a typical response to a task.

In our analyses, we found that toenail Mn concentrations trended negatively with brain activity, suggesting that past Mn exposure may be weakly related to inefficient recruitment of the dorsolateral prefrontal cortex. Lastly, with our study, we could show that fNIRS can be a useful and feasible tool in environmental epidemiology for examining the effects of toxicants, like Mn, on neural function (Palzes, Sagiv et al. under review).

Uganda

Ten farmers out of 302 (3%) self-reported an acute pesticide poisoning, but more than half of them (55%) reported feeling changes in their body or health within 24h of applying pesticides. Specifically, two out of three farmers (66%) applying exclusively synthetic pesticides reported having felt changes in their body or health after applying pesticides.

The findings of the neurobehavioral testing did not show an associations between self-reported farming practices and neurobehavioral outcomes (Manfioletti 2018). At the same time, there seems to be a connection between conventional farming practices and psychiatric distress and symptoms of depression, anxiety, and somatisation. More specifically, self-reported use of glyphosate and pyrethroids was related to these psychiatric disorders.

In Wakiso district, almost all farmers (98%) had normal levels of acetylcholinesterase in their blood. In the analyses of urine samples from 50 farm workers (84 for conventional and 12 from organics farms), we observed that six pesticides metabolites were detected in most urine samples (Figure 11). Higher concentrations of ETU, 2,4-D, glyphosate, and pyrethroid metabolites were found in farmers who reported using these pesticides during the week before the urine collection (compared to non-users). Urinary TCP concentrations were highest among farmers who sprayed pesticides against bedbugs or on their cattle.

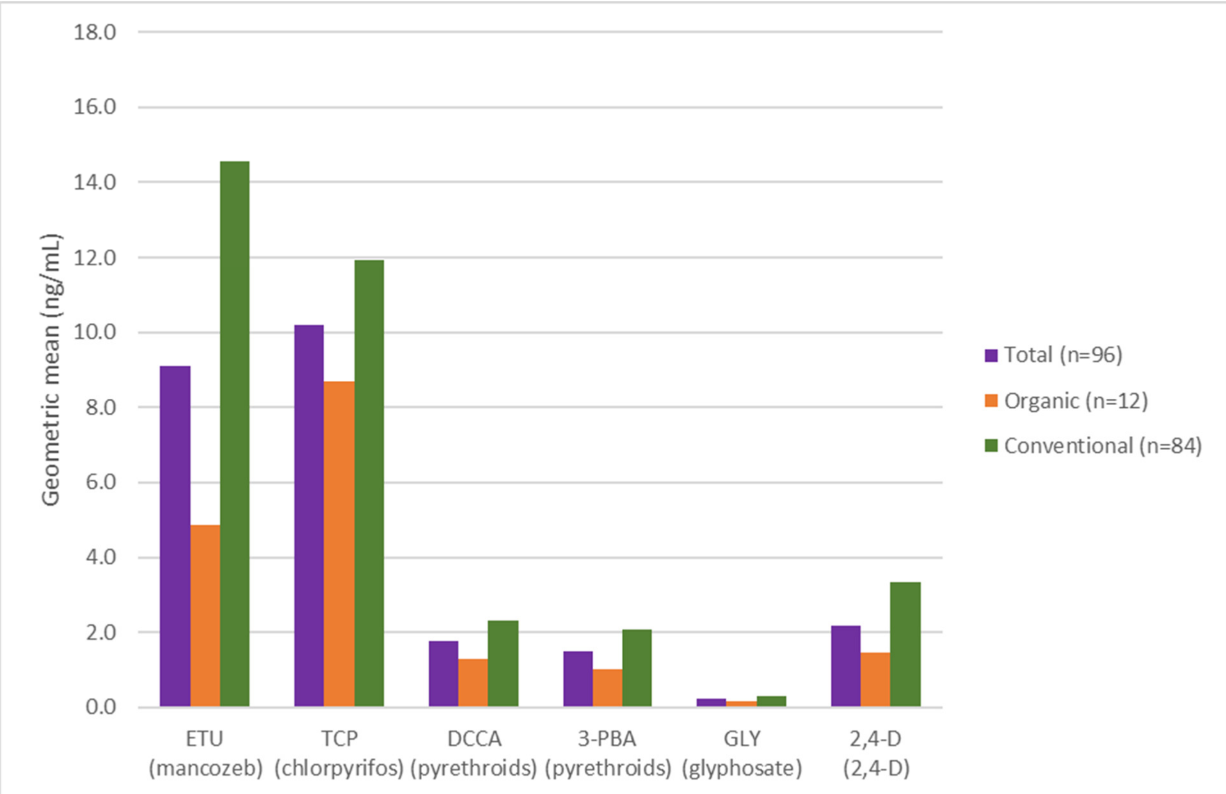

Figure 11. Geometric mean urinary concentrations of pesticide metabolites in urine (specific gravity-corrected in ng/mL) of farmers in the Wakiso district, Uganda, for conventional and organic farms.

Comparison between study areas

Urinary pesticide metabolite levels suggest that pesticide applications caused higher pesticide burden to the applicators compared to non-applicators in both study areas.

Institutional analysis

The key question asked in this part of the analysis was: "which *policy design, competence allocation, and user right definitions are needed for the creation of an Institutional Resource Regime (IRR) that efficiently reduces human and environmental exposure to pesticides?"* To investigate these questions, we needed to analyse the legal documents according to three different dimensions: (i) extent to which all uses provided by the resource are actually regulated, (ii) how the different public policies and property regimes "speak to each other", are complementary and have the potential to create synergies (coherence), and (iii) intensity of obligation evaluates to what extent compliance mechanisms are foreseen. Coherence and extent can be combined to classify the IRR into four categories as depicted in Figure 12.

Increasing intensity of obligation →

	Low extent	**High extent**
Low coherence	Non existent	Simple
High coherence	Complex	Integrated

Figure 12: Classification of the Institutional Resource Regime (IRR) based on coherence and extent of legal documents.

Costa Rica

Costa Rica has a very well developed regime related to pesticide use and human health. There is a clear portfolio of measures to protect humans from pesticide use. Furthermore, the target groups of these measures and street-level bureaucrats implementing these measures are well defined: mainly medical personnel, medical doctors, and other experts and practitioners in the medical sector are identified as the stakeholders who have to implement those concrete measures. The situation related to the resource water is quite different; for both drinking water and aquatic ecosystem the regime is complex. There are different conflict lines between pesticide use and resource water identified in the legal texts. But the law is outdated and almost solely concentrates on end-of-pipe and not source directed measures to prevent the aquatic ecosystem and drinking water from pesticide input.

The analysis of all actors involved in the implementation of organic farming initiatives driven by the national government showed that national actors represent the group that is best integrated in the implementation process of organic farming in Costa Rica. Local actors also integrate themselves, while global actors seem to show less interest in the issue. Furthermore, it makes no differences if actors are private or public, as both groups collaborate equally well with each other.

More specifically, these results show that local actors want to participate in land use policies and that their integration is most effective when aimed at resolving local issues. However, international actors like multinational organizations, influence organic farming in Costa Rica through the certification regulations and export provisions. National actors could thus start to act as gatekeepers between these international actors and the local authorities and farmers' associations when they establish new laws about regulation, certification, or promotion of organic products and production. Furthermore, stronger laws for commercialization, and a boost in the national and regional demand for organic products might give an additional incentive besides the national law to switch to organic or more sustainable farming practices.

Uganda

Comparing to Costa Rica, we see differences in economics as well as agricultural structures. In Costa Rica, pesticides are in most cases used by contracted farm workers. In Uganda, the target group of pesticide mitigation measures (e.g. protection clothes, organic farming practices) are mostly the small-holder farmers (owner) themselves exposed to pesticides through their regular application.

The legal situation in Uganda is complete and dense and comparable with Costa Rica. However, the intensity of obligation is missing. Interviews with two key experts in the field (two district officers in charge of agricultural matters in Wakiso district) confirmed that the policy design and, thus, the regulation of pesticide use on paper is not the key challenge. Concrete law enforcement is hindered through other priorities on the national political agenda and few resources on the local level (e.g. street level bureaucrats) that control the concrete implementation of several measures.

Comparison between study areas

Overall, we found that, IRR regimes regulating pesticide use in both countries are complex but not integrated. This means that while the potential conflicts between pesticide use and water/human health are regulated on paper, the different legal texts, as well as authorities and target groups, do not strongly coordinate actions. This indicates that so called policy dysfunctions (e.g. substances that are regulated twice) are very probable. One key result from our study is the systematic list of all different legal texts and related articles in the field. This list could serve as a background for key authorities and administration in order to engage in further policy coordination and effective implementation.

We also noticed that the target groups of policy measures to regulate pesticide use are not always clearly identified. This is particularly the case with water policy in Costa Rica and health policy in Uganda. As long as the stakeholder group, which should change the behavior or benefit from measures, is not clearly identified, policies will not be effective.

Restitution activities

In both study areas, stakeholders showed large interest in the restitution activities (Figure 13 to Figure 17). Different stakeholder groups wanted to learn about our findings and farmers were keen to obtain their personal health assessment data. This interest was a good basis for workshops and discussions for further clarification about the underlying causes of pesticide-related problems and possible mitigation strategies that could be developed. The design-thinking workshop on the district level in Wakiso area was especially fruitful demonstrating that stakeholders were open for novel forms of developing possible solutions. Proposed solutions covered a broad range of activities including demonstration farms, coordination of information campaigns among extensionists to sensitisation of farmers via drama and theatrical performances.

Figure 13. Farmers workshops in Las Brisas, Palmira, and Tapezco County of Zarcero, Costa Rica, in November and December 2018 (pictures: Mirko Winkler).

Figure 14. Forum "Nuestra responsabilidad como consumidores en el uso de los plaguicidas en la agricultura costarricense", Heredia, Costa Rica, in December 2018 (pictures: Mirko Winkler).

Figure 15. Design Thinking Workshop, Wakiso, Uganda, in January 2019 (pictures: Anne Witteveen).

Figure 16. National Stakeholder Workshop, Kampala, Uganda, in January 2019 (pictures: Anne Witteveen, Philipp Staudacher, Mirko Winkler).

Figure 17. Farmer restitution workshops, Masulita town, Uganda, in January 2019 (pictures: Anne Witteveen and Philipp Staudacher).

Integrated assessment

We observed negative impacts of pesticide use on human and environmental health in both study areas. We expected that these negative associations were the result of poorly defined policies and user rights, as well as weak institutional arrangements. This general hypothesis could be only partially confirmed. On paper, the regulation of pesticide use in the water and human health regime is clearly outlined in both countries. More concretely, the problem has been identified and different policy instruments were introduced to mitigate pesticide exposure of humans and aquatic ecosystems. Hence, public policies are generally established. One exception is the outdated water law in Costa Rica. For instance, this law does not clearly outline how concessions for water use (related to drinking water provision, but also other uses such as irrigation) are attributed and how user rights are monitored once concessioned. The institutional arrangements are not weak, but the problem of pesticide use is still not sufficiently addressed for the following reasons: First, in Uganda, pesticide use is not an urgent priority to national decision-makers and implementation strategies at the lower, district level are missing. In Costa Rica, the topic appeared to be higher on the political agenda compared to Uganda. This was confirmed in expert interviews and the topic of pesticide use was present in public documents and minutes of the ministries. Second, in both countries, consumers (of drinking water, but also of food) are not seen as target group of pesticide related regulations. Third, in the water sector, policy instruments are directed at the alleviation of contamination (end-of pipe instruments), but source-directed measures (to prevent water bodies from being contaminated in the first place) are needed as well.

In our study, we identified a miss-fit between policy design and local pesticide application result in environmental and human exposure to pesticides. Even though the institutional arrangement in both countries is complete and effective on paper, the link to the target groups and pesticide appliers is missing. As interviews with farmers and farm workers showed, problem awareness and the accessibility or affordability of protection measures is widely lacking. These observations were confirmed during the restitution activities. Notably, during these activities, many stakeholders also expressed the view that pesticides were considered an important topic and that they support a broader approach to tackle the problem at a national level.

Comparison between study areas

We found a number of similarities across both study areas. In both countries, there is agreement among many stakeholders that pesticide use is an important topic that needs to be more proactively addressed at the national and local level. Further commonalities are: (i) the observed discrepancies between regulations/policies and their implementation on the ground; and (ii) poor education and training of farmers and farm workers regarding pesticide use practices (including knowledge about non-chemical alternatives). In both countries this contributes to insufficient personal protection of many farmers/farm workers and respective pesticide exposure of pesticide applicators as demonstrated by the elevated levels of some pesticide biomarkers in urine. We also observed, in both study areas, a relatively high background exposure to pesticides among non-applicators suggesting that for some compounds (e.g. chlorpyrifos (in Uganda), pyrethroids (in Costa Rica)) other pesticide sources besides occupational exposure need to be considered (e.g. residential pesticide use, vector control, gardening; or ingestion of food and water containing pesticide residues).

There were also important differences between the two study areas that need to be considered when thinking how to set priorities for mitigation. The use of pesticides not aiming at crop protection (e.g. livestock, vector control, product conservation on the market) seems to be more important in Uganda than in Costa Rica. In Costa Rica, about 14% (n=42) of farmers reported having had at least one pesticide poisoning, while in Uganda only 3% (n=10) of farmers reported such an incident. In addition, 8 farmers in Costa Rica report more than one pesticide poisoning for a total of 71 self-reported pesticide poisonings in the cohort, while the 10 farmers in Uganda reporting a pesticide poisoning report only one. The intensive pesticide use in Costa Rica was also reflected in very high levels of pesticide concentrations in the streams while much lower exposure levels were observed in Uganda. Our data however suggest that some of the domestic water sources in Uganda were poorly protected against pesticide pollution while the infrastructure in the case of Costa Rica provided better security.

Recommendations

Overall, our findings demonstrate first the need for better protection of human and environmental health in both study areas and second that poor practices at different levels (farm level, local to national authorities, and private pesticide sector) jointly contribute to the current situation, leading to high environmental and human pesticide exposure. Accordingly, recommendations need to be formulated specifically for different stakeholders or institutional levels:

Farmers, farm workers

Many recommendations for improving the situation correspond to those included in good agricultural practices (e.g., only applying the recommended dose for each pesticide, apply the triple rinsing method for empty pesticide containers). However, such general advice needs to be adapted to the local context. Furthermore, one has to consider that the educational level of many farmers and farm workers in both countries is poor and that they have limited access to specific training. Therefore, it seems important to leverage established information channels among pesticide users to promote safe use practices and to make information about organic and integrated pest management more continuously available in farmers' lives. For example, farmers should be instructed to always contact/seek advice from agricultural experts in their communities (extension workers) on the best pest/disease management options before rushing to buy pesticides from agro-input shops. Such educational aspects, however, need to go hand in hand with making appropriate equipment for proper practices (including non-chemical alternatives) available at all.

Policy recommendations

Several policy recommendations can be given for improving environmental and occupational health. One key aspect seems to be strengthening the local levels of government and enhance collaboration between local and national level. Main shortcomings at the local level are resources (financial and personal), but also information. Another central element for policy improvement could consist of a better coordination across different sectors. Our systematic list of all different legal texts and related articles in the field could serve as a background for key authorities and administration in order to engage in further policy coordination and effective implementation.

Along the same line, it might also be useful to make policy measures more target group specific (farmers). In order to achieve this, it may be necessary to raise awareness with decision makers at the national level about the environmental and health problems related to pesticide use. Scientific evidence needs to be presented in appropriate form such as policy briefs.

Finally, a redefinition of property titles (e.g. the water law in Costa Rica to better define allocation of property titles and rights to use and dispose of water) could lead to better protection of environmental resources.

The promotion of IPM and organic farming is one strategy to reduce pesticide exposure of humans and the environment in general. In both countries, the full potential for IPM and organic farming is not yet reached: In Costa Rica, a law and corresponding regulation promoting organic farming exist, but main aspects such as increasing the local demand and international trade as to make organic farming an interesting option for farmers are lacking. In Uganda, IPM and organic farming are mainly managed through international NGOs, but a sustainable application of it and public support is not guaranteed yet. Generally, best practice examples and showcase projects at the regional and local level would be important to reduce uncertainties and convince a larger number of conventional farmers to shift to more sustainable framing practices.

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