Pesticide use and biodiversity conservation in the Amazonian agricultural frontier

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Agricultural frontiers are dynamic environments characterized by the conversion of native habitats to agriculture. Because they are currently concentrated in diverse tropical habitats, agricultural frontiers are areas where the largest number of species is exposed to hazardous land management practices, including pesticide use. Focusing on the Amazonian frontier, we show that producers have varying access to resources, knowledge, control and reward mechanisms to improve land management practices. With poor education and no technical support, pesticide use by smallholders sharply deviated from agronomical recommendations, tending to overutilization of hazardous compounds. By contrast, with higher levels of technical expertise and resources, and aiming at more restrictive markets, large-scale producers adhered more closely to technical recommendations and even voluntarily replaced more hazardous compounds. However, the ecological footprint increased significantly over time because of increased dosage or because formulations that are less toxic to humans may be more toxic to other biodiversity. Frontier regions appear to be unique in terms of the conflicts between production and conservation, and the necessary pesticide risk management and risk reduction can only be achieved through responsibility-sharing by diverse stakeholders, including governmental and intergovernmental organizations, NGOs, financial institutions, pesticide and agricultural industries, producers, academia and consumers.

1. Introduction

Agricultural frontiers have been defined as the outermost edge of modern human settlement [1]. These transition zones represent dynamic environments characterized by pervasive land use and land cover change [2], usually from forest to agriculture, but also following complex nonlinear patterns [3–5]. Frontiers share common characteristics that include an abundance of unsettled land, low human population densities, remoteness from major urban and industrial centres, limited labour and capital, land tenure insecurity, poor technical and social infrastructure and market conditions and limited presence of research, extension or other services [6–11]. Moreover, most current agricultural frontiers are located in areas where diverse, tropical habitats are undergoing anthropogenic conversion. Owing to this high biodiversity, they not only have more species to be lost in absolute terms, but also contain relatively more sensitive, vulnerable or endemic species. Thus, these are areas where the highest incidence of species losses is expected.

This ‘Opinion’ paper aims first at setting the stage for an evidence-based debate of the largely neglected issue of pesticide contamination in agricultural...
frontiers, and then discussing what contributions different stakeholders could provide in reducing the risk of pesticides to biodiversity and human health in these regions. Our geographical focus is the Brazilian Amazon, a region of high social, economic and environmental relevance for being the largest area of the world currently undergoing frontier settlement [12] in a country that controls more unused farmland than any other [13], that recently became the world’s largest consumer of pesticides [14], and that houses the largest fraction of the world’s terrestrial and freshwater biodiversity [15]. For the first time, the present study makes available pesticide use pattern profiles for three land use scenarios at different stages of intensification in frontier regions of the Amazon Basin.

Agricultural pesticides are powerful chemical tools that are developed, produced and used to mitigate crop damage or loss by pest organisms. Their wide diversity, in terms both of chemical classes and modes of action, allows for cost-effective combat of various pest organisms—particularly at large scales of production—while simultaneously permitting a uniform product quality for a large globalized market. Thus, pesticides are important for the economic production and storage of food, feed and non-food crops [16]. However, pesticides are compounds deliberately designed to negatively impact organismal survival, development, growth and reproduction, and as such can adversely affect a broad range of non-target species. There are not only many non-pest species phylogenetically related to pest species (for example, in the same family of the important soya bean pest, the velvet bean caterpillar moth Anticarsia gemmatalis, there are 723 species of moths in the cerrados [17]) but also many pesticides act upon basal physiological processes (e.g. mitotic spindle formation, membrane ion channel transport, mitochondrial electron transport, neurotransmitter and ATP formation [16]), which are common to a wide array of largely unrelated, non-target organisms. Therefore, pesticides have the potential, often realized, to detrimentally affect biodiversity and ecosystem structure and function [18].

By focusing on pesticides, we do not imply that pesticide contamination is necessarily the most important driver of biodiversity loss in frontier regions. In fact, native habitat loss owing to land conversion itself is of paramount importance [2]. However, pesticide contamination ranks among the most important threats to biodiversity in agricultural landscapes in general [19] and, if we aim to reconcile agricultural production with biodiversity conservation, better land management practices, including sustainable pesticide use, have to be devised and implemented. In addition, pesticide application profiles provide an excellent indicator of the degree of agricultural intensification, as well as a prime example of a hazardous land management practice in which risk mitigation requires responsibility-sharing by, and involvement of, a wide diversity of stakeholders.

To date, detailed reports on patterns of pesticide use in agricultural frontier regions in general, and in the Amazon in particular, are not available. However, it is a reasonable expectation that pesticide application rates should increase over time as frontiers are opened up due both to an increase in pest populations and to a decline in pest enemy populations. It is a common pattern that the vulnerability of crops to pests, weeds and diseases increases as the landscape is simplified by the expansion of agricultural land, enlargement of field size, decrease in non-crop habitats [20,21] and replacement of polycultures by monocultures, especially in the absence of crop rotation [22]. These patterns are consistent with a central tenet of epidemiology that both the number of diseases and the disease incidence should increase proportionately to host abundance [22]. Furthermore, pests are frequently less susceptible to pesticides than their natural enemies [23] because they tend to have shorter life cycles and faster rates of population growth, facilitating faster recovery and a more rapid evolution of resistance; in turn, many predators depend on a tight synchrony of development with their hosts for a window of opportunity for infection, and disruption of development is a frequent effect of pesticides [24,25]. There are globally 7747 reported cases of evolution of resistance of arthropods to insecticides; of these, 4875 (63%) refer to agricultural pests and only 128 (less than 2%) to parasitoids [26]. Taken together, these observations are consistent with the hypothesis that pest populations increase faster than those of their natural enemies as frontiers are opened up. Finally, additional increases in pesticide use in frontiers over time are expected as agricultural intensification takes place, for example, in the transition of single to double cropping or with the extension of planting seasons through irrigation.

2. Patterns of pesticide use in the Amazonian frontier

Current land use in the Amazon is characterized by different actors, production scenarios and land use pathways [5]. Here, we present three case studies to illustrate patterns of pesticide use in the Amazonian agricultural frontier. The first case study reports on pesticide use in small scale, fruit and vegetable-producing farms in the fertile floodplains of the Solimões and Amazonas Rivers in Central Amazon. Between 1986 and 1996, these small farms expanded in number from 1.3- to 16-fold in several municipalities surrounding the state capital Manaus. This expansion was driven by demand for local food production by a growing urban population, as Manaus grew from 0.3 to 1 million inhabitants between 1960 and 1990, and to 1.8 million in 2010 [27,28]. Data for this case study are based on interviews conducted in 2005 by one of us (A.V.W.) with 220 smallholder farmers from 26 floodplain villages in Iranduba, Careiro da Várzea, Manacapuru and Manaus (a reanalysis of [29]). The second case study reports on pesticide use in a pilot, 4000 ha sugarcane plantation implemented in converted floodplain forest near the Reserves of Apaúzinho and the National Park of Anavilhanas in Central Amazon. These plantations were established in a 60 000 ha farm as part of the general trend of expansion of biofuel crops in Brazil [30]. Data from pesticide use in the 2009/2010 season were provided by landowners. The third study case documents a process of land use intensification by a high-profile, large-scale soya bean-producing farm in the ‘arc of deforestation’, the main Amazonian frontier region that developed since 1980s in its southern and Western wrinches. Frontier expansion in the ‘arc of deforestation’ was initially a state-led process in which agriculture, and especially extensive cattle ranching, provided a cheap means for land tenure. Later, this process was replaced by a market-oriented process motivated by global demands and based on policies encouraging agricultural exports, agricultural intensification and land privatization [3,6,31–33]. The studied farm is located in the region of the headwaters of the Xingu in the state of Mato Grosso. In the 1980s, approximately 45 per cent of the
82,000 ha of the farm, covered with transitional cerrado/broadleaf Amazonian rainforest was cleared for pastures for extensive cattle ranching. In 2003, 462 ha of pastureland were converted to soya bean fields, and in the following 5 years soya bean expanded progressively to reach 31,052 ha. Since then conventional soya bean has been cultivated using no-till agriculture and no irrigation; thus the soya bean cycle, lasting approximately four months, is restricted to the rainy season. Land management is fully mechanized. Data from pesticide use from the soya bean cycles of 2003/2004, 2004/2005, 2005/2006 and 2008/2009 were provided by the landowners.

The three study cases depict distinct production scenarios that are relevant to understanding frontier development and its drivers in the Amazon and, although the third case may be considered geographically more typical, other cases are informative for other phases or drivers in frontier development. For example, knowledge of smallholder land use change in the Amazon is still limited despite its key role in shaping forest frontiers through slash-and-burn and shifting cultivation systems [5].

(a) Smallholder pesticide use for local production of fruits and vegetables

Pesticide use by smallholders portrays an overall scenario of overutilization and inappropriate use. Seven insecticidal, two fungicidal and two herbicidal active ingredients were employed. Seventy-one and 96 per cent of all recorded applications were outside the technical recommendations for doses and frequencies of application provided in the commercial product labels and leaflets (see figure 1a, b and electronic supplementary material, table S1; average percentage of applications across all active ingredients for dosage, average percentage of active ingredient-by-plot combinations for frequency; see the electronic supplementary material for detailed methodology). Underdosing (e.g. copper oxychloride and glyphosate) was more common than overdosing (e.g. indoxacarb and methyl parathion), as 44.5 per cent of all applications were below minimum recommended doses when compared with 26.8 per cent above maximum recommended doses. By contrast, 96 per cent of all active ingredient-by-farm combinations were applied more frequently than recommended. In fact, on average, application frequencies were fivefold more than those recommended. Finally, in several instances, the active ingredients employed were not even recommended for the pests they were intended to control. Adherence to technical recommendations is relevant because they follow guidelines established by the Brazilian Ministries of Agriculture, Health, and Environment to assure on the one hand agronomical efficacy, and on the other minimization of risk to human and environmental health.

Several factors may contribute to this overall pattern. Technical guidance from governmental rural extension services is not available or very limited; for this reason, 70 per cent of the farmers reported to have followed recommendations by neighbours and, to a lesser extent, by pesticide suppliers [29]. Most farmers have a low level of education and hence a very deficient understanding of what is written on the product label [34]. Finally, for these crops, pesticides contribute little to the total cost of production and therefore farmers, believing that the more frequently they apply them the more effective pest control will be, proceed to, in their perception, minimize economic risks and maximize yields.

(b) Pesticide use by a large-scale sugarcane plantation at implementation

Pesticide use by the large-scale sugarcane producer portrays an overall scenario of general adherence to technical recommendations. Three insecticidal and 11 herbicidal active ingredients were employed. Fifty per cent of all recorded applications were outside the technical recommendations for doses: 37 per cent below minimum recommended doses and 13 per cent above maximum recommended doses (see the electronic supplementary material, table S1). Nineteen per cent of all active ingredient-by-plot combinations were
above technical recommendations for frequency of application. On average, application frequencies were 1.3-fold those recommended.

(c) Pesticide use by a large-scale soya bean plantation for export

Pesticide use by the large-scale soya bean producer portrayed a scenario of intensification of pesticide footprint over time despite general adherence to technical recommendations and even voluntary replacement of more hazardous pesticides. Expansion of soya bean plantation in the farm was accompanied by a significant increase in the total mass of pesticide formulations applied—from 2.4 to 13.7 tons per cycle. Most importantly, there was also a marked and monotonic increase in dosage, as masses of pesticides applied per unit area increased fourfold between 2003/2004 and 2008/2009 (figure 2a). In the same time period, the number of active ingredients applied increased from 16 to 39 (figure 2b). By 2008/2009, 18 herbicidal, 13 insecticidal and eight fungicidal active ingredients were employed. Fifty-seven per cent of all recorded applications were outside the technical recommendations for doses, 46 per cent below minimum recommended doses and 10 per cent above maximum recommended doses (see the electronic supplementary material, table S1). Ten per cent of all active ingredient-by-plot combinations were above technical recommendations for frequency of application. On average, application frequencies were 0.9-fold those recommended.

Notably, our time series indicates a significant trend towards a proportional reduction in the employment of formulations that are more harmful for human and environmental health. The proportion of formulations considered ‘Extremely Toxic’ or ‘Highly Toxic’ (Toxicological Classes I or II) to human health decreased monotonically from 76 to 37 per cent of the total mass of pesticides applied (figure 2c; see the electronic supplementary material for methods and table S2). Similarly, the proportion of masses of formulations considered ‘Highly Dangerous’ or ‘Very Dangerous’ (Environmental Classes I or II) to the environment fell from 93 to 35 per cent of the total mass of pesticides applied (figure 2d). This proportional decrease in more hazardous compounds cannot be attributed to changes in legislation: 4/5, 14/15 and 13/15 of the Toxicological Class I and II formulations and 9/10, 16/18, 15/18 of the Environmental Class I and II formulations applied in 2003, 2004 and 2005, respectively, were still registered—and therefore could be legally applied—in 2008. Thus, replacement of pesticide formulations towards less hazardous compounds appears to have been voluntary.

Several factors may contribute to this pattern. This farm belongs to a corporation that is a leading global soya bean producer and that is, as a consequence, in the spotlight of the media, of the public and of legal control. This corporation has a high level of technical expertise and human and financial resources; at the same time, plantation management, including agrochemical use, corresponds to the largest share of the costs of soya bean production, which places an immediate economic incentive to reduce unnecessary pesticide use (personal communication of the farm manager to L. Schiesari, 2011). Finally, it focuses on the external market, which imposes more restrictive socio-environmental criteria of production. As a consequence, the farm adopted better land management practices and in 2011 became one of the first soya bean farms in the world to be certified by the Roundtable of Sustainable Soy.

In order to understand the temporal trends in total toxicity (i.e. the ‘pesticide footprint’) for a scenario in which there is an absolute increase in doses and diversity of pesticides but a proportional decrease in the volumes of more hazardous pesticides, we translated the mass of each active ingredient applied per hectare into toxic units for each of four model experimental organisms (rats, which are used as model organisms for mammal toxicity in general and human toxicity in particular; fish—usually rainbow trout, Daphnia and algae, the standard test species for aquatic organisms) and summed the toxic units of the different active ingredients for each model organism (see the electronic supplementary material for methodological details). Such analysis indicated that the toxicity per unit area declined by 56 per cent over time for mammals. In strong contrast, however, the toxicity to aquatic organisms increased 5.4 times for fishes, 135 times for Daphnia and 1.7 times for algae (figure 2e). This can be explained by the fact that model organisms varied in their sensitivity to pesticides, but also because there apparently was no correlation in the toxicity of 51 active ingredients employed on the farm between terrestrial and aquatic organisms (Spearman $r = 0.097$, $p = 0.503$ between rat and fish; $r = 0.257$, $p = 0.072$ between rat and Daphnia; $r = 0.016$, $p = 0.915$ between rat and algae). In other words, selection of pesticides that might be more protective of mammals does not guarantee protection of aquatic organisms.

Note that these estimates are not expressing total volumes of pesticides applied on the farm—which would be trivial considering the increase in area planted—but the volume applied per unit area. Note also that the effect concentrations considered in this pesticide footprint analysis are median lethal concentrations and that threshold levels or sublethal effects of priority concern, such as carcinogenicity, neurotoxicity, reprotoxicity and endocrine disruption, that are known for several of the active ingredients employed [30], were not a focus of this study. Finally, the farm is now undergoing a second level of intensification with maize being planted after the harvest of soya bean. This double cropping will inevitably imply a significantly higher annual input of pesticides and a broader diversity of active ingredients.

(d) Comparison across the three production scenarios

A comparison of the observed pesticide application patterns in the three production scenarios revealed two classes of critical deficiencies in pesticide use, with detrimental consequences to biodiversity. These are a high degree of violation of application guidelines (particularly among smallholders but also notable in the large-scale sugarcane plantation) and an imbalanced replacement of pesticides towards increased hazard for aquatic biodiversity, notwithstanding the positive example given by general adherence to technical recommendations and voluntary replacement of pesticides towards the protection of fieldworkers, nearby inhabitants and mammals, including domestic animals and wildlife (in the large-scale soya bean plantation).

These observations indicate that there is ample need for improvements in pest management in diverse tropical regions in general, and in agricultural frontier regions in particular; but also that no single actor or action will lead to such improvements. We argue below that this is a multi-stakeholder task that requires responsibility-sharing by intergovernmental organizations, national and local governmental organizations, NGOs, the pesticide industry, pesticide retailers, farmer organizations,
large and smallholder producers, agricultural marketing organizations, consumers and academia towards (i) improving regulation, control and penalty, (ii) rewarding the voluntary adoption of sustainable land management practices, (iii) educating producers for better land management practices, and (iv) promoting research for more sustainable agriculture.

Figure 2. Temporal trends in the application of pesticides in a high-profile agroindustrial farm in the Amazonian ‘arc of deforestation’ over the first years of conversion of pastureland into soya bean plantation. (a) Doses (mass per hectare) and (b) diversity of active ingredients increased over time. There was a gradual substitution of pesticide formulations towards less hazardous formulations to human health, as indicated by their (c) Toxicological Class (as defined by the Ministry of Health), and to their (d) Environmental Class (as defined by the Ministry of the Environment). (e) The result of increasing doses of presumably less hazardous compounds is that toxicity per unit area decreased for mammals, but increased from 1.7 to $135 \times$ for aquatic organisms (note log scale).
3. The way ahead

Sustainable agriculture seeks to guarantee food provision and food security by explicitly integrating ecological processes into land management practices while minimizing the use of inputs that cause harm to the environment or to human health [35]. Pest control occupies a pivotal position in this quest. Without effective crop protection, estimated losses in agricultural products owing to pests, weeds and diseases may vary from 26 to 50 per cent [36]. Considering such losses, pesticides are most likely to continue to play an important role. Under the condition that they are used in a sustainable way—particularly if incorporated under the concept of Integrated Pest Management (IPM) and associated with preservation of native habitat patches—we assume that tropical frontier agroecosystems can be designed and managed to host acceptable levels of biodiversity and ecosystem services without negatively affecting agricultural production and livelihoods.

To minimize pesticide effects on non-target biodiversity vital for ecosystem services several challenges have to be tackled. These challenges, and possible solutions, for sustainable pesticide use in tropical agricultural frontiers involve multiple stakeholder participation and strategic lines of action, which we detail in the electronic supplementary material, table S3 and discuss below.

(a) Improve regulation and control

The scientific basis for the environmental regulation of agricultural pesticides is conducted worldwide through a strategic conceptual framework named environmental risk assessment (ERA [37]), which can be either prospective or retrospective. The prospective ERA of a given pesticide is conducted prior to its marketing, release or agricultural use, and concerns the evaluation of the probability of adverse effects occurring from exposure of ecosystems to this pesticide. For this, a more or less reductionist, chemical by chemical approach is followed by making use of information on pesticide physicochemical properties, scenarios and models, to estimate environmental exposure; and by adopting a tiered scheme based on standardized, and internationally accepted, ecotoxicity tests and extrapolation techniques to assess effects [38].

The methodology for prospective ERA developed and applied in the USA and EU, for example, can easily be adapted for tropical regions in general, and their agricultural frontiers in particular, provided that (i) representative exposure scenarios are developed, (ii) specific protection goals are defined (i.e. what to protect, where to protect and over what time period), and (iii) the biological traits of vulnerable biological populations typical for these regions are taken into consideration. Recently, the ecosystem services concept (which includes biodiversity) was advocated as an overarching framework for deriving specific protection goals in the EU [39]. Such a framework is important not only because it facilitates communication between stakeholders—because ecosystem services highlight the linkage between environmental integrity and human well-being—but also because it makes transparent the many trade-offs that underlie decision-making in environmental management. Assuming that the ecosystem services framework is adopted, an additional issue to be dealt with, particularly in countries with diverse landscapes, is whether the types and levels of ecosystem services deemed to be essential for protection are the same across biomes, watersheds and ecosystems. Considering that the answer is most likely no, then regional or zonal regulations would have to be devised, at a cost of more complicated enforcement.

Retrospective ERA considers the impact from existing and/or past releases of pesticides to the environment and usually makes use of measured exposure concentrations or biological effects in the exposed ecosystems of concern. Consequently, retrospective ERA follows a holistic approach with a focus on the ecological status of the stressed ecosystems of concern, and also considers the cumulative effects of exposure to multiple pesticides by applying eco-epidemiological approaches, including ecological indicators [38,40]. As mentioned earlier, such studies are relatively uncommon in diverse tropical regions and largely absent in agricultural frontiers. Yet, an important management challenge for the Amazon and other biodiversity-rich regions would be to operationalize feedback mechanisms between prospective and retrospective ERA to allow an ecological reality check of the pesticide registration procedure, the identification of the combination of pesticides that probably cause most of the ecological stress, the re-evaluation of the registration of problematic pesticides and the evaluation of appropriate risk mitigation measures.

Implementing prospective and retrospective ERA procedures are duties of governmental organizations. However, governmental organizations have to reconcile several legislative frameworks for designing risk reduction strategies. For example, the Brazilian Congress recently revised the Forest Code, legislation that regulates land use and that mandates preservation of riparian vegetation buffering streams and rivers in all private properties in the country. The revised Forest Code reduced the minimum width of buffer zones from 30 m from the stream’s maximum level to 30 m from its regular level (and even 15 m in certain cases). Considering how sensitive freshwater communities appear to be to agricultural intensification and pesticide stress (figure 2), the revision of the Forest Code is of great concern and might justify stricter pesticide use regulation to achieve the same level of protection.

Regulation is ineffective if there is no control and penalty. Governmental mediated control can be applied at any scale from international to local. That enforcement in frontiers is by definition less effective might argue for a stronger control upstream—that is stronger international, national and state-level control on the production, distribution, use and disposal of agrochemicals [41]. At local level, the enforcement of national legislation could be effective through well-equipped and trained local governmental employees (e.g. providing permits to and controlling local pesticide retailers), retailers (e.g. by enforcing the need for a prescription and by storing used pesticide containers and remnants of pesticides) and extension services (to advice farmer organizations, commercial farmers and smallholder farmers on legal, safe and sustainable use of pesticides).

(b) Reward the voluntary adoption of sustainable land management practices

Improved ERA-based regulation is an essential, but not sufficient, step towards sustainable pesticide use. This is because pesticides legally placed on the market may be used in an illegal way (in other crops; at higher doses; without prescribed mitigation measures) or because, even when fully legal,
pressure on the environment tends to increase with agricultural intensification. Therefore, better land management practices beyond legal requirements have to be stimulated and rewarded through special loan and/or subsidy concessions, recognized through certification systems and selected by consumers despite potentially higher costs.

Loan concessions are a strong bottleneck for production. Therefore, intergovernmental, governmental and private financial institutions have a very important role to play in conditioning loan concessions (and tax subsidies, in the case of national governments) to the implementation of biodiversity-friendly land management practices. In fact, several of the world’s largest private financial institutions comprising the Equator Bank Initiative [42] already place environmental criteria in analyses of loan concessions. Concession policies, however, have to be carefully designed. For example, the Brazilian programme for family agriculture PRONAF provided federal loans only to producers who adhered to a predetermined package of land management practices, including traditional pesticide management. As a consequence, a positive association between access to PRONAF credit by smallholders and consumption of pesticides was found [41,43].

Agricultural marketing organizations (e.g. importers and distributors of food and supermarket chains) and multi-stakeholder roundtables have a role in setting standards of production that signal to consumers a comparatively reduced environmental footprint in agricultural production [44]. The Amazon Soy Moratorium, adopted by the Brazilian Association of Plant Oil Industry and the National Association of Cereal Exporters to avoid negative public opinion, prohibited the purchase of soya beans from newly deforested areas in the Amazon [42]. Roundtables such as the Roundtable of Sustainable Soy and the Better Sugarcane Initiative set recommendations and standards for production of agricultural commodities that include keeping daily records of pest incidence, setting damage thresholds for initiating pest control, using both biological and chemical pest control when necessary and avoiding highly hazardous compounds. Although the targets are overall modest, they demonstrate a shift in the relationship of the industrial private sector with sustainable agriculture.

A final but crucial bottleneck for the adoption of better land management practices is the selection of products by consumers, despite higher prices. The global organic food market reached US$ 33 billion in 2005, but 84 per cent of the consumption was concentrated in six affluent countries in Europe and North America [45]. Therefore, either local or regional markets have to be developed to reward sustainable agriculture, or exports to developed countries, where demand for organic products exceeds supply [45], have to be made viable. These may be viable options for food production close to urban centres, but are unlikely to be achieved in frontier regions, typically characterized by poor infrastructure.

(c) Educate producers for better land management practices

Deciding when, how and how much to use pesticides, and which active ingredients to choose among virtually hundreds available in the market (for example, 137 active ingredients in more than 400 formulations registered for soya bean only [30]) is among the most technically elaborate agricultural land management practices. The Brazilian legislation recognizes this complexity and determines that only agronomists can prescribe pesticides, and that a prescription is necessary for purchasing pesticides at retailers. However, considering the fraction of producers that have private access to agronomical advice, it is a reasonable argument that the success of this measure depends on governmental extension services. Only the government in its federal, state and municipal spheres could reach both historical agricultural areas and distant frontiers with infrastructure and technical advice. At the same time, such extension should unite the duties of Ministries of Agriculture, of Health and of the Environment, with very high societal and environmental return relative to its costs—improving rural economy, reducing the worrisome demographic exodus from the countryside to cities, improving human health and decreasing the burden on the public health system and reducing the ecological footprint of agriculture. The need for investment in this area can be illustrated by the observation that even in historically cultivated areas of the country governmental extension programmes are insufficient; this vacuum is sometimes filled by technicians linked to the agrochemical industry (e.g. 80% of all available technical advice in the state of Rio de Janeiro [41,46]). This creates evident conflicts of interest. At the same time, the chemical industry has a significant fraction of responsibility in reducing the risk of environmental contamination and could contribute through training pesticide retailers and farmers in safe use practices of their products, and increasing the readability of pesticide container labels. NGOs may play an important role in educating both producers and consumers to stimulate safe use practices and to promote platforms that bring together relevant stakeholders [47].

(d) Research for a more sustainable agriculture

Several important research topics have to be addressed—both by industry and independent researchers in academia—to mitigate the impacts of pesticides on biodiversity in tropical regions in general and in agricultural frontiers in particular. These include the development of better agronomic practices, the improvement of ERA and the development of science-based indicators of sustainable agriculture.

Better agronomic practices comprise the development of new products with adequate efficacy but improved human health, environmental and agronomical profiles (i.e. less likely to elicit evolution of pest resistance), as well as the refining of existing, or design of alternative, cropping systems. These include advances in IPM practices, which remain essential as evidence accumulates that most pests and pathogens of agricultural crops are kept in check not by pesticides but by natural enemies and by various ecological and physiological plant defence mechanisms [48]. For this reason, recent IPM programmes show that in several cases pesticide use can be reduced without yield penalties [35] and more broadly, that even in the case of some yield reduction, a decrease in pesticide use can be economically advantageous because of the high costs of chemical pest management [49].

The scientific underpinning of both cost-effective and efficient pesticide risk assessment procedures remains an important priority. From one side, it is important to develop strong, local and landscape-level research programmes that assess the impact of landscape-level use of pesticides on biodiversity in tropical agriculture frontier regions, and how this retrospective assessment compares with predictions derived...
from conventional models of prospective ERA. Comparative studies at larger spatial scales should in turn investigate to what extent we can harmonize land management practices across regions that differ so broadly in biotic and abiotic properties. For example, in Brazil pesticide use is regulated at the federal level, but the same general recommendations are to be followed in biomes as distinct as the Amazonian rainforest, the northeastern semi-arid and the pampas. Fixed recommendations bear the unlikely assumption that pest and non-pest species identity, sensitivity and population dynamics, as well as the environmental fate and effect of pesticides, are homogeneous across space.

Finally, financial institutions, certification bodies and roundtables are demanding science-based standards and indicators for sustainable agriculture, including pesticide use, which are in part still to be developed and validated.

4. Conclusions

The unifying characteristics of agricultural frontiers as regions with limited capital, technical and social infrastructure result in a high probability of gross misuse of pesticides by early colonists. Development of frontiers through intensification can either imply scaling up of inappropriate pest management practices or adoption of practices that not only meet, but even surpass, those demanded by law. This occurs in cases where capitalized producers target more restrictive markets, usually by demonstrating superior socio-environmental standards through certification. Therefore, in such regions where governmental reach and control is limited, market pressure can be directly or indirectly important in biodiversity conservation. However, even when there is adoption of presumably better pesticide management practices, the total footprint of pesticides tend to increase over time because of the need for increased dosage, implementation of double cropping, or because formulations that are less toxic to humans may be more toxic to other biodiversity. These observations suggest that there is ample need for pesticide risk mitigation at all scales of production. This can only be achieved through responsibility-sharing by, and involvement of, a wide diversity of stakeholders. Such involvement is critical if we are to move towards a more sustainable agriculture where production and biodiversity conservation are reconciled.

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