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RESEARCH ARTICLE

Pesticide misuse among small Andean farmers stems from pervasive misinformation by retailers

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Abstract

A critical issue in the context of sustainable agriculture is the reduction of pesticides. Despite well-known adverse effects, farmers around the world continue using pesticides with mostly inappropriate ways. Relevant policies have assumed that farmers themselves are primarily responsible for pesticide misuse. However, the responsibility of pesticide retailers has never been quantified due to the difficulty in obtaining reliable data. An empirical study was conducted with smallholder farmers who collected 9,670 pesticide retailers' recommendations from 1489 surveys in the highlands of Bolivia, Ecuador and Peru. This original design allowed obtaining for the first time genuine responses about pesticide recommendations from retailers at a large scale. When comparing retailers' recommendations with product datasheets, the results suggest that 88.2% of recommendations standards were incorrectly followed resulting in dosing recommendations that were either excessive or insufficient and accurate less than 12% of the time. An in-depth analysis also showed that 79.2% of recommended products pertained to only 6 modes of action, thus increasing the risks of pest resistance. An expert retailer model further showed that all highly toxic pesticides could be replaced by less-toxic ones. Several ways to alleviate these detrimental consequences are proposed, by acting at the root of pesticide misuse–at the retailer's recommendation stage.

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Author summary

Pesticides have become an enduring feature of modern life and their use is rising almost everywhere on the planet, especially in lower income countries where pesticides are more weakly regulated. Impacts of pesticides on human health and environment remain a hot debate in the political arena. This issue is particularly worrying in developing countries where populations are most at risk. In agriculture, pesticide misuse and its detrimental consequences have repeatedly been assumed to be farmers' responsibility. However, many smallholder farmers strongly depend on retailers as a primarily source of information in terms of pesticide use. To the best of our knowledge, no study has evaluated the quality of retailers' recommendations compared to legal references. We conducted an empirical study in which smallholder farmers collected 9,670 pesticide retailers' recommendations from 1489 surveys in the highlands of Ecuador, Peru and Bolivia. Our original design allowed obtaining for the first time genuine responses from retailers at a large scale. When comparing retailers' recommendations with product datasheets, we found that 88.2% of recommendations standards were incorrectly followed with the result that dosing was either excessive or insufficient and accurate less than 12% of time. We also performed an in-depth analysis of the products showing that few pesticides' modes of action dominate, thus increasing pest resistance risks. Our expert retailer model further showed that all highly toxic pesticides could be replaced by less-toxic ones. We propose several ways to alleviate these detrimental consequences by acting at the root of pesticide misuse–at the retailer's recommendation stage.

1. Introduction

According to FAOSTAT the global consumption of pesticides for agricultural use has reached more than 4.1 million tons in 2017 [1]. Although the largest volumes of pesticides are applied in developed countries, pesticide use has dramatically increased in developing countries over the last decades [2,3]. In order to counter pesticide resistance by target pests and diseases, farmers have generally increased the quantity, concentrations and application frequency of pesticides [4]. This continuous increase in pesticide dependency has resulted in dramatic environmental and human health consequences including chronic human diseases, such as Parkinson, Alzheimer or cancers [5–7], contamination of food, soils and water resources [8–10] and the decimation of pollinators and beneficial natural enemies of pests [11]. Pesticide effects on human health and non-target organisms have been a source of worldwide concern for more than four decades and are the basis for most legislation aimed at controlling or prohibiting the use of specific products [12].

Despite high environmental, health and financial costs, farmers continue to use pesticides and often at inappropriate doses [2,13–16]. Overall, most research on pesticide misuse in developing countries has been done at the farmer level, assuming that pesticide misuse is mainly the responsibility of farmers. Some examples include studies on scaled-up extension programs about safety precautions [5,17], new technologies of smart spray systems [18], improvement of timing of application and product formulations [19] or farmer's personal and collective motivations to use pesticides [20,21]. However, a few studies have also suggested that pesticide retailers and chemical company representatives may be partly blamed for pesticide over- and misuse [13,22–27]. It could be explained by the fact that conflict of interests may force them to favor economic benefits over farmers' best interest [22,23]. Furthermore, it has been reported that retailers are in many cases farmers' primary source of information about pesticides [13,28,29]. Many farmers even disregard extension services for pesticide guidance, preferring to follow their own experience or retailers' advice instead [13,29,30]. Despite this well-known situation, no study has ever quantitatively evaluated the accuracy of retailer recommendations and to what extent these align with legal recommendations on product data sheets and labels. This is an important issue for enhancing sustainability and reducing human health risks, because tackling a root cause of pesticide misuse at the recommendation stage may ultimately be more efficient and effective than trying to relieve its symptoms at the application one. Also, it should be easier to change the practices of a handful of retailers than those of thousands of diverse farmers.

While most of the studies about pesticide misuse in developing countries have been carried out in Asia or Africa [13,14,17,31], small farmers in the Andes also widely use pesticides to protect their crops, often failing to follow proper guidelines [29,32,33]. These farmers are particularly at risks of pesticide poisoning due to low economic and social incentives to use protective equipment, the abundance of highly toxic pesticides, and the lack of training [33]. In addition, understanding pesticide operating instructions from labels is difficult for non-native Spanish-speaking farmers [33]. This may increase their dependency to pesticide retailers' guidance about pesticide use [29]. Therefore, assessing the quality of pesticide retailers' recommendation in the context of Andean small farming is of particular importance for agricultural sustainability in South America.

Here, an empirical study was co-constructed and conducted by a network of local farmers in the Andes to assess the overall quality of recommendations by pesticide retailers compared to official recommendations provided by manufacturers.

2. Materials and methods

2.1 Study sites

A total of 1489 retailers were surveyed in the highlands of Ecuador, Peru and Bolivia covering differing levels of pesticide use and a range of crops and pests. Samples were geographically stratified among 15 regions of Bolivia (Chuquisaca, Cochabamba, Oruro, La Paz and Potosí), Ecuador (Chimborazo, Imbabura, Cotopaxi, Tungurahua and Carchi) and Peru (Junín, Pasco, Huancavelica, Huánuco, and Ayacucho; see map in S1 Fig, Supplementary Material).

The main crops grown at the study sites were potato (*Solanum tuberosum*) and maize (*Zea mays*). Other common crops grown varied across country and regions, such as quinoa (*Chenopodium quinoa*) in the Altiplano of Bolivia, or Andean lupine (*Lupinus mutabilis*) in the Ecuadorian highlands.

Pesticide retailers in the study regions vary in terms of size, reach, training, importation activity or field visitation. These characteristics may influence the quality of recommendation and were therefore characterized. Different types of retailers were defined by local experts, but could not easily be aggregated across countries. Indeed, in Ecuador stores and chain stores were the only types while in Bolivia farmers also encountered retailers in market and itinerant retailers. In Peru, distributors and wholesalers were also accessible to farmers (S2 Fig, Supplementary Material).

2.2 Data collection

The survey design focused on 46 Andean localities cultivated by smallholder farmers. Within these localities, an exhaustive sampling was performed with a two-step process. First, official lists of retailers available from the ministries of agriculture were used to plan the survey's route. Second, if additional retailers were accidentally encountered on the route, they were also surveyed. These retailers could either be recently open, unofficial shops, itinerant or market retailers.

Surveys embraced 11 crops and 20 pest complexes (12 insects and 8 fungi) both locally abundant, and identified by local experts (S1 Table, S2 Table, Supplementary Material). Pest complexes (i.e. multiple species damaging a crop) were used instead of pest species because they are the basis for crop protection advices, as reflected in recommendations on pesticide labels. Pest complexes for potato crop (*Solanum tuberosum*) included the potato late blight (*Phytophthora infestans*) considered as the most important potato disease in Peru and Ecuador, also damaging other plants from the Solanaceae family such as tomato (*Solanum lycopersicum*) [34–36]. The Andean potato weevil (*Premnotrypes sp.*) and Potato flea beetle *(Epitrix sp.)* were also considered due to their important damage on potato crops [37–39]. Pest complexes damaging maize (*Zea mays*) included the fall armyworm (*Spodoptera frugiperda*) and the corn earworm (*Heliothis zea*) [40,41]. Finally, pest complexes for Andean lupine (*Lupinus mutabilis*), an important crop in Ecuador [42], included the Seedcorn maggot (*Delia platura*) and a stem borer (Anthomyiidae) [43,44].

Surveys were carried out by incognito farmers to obtain responses reflecting the realities experienced by local farmers asking for pesticide recommendations. Incognito farmers were local ones or students in agronomy who came to the retailer with a fictional pest problem asking for retailer's help. More specifically, they showed a locally-acquired picture of a common pest attacking their fictional crop to the retailer and asked for pest identification, along with pesticide solutions (commercial names) and operating instructions (dose and frequency of use). They also asked if any organic alternative method was available and registered the type of reseller. Farmers did not buy any product.

After the interview, incognito farmers were immediately surveyed by researchers who recorded the memorized retailer's recommendations on electronic handheld devices using KoBoToolbox. The fictional stories of crop location, history and management were co-designed with farmers to reflect realistic local cropping conditions (e.g. plot area, crop variety, plant density; S2 Table, Supplementary Material). This protocol allowed us to capture genuine responses from retailers that reflect the realities experienced by local farmers asking for pesticide recommendations.

The survey process of using incognito farmers precluded obtaining prior consent from the retailer to avoid any Hawthorne effect (i.e. a behavioral change due to an awareness of being studied). The study relied on retailers' unguarded recommendations, and their advice would have been considerably different if the shopkeepers had known they were part of a study. However, we took maximal care to minimize detrimental effects on retailers by ensuring their anonymity (both their names and the exact location of the shop). Surveys were carried out only when customers were absent to avoid any potential financial harm to retailers. Therefore, benefits for society arising from the study would outweigh any inconvenience caused to retailers.

2.3 Data treatment and analysis

Local pest names given by retailers were harmonized using OpenRefine and compared with a synonymy table built by local experts to determine pest species (Spanish or scientific names). Wrong species identification and broad terms such as larva (*gusano*) or insect (*insecto*) were considered as incorrect as they are not appropriate for providing proper recommendations of chemical control.

Commercial names of chemical products recommended by retailers were also harmonized with OpenRefine and then compared with national pesticide databases to enrich the dataset with several variables (e.g. active ingredients, concentration, toxic category). Unmatched commercial names were excluded from product and dosage assessments. When the concentration of a recommended product was not specified and matching products in the database showed several possible concentrations, the product was excluded from dosage analysis only (S3 Fig, Supplementary Material). Product comparisons were achieved at national level because several products with identical commercial names among countries may have different formulations and/or concentrations. All products were subsequently pooled together and their active chemical substances (and CAS number) were determined from Wikidata through OpenRefine reconciliation function. Pesticides' mode of actions were determined matching active substance with the IRAC classification v9.4 [45] for insecticides and FRAC classification [46] for fungicides.

Adequacy between retailer's recommendation and recommended use from datasheets was assessed in a three-step manner. First, the broad adequacy between pest phylum (insects or fungi) and product type (insecticide or fungicide) was assessed. Second, the presence of pest name (either Spanish or scientific name) and crop on the products' datasheets was checked for. A product was considered adequate if both the pest and the crop were present on its datasheet and inadequate if either crop or pest species were missing. Correct product classification was expanded to all products with the same active substances when at least one of these products' datasheet mentioned the crop-pest combination. Third, the datasheet of adequate products were further inspected and lower and upper bounds were recorded when specified. Doses given by retailers were first converted from local units (e.g. spoon, bottle cap) to international units using a conversion table established by local experts (S3 Table, Supplementary Material). Then, converted dosages were classified as correct if they fell within the lower and upper bounds from datasheets, as overuse if higher than the upper bound, and as underuse if lower than the lower bound. Dosage were expressed in dose ratio (g/L or mL/L) and not in volume per area (e.g. g/ha) for two reasons. First, the majority of recommendations, both from retailers and datasheets, were usually given in dose ratio. Second, the volume of pesticide solution necessary to cover 1 ha depended on a number of parameters (e.g. plant height, density) varying across fictional stories, which would have increased the uncertainty and may have led to overrepresentation of misuse in our results. When retailers recommended several products, these recommendations were considered as correct only if all the products were adequate for the pest and all their doses were correct. Fertilizers, herbicides and bactericides were excluded from the analysis because they were unrelated to the pest species studied.

Product toxicity was defined using two distinct classifications. The first classification was based on the World Health Organization toxic categories (I, II, III and IV) identified from product labels' color. This classification was used for the expert model recommendation (see below) as it depends on a national classification, and is therefore a relevant indicator for a retailer to choose between products. The second classification used the EU Pesticides Database [47] to identify active substances not approved in the EU, reflecting potentially hazardous substances. While WHO toxic categories vary for the same active ingredient and between countries, the EU classification is defined for active substance and was therefore used to characterize the potential hazard of the active ingredients recommended.

2.4 Expert model for pesticide recommendation

An expert model was built to quantify the room for improvement in pesticide recommendations. The model focused on i) proposing recommendations based on values provided by national datasheet, and ii) offering the least harmful products available for a given pest. The model used the sample of crop-pest combinations carried out during the survey (n = 1489). For a given crop-pest combination and country, the model pooled all the previously-identified correct products in the country and randomly chose a product with the least toxic category available (see S4 Fig, Supplementary Material). All recommendations provided by the model were then pooled across countries, and compared individually with its corresponding observed recommendation. All analyses were performed with R (v 3.5.1) and OpenRefine (v 3.3).

2.5 Ethics statement

The study design has been co-constructed and approved by the McKnight Institutional review board (through grant 16–213), and followed the good practices guide from the French National Research Institute for Sustainable Development (IRD). Verbal informed consent was obtained from all incognito farmers prior to the interviews and witnessed by the authors. Most of them also participated actively in the construction of their local fictional pest story.

3. Results and discussion

3.1 Errors in retailer recommendations

The study revealed that only 11.8% of retailer's recommendations were correct throughout the entire recommendation process (Fig 1), with the most- problematic steps being pest-product adequacy and dosage. Indeed, around 49% (48.7%) of the retailers surveyed proposed erroneous pesticides for a given pest, and 52.4% recommended an inadequate dose compared to reference amounts from the manufacturers (Fig 1). Taxonomical identification by retailers and broad product-pest adequacy were less-problematic compared to the other steps. Indeed, 23.3% of the retailers misidentified common local pest species and 13.9% proposed an inadequate product type (fungicide or insecticide) for a given pest type (fungus or insect). This suggests that product-pest inadequacy and incorrect taxonomical identification constitute a critical obstacle to appropriate pesticide practices. Misidentifying a pest or a product leads to the use of potentially ineffective product to control the pest, while maintaining all detrimental consequences on human health and the environment [13]. As a snowball effect to remedy such ineffective applications, farmers may be tempted to use a larger quantity of pesticides as a countermeasure, which leads to pesticide overuse.

Dosage analysis revealed that 47.9% of retailers proposed a proper pesticide dose while 33.5% recommended a dose up to 8 times higher than the upper bound in reference datasheets and 18.6% recommended a lower dose up to five times lower than the proper one (Fig 2). Dose is a key variable in pesticide issues as it can influence the mechanism of evolved resistance to pesticides. Indeed, high doses favor target site resistance and low doses favor pest resistance and resurgence [48]. The proper dose is defined by a trade-off between the manufacturer's will to ensure an efficient product under exceptionally bad conditions and the regulating national agencies wanting to reduce the environmental and health risks associated with pesticides [49]. Overuse has been extensively studied and commonly observed in smallholder farmers settings in several countries [2,13–16]. However, underuse has received little attention, even though it has serious consequences on pest dynamics [13]. The current's study findings also revealed that overuse and underuse practices were significantly influenced by the type of retailers and the pest species (S4 Table, Supplementary Material). For example, 93.4% of correct recommendations occurred for pests and diseases of potato, a crop with national importance in all Andean countries (S5 Fig, S6 Fig, Supplementary Material), for which retailers proposed more overuse for insect and underuse for disease (S7 Fig, Supplementary Material). Moreover, retailers in markets tend to propose higher dose compared to retailers in shops (S8 Fig, Supplementary Material). Many smallholder farmers grow minor crops, for which no reference data on pesticide use is available for associated pests and diseases. Recommendations for these minor crops and associated pests are therefore usually based on the retailer's knowledge and

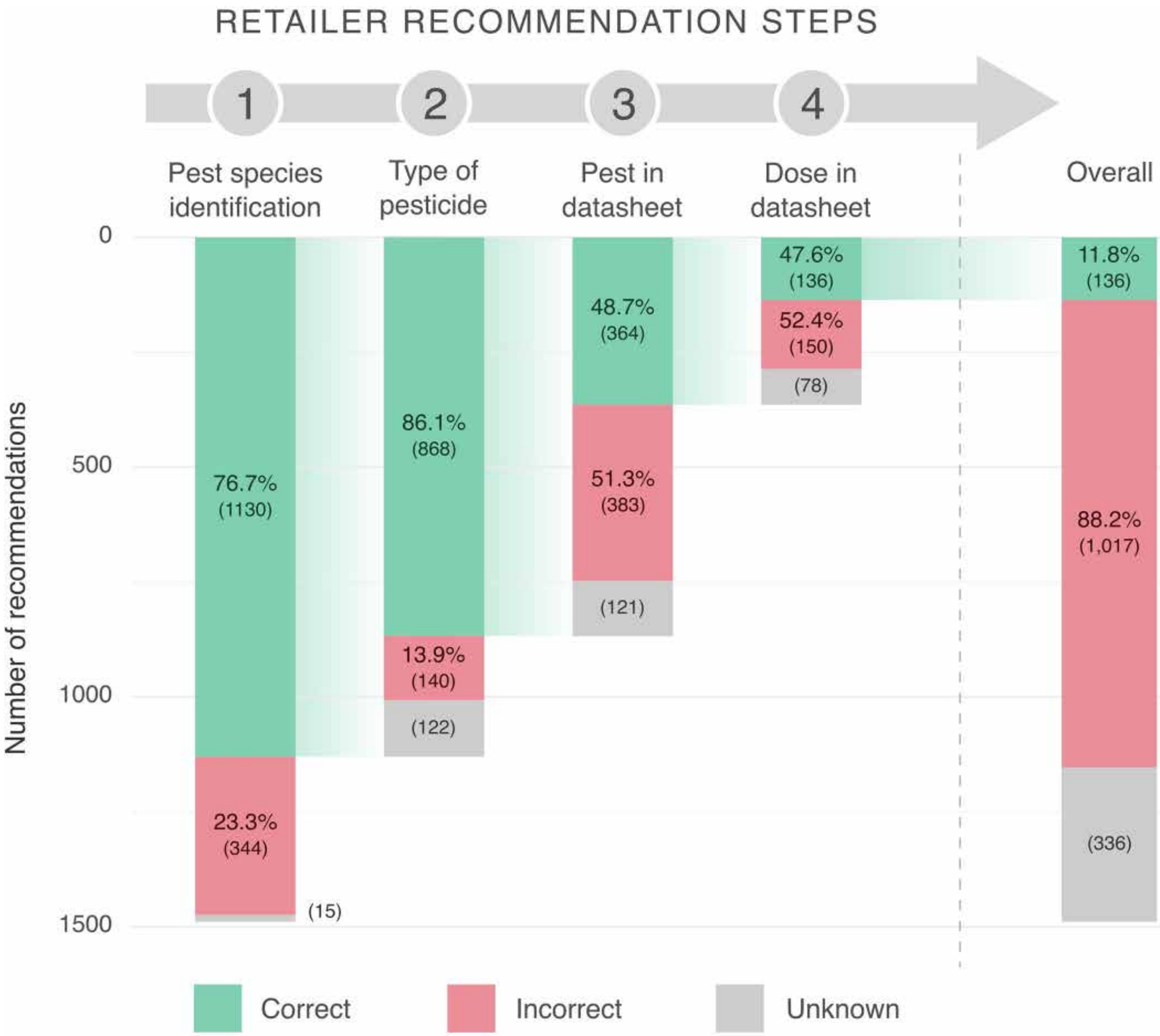

Fig 1. Accumulation of errors along the retailer's recommendation process. The first step evaluates whether pest species were correctly identified, the second step whether pesticide type (e.g. insecticide) corresponded to pest type (e.g. insect), the third step whether the pest species were present on product's reference datasheet, and the fourth step whether the recommended dose fell within the reference boundaries. Each step is dependent on the previous steps. Recommendations were classified as right (green, top), wrong (red, middle) or unknown (grey, bottom). Unknown category stands for recommendations for which data was missing to allow classification as right or wrong and were excluded from the calculation of proportions.

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experience of control measures for other phylogenetically similar pests and crops. However, these recommendations are variable because they depend on each retailer's knowledge.

3.2 Increased risk of pesticide resistance due to wrong retailers' recommendations

Retailers need to sell products that are efficient at controlling pests in order to maintain a good relationship with customers. Therefore, they generally seek to reduce the risks of development

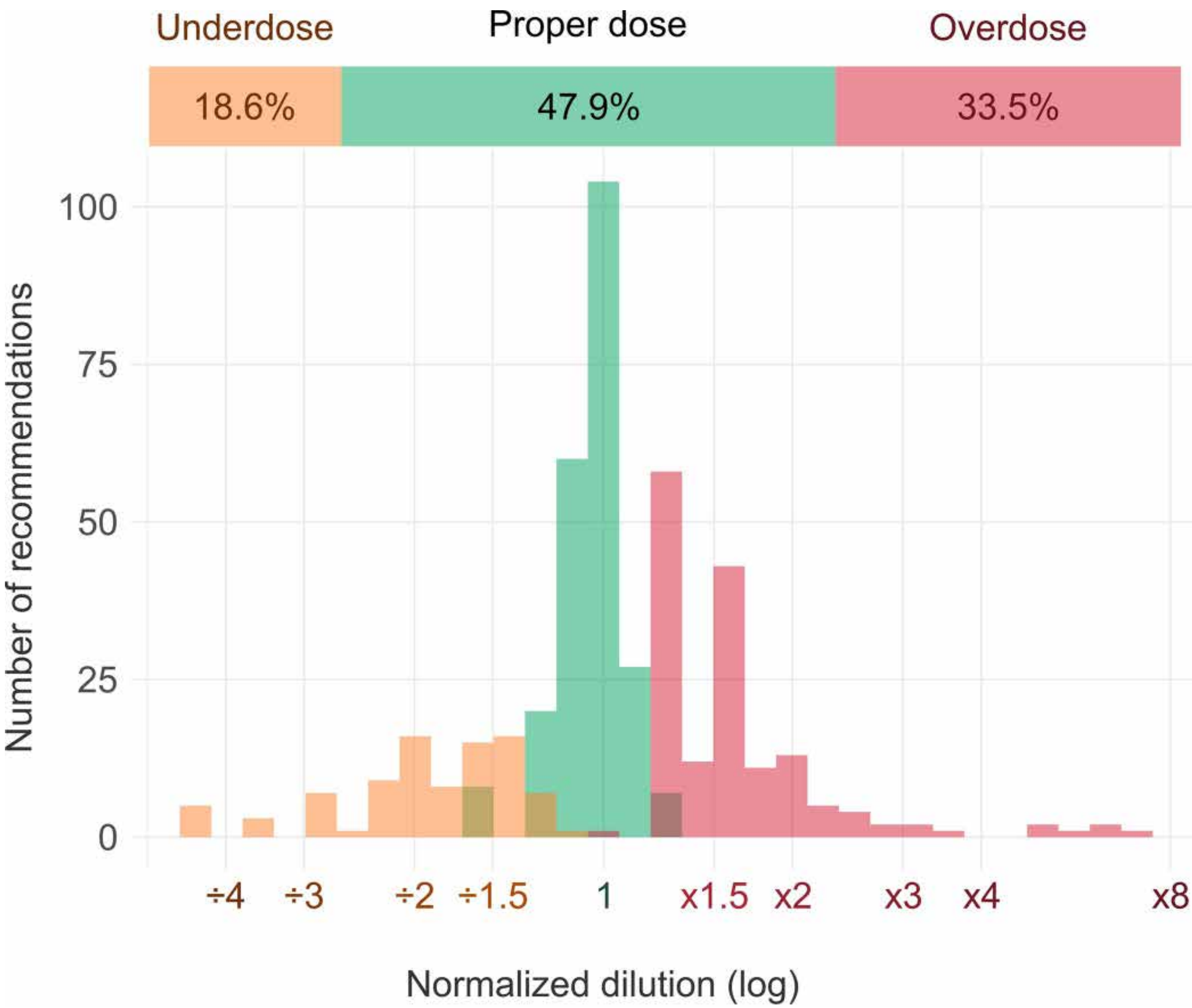

Fig 2. Magnitude and proportion of pesticide under- and over-dosage from retailer's recommendations. Under dose (orange, left) occurs if the dilution ratio is lower than the lower bound dilution provided within the product's datasheet, over dose (red, right) if higher than the upper bound and proper dose (green, middle) if within the lower and upper bounds.

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of pesticide resistance. This is achieved by recommending either rotations or mixtures of products with different modes of action (MoA), even though the latter is not likely to reduce pesticide resistance [50].

The current study revealed that mixtures and rotations of different pesticides were proposed in around one-third of retailers' recommendations (23.2% of recommendations with two products and 8.8% with three and more products; S9 Fig, Supplementary Material), which is concordant with previous studies [13,51]. Among the recommended mixtures, 25.4% combined products with the same MoA (Fig 3), therefore increasing the risks of pesticide resistance development [50]. Additionally, 13.8% of the recommended mixtures combined both insecticide and fungicide, which suggest a retailer's strategy to control unidentified pest species. Moreover, 19.5% of the mixtures included at least one product containing two or more active ingredients. Pesticide

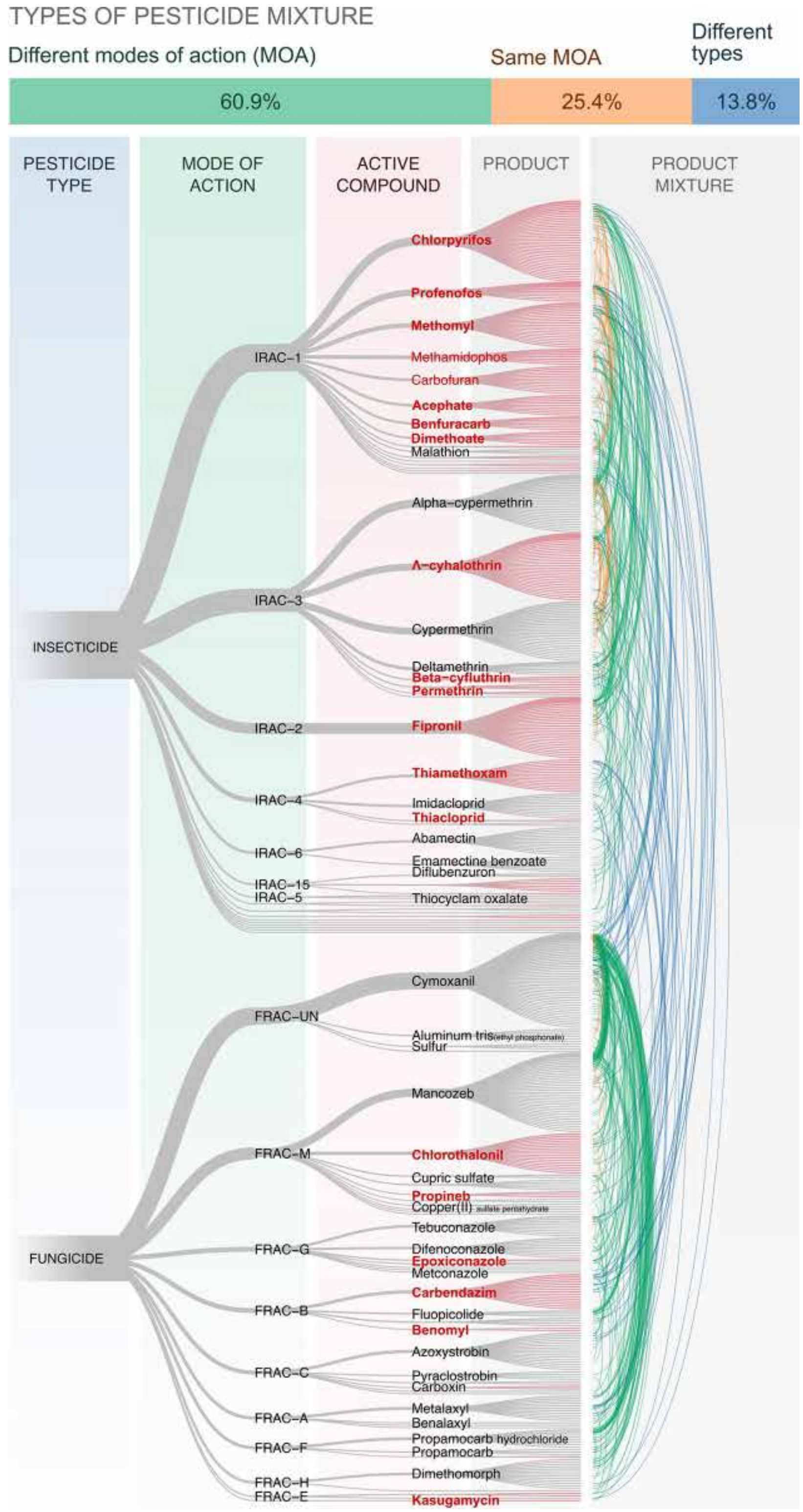

Fig 3. Diversity and mixture or rotations of products recommended by pesticide retailers nested by pesticide type, mode of action, active ingredient and product commercial name. Pesticides were either recommended alone or as mixtures (arc diagram). Mixtures were either composed of products with different pesticide types (blue), different modes of action (green) or with the same mode of action (orange). Red edges and labels correspond to hazardous products. Edge widths are proportional to the number of products recommended within each nested category. In the

case of several active ingredients per products, only the first ingredient was considered. Labels for pesticide families and active ingredients are shown for cases where the number of recommendation was higher than 10 to improve readability (see S10 Fig in Supplementary Material for all active substances).

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mixtures are of particular concern for human health due to their potential synergistic effects on toxicity. Pesticide mixtures with the same MoA often show additive effects, while those with different MoA produce effects that are difficult to anticipate [52].

Overall, the capacity of retailers to propose effective mixtures or rotations also depends on the availability of pesticides with different modes of action [53]. The current study showed that retailers proposed 552 different products based on 90 active substances and a total of 26 different MoA (Fig 3, S11 Fig, Supplementary Material), out of the 44 known modes of actions (32 for insecticides and 12 for fungicides [45,46]). It also highlighted that half of the existing insecticide MoA was available across all retailers' recommendations, and that the three most-recommended insecticide MoA (IRAC-1, 2 and 3) featured in 88% of recommendations. Similarly, the top three fungicide MoA (FRAC-UN, M and G) featured in 70.5% of all recommendations (Fig 3, S11 Fig, Supplementary Material). The prevalence of few MoA in retailer's recommendations stresses the need to diversify product's MoA to prevent the emergence of pest resistance [45,50].

3.3 Reduced pesticide toxicity through improvements in retailers' recommendations

The study revealed that 44.8% of all recommended products (and 64.9% of all insecticides) were hazardous for humans and the environment, and that these products were proposed in 46.6% of recommendations (S5 Table, Supplementary Material). Importantly, 95.6% of the insecticides with IRAC-1 MoA were hazardous (S12 Fig, Supplementary Material). Both the prevalence of IRAC-1 insecticides in the current study and their hazards emphasize the need to reduce the use of these insecticides, and replace them with products with other MoA and lower toxicity. Indeed, diversifying the MoA should be done while avoiding the most toxic products. For example, the omnipresent IRAC-1 MoA could be replaced by IRAC-6 MoA with all products approved in the EU (S12 Fig, Supplementary Material).

To further analyze to what extent retailers' recommendations could be improved with regards to pesticide toxicity reduction, an expert-retailer model was built based on the totality of products recommended by retailers in the study region. Results suggested that an expert retailer following the manufacturer's recommendations and choosing the least toxic products could completely avoid recommending extremely and highly toxic pesticides (WHO toxic category I). These results also indicated that 14.7% of the extremely, highly and moderately toxic pesticides (categories I, and II) could be replaced by less toxic products (Fig 4). Similarly, the proportion of practically non-toxic pesticides could be increased by 12.4% through proper pesticide recommendations by retailers. These figures could be greatly improved if retailers would propose biopesticides currently available on the market. However, only 2% of the retailers surveyed could offer organic alternative to synthetic pesticides when asked for (S13 Fig).

3.4 Recommendations for policy and practice

3.4.1 Increase modes of action, decrease toxicity and wrong dosage. The study showed that a few MoA are preferentially recommended by retailers (Fig 3, S11 Fig, Supplementary Material). Therefore, a step forward towards better recommendations consists of simultaneously diversifying the products' modes of action and replacing the most-toxic products [45,50,54]. While toxicity appeared on the labels' color and was therefore easily understandable

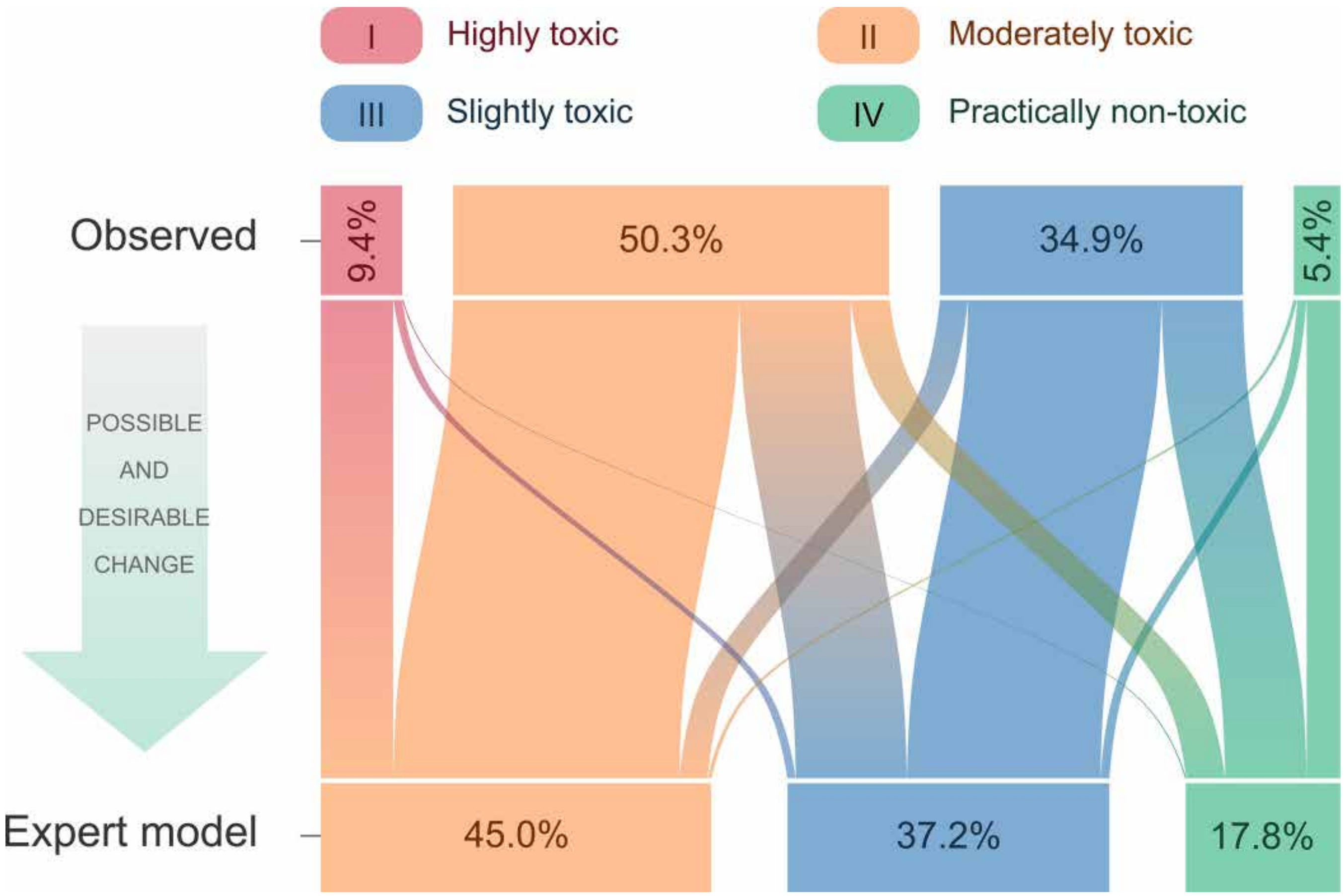

Fig 4. Room for improvement in pesticide toxicity between observed recommendations by retailers and expert model. Expert model assumes that the least toxic product should always be recommended and proposes only adequate products for a given pest. Pesticides are classified from their datasheets as either highly toxic (red), moderately toxic (orange), slightly toxic (blue) and practically non-toxic (green).

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by retailers, the mode of action of the product was not mentioned on the labels. Therefore, an easy way to improve the efficacy of pesticide use would be to mention the mode of action on a product's label [55]. In parallel, for insecticides, the most-recommended MoA encompassed with products with a high toxicity. Therefore, retailers should also look for less-toxic products with the same mode of action when available (Fig 4). Finally, the underuse and overuse of pesticides could be reduced by standardizing datasheets format and the dose units. Similarly, pesticide bottle caps could also be standardized as it has been used by retailers as a unit of measure and linked to overuse in the current study (S14 Fig, Supplementary Material).

3.4.2 Build pan-Andean recommendations for minor crops. This study highlighted that product-pest adequacy is partly a problematic step in the recommendation process, because no information for minor crops was available on products' datasheets (S5 Fig, Supplementary Material). In this context, retailers are unable to propose a proper recommendation and may recommend broad-spectrum pesticides to ensure effective pest control, with detrimental consequences on both health and non-target organisms [48]. The absence of official and sound references for pesticide use is undesirable and we therefore call for the development of national guidelines for these minor crops. As the lack of national interest for these crops is probably due to the low economic value compared to major crops, coordinated efforts across Andean countries could help develop these guidelines with a pan-Andean scope. Indeed, this information exchange has already begun through informal recommendations by plant clinics [56], which could be a foundation to build upon.

3.4.3 Promote alternatives to synthetic pesticides. A striking result of the current study is the very low proportion (2%) of retailers that were able to propose alternatives to synthetic pesticides, even though these are being developed [57] (S13 Fig, Supplementary Material). For example, biopesticides and botanical extracts could replace many more toxic synthetic products and would be relevant in a low-income and tropical context with strong traditional knowledge [58]. Moreover, biopesticides proposing new MoA are easily integrated into flexible pesticide regulations of Andean countries, and could be locally-produced [59]. Therefore, the pan-Andean guidelines proposed above could integrate these biopesticides.

3.4.4 Train pesticide retailers. Overall, the current study shows that many aspects of retailers' recommendations could be enhanced if they were correctly trained (Fig 4). There is a wide margin of improvement, especially in dosing recommendations and alternatives to chemical pesticides. This is in line with another study in Ecuador and Peru that found illiterate retailers behind the counter, which is contrary to the FAO Code of Conduct on the Distribution and Use of Pesticides [33]. However, several studies suggest that alternative solutions are difficult to implement due to interferences by the pesticide industry [24,60]. Similarly, other studies suggest that retailer are pressured by the agrochemical industry to increase doses and sell toxic products that are banned in other countries [22,27]. In view of this complex situation for retailers, several authors call for a dissociation of sale and advice activities [23,24]. Indeed, the conflicting roles of selling and advising, that has been flagged since 1979 [61], point to the need to delink extension services from the pesticide industry. Agricultural extension systems should act as safeguards between retailers and farmers by providing guidance on pesticide use and pest identification, while retailers should stick to retailing. Extension agencies should be reinforced and funded to regain their primary role, namely to advise farmers without economic incentives. Extension personnel could also offer taxonomic guidance to help farmers to correctly identify pests and propose a control method only when the pest is present, thereby reducing untargeted use [62].

3.5 Limitations

The sampling method was stratified across countries and provided a cross-sectional picture of the quality of recommendations offered by retailers. However, this sampling approach did not take into account another important driver, i.e. the type of retailer. The type of retailers vary in size, number of employee and their training, marketing strategies or services. While this information has been recorded during the surveys, it was difficult to harmonize across countries through a common typology, and the sample sizes were uneven across retailer types (S2 Fig, Supplementary Material). Nevertheless, this information could be useful to target retailer-specific recommendations. Therefore, a next step would be to conduct a similar study with a stratified sampling based on retailer type in addition to geographic context.

The current study also revealed that 23.7% (n = 182) of the products recommended were absent from the official pesticide databases (S3 Fig, Supplementary Material). These products may come from the black market, and could therefore be more toxic or less effective than official products [22]. However, the current study could not take these products into account due to the inherent lack of information. Similarly, adjuvants that help to stabilize pesticide compounds were not taken into account, even though their presence can increase toxicity [63].

The expert-retailer model may have underestimated toxicity because it only relied on products recommended by retailers. Another approach would be to feed the model with the complete official pesticide databases, from which less-toxic products absent from our survey could be recommended.

Finally, retailers have a dual role of advising farmers and selling products. Therefore, the economical motivations behind retailers' recommendations should be integrated in future studies to propose realistic changes for retailers.

4. Conclusion

This study offered for the first time reliable information about the quality of pesticide recommendations provided by pesticide retailers in the Andes. The empirical approach using fictional stories allowed to retrieve information close to what small farmers experience when seeking pest management advice. Moreover, by comparing recommendations with legal references from product datasheets and by enriching pesticide data from international databases, the adopted methodology allowed to identify margins of improvement at the root of pesticide misuse. The results showed that more than 88% of all recommendations were erroneous during at least one step of the recommendation process. These recommendations proposed pesticides pertaining to a few modes of action and roughly half at inappropriate doses, therefore increasing the risk of pest resistance. Finally, almost 15% of the most-toxic product recommended could be avoided if retailers were better trained and followed label's guidelines. This study could be implemented in other regions where small farmers are dependent on retailers' recommendations as a primary source of information about pesticide use, potentially leading to more sustainable pest management.

Supporting information

S1 Fig. Geographic distribution of the 1489 surveys conducted in the study. Surveys have been aggregated at the Department (Bolivia, Peru) or Province (Ecuador) administrative levels to ensure retailers' anonymity. Base layer with administrative boundaries has been obtained from https://public.opendatasoft.com/explore/dataset/world-administrative-boundaries.
(PDF)

S2 Fig. Distributions of recommendations by retailer type. Retailer in Peru corresponds to Store in Bolivia and Ecuador.
(PDF)

S3 Fig. PRISMA diagram for product exclusion along the data cleaning and enriching steps. Justifications to exclude products are highlighted in red.
(PDF)

S4 Fig. Schematic representation of the algorithm used to build the expert-retailer model.
(PDF)

S5 Fig. Recommendation step at which an erroneous answer has been given by retailers considering each crop. Justifications to exclude products are highlighted in red.
(PDF)

S6 Fig. Recommendation step at which an erroneous answer has been given by retailers considering each pest complex. Justifications to exclude products are highlighted in red.
(PDF)

S7 Fig. Distributions of recommendations with overuse (red), underuse (orange) and proper dose (green) of pesticide depending on the pest species and complexes.
(PDF)

S8 Fig. Difference in dilution ratio depending on the retailer type. Market type includes Trade fair, Market, and Itinerant retailer categories. Retailer include all other categories (Store,

Chain store, Distributer, Wholesaler, Retailer and Other).
(PDF)

S9 Fig. Number of products proposed per recommendation.
(PDF)

S10 Fig. Active substances of all recommended products per country, excluding herbicide, antibiotics and fertilizers. Chemicals highlighted in red are not approved in the EU.
(PDF)

S11 Fig. Repartition of modes of action recommended for fungicides and insecticides.
(PDF)

S12 Fig. Modes of action and legal status in the European Union of products recommended.
(PDF)

S13 Fig. Number and proportion of surveys where retailers had an alternative to chemical pesticides.
(PDF)

S14 Fig. Prevalence of underuse and overuse based on unit given by the retailer.
(PDF)

S1 Table. Pest complexes combining several pest species.
(DOCX)

S2 Table. Fictional stories for the plots defined by farmers. These stories were used along the pictures showed to pesticide retailers to ask for recommendation.
(DOCX)

S3 Table. Conversion table between local and international units. Correspondence between local and international units (mL) as defined by local experts for each country and organization.
(DOCX)

S4 Table. Effects of retailer's sex and type and pest species on pesticide dose. Family "Gama" and link function "inverse".
(DOCX)

S5 Table. Legal status in the European Union of products recommended.
(DOCX)

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Datasheets sources

Datasheets for Bolivian products were obtained from the SENASAG (https://paititi.senasag.gob.bo/egp/productosAgroquimicos.html), while those of Peruvian products were retrieved from the SENASA (https://servicios.senasa.gob.pe/SIGIAWeb/sigia_consulta_producto.html). No similar web service was available for Ecuadorian products, thus datasheets were downloaded from manufacturers' websites when available. Overall, 500 datasheets out of 552 different products identified were found using these sources.

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