Assessing Potential Environmental Impacts of Pesticide Usage in Paddy Ecosystems: A Case Study in the Deduru Oya River Basin, Sri Lanka

Maveekumbure M. J. G. C. N. Jayasiri, Sudhir Yadav, Catherine R. Propper, Virender Kumar, Nandani D. K. Dayawansa, and Grant R. Singleton

Abstract: Rice paddies are unique ecosystems that provide rich wetland habitat. Their enduring existence across vast stretches of land has led them to evolve into unique systems serving a diverse assemblage of organisms and sustaining a staple grain for many people. With food demand rising, agricultural intensification through agrochemical application is a common practice used to boost food production in developing countries, including Sri Lanka. The aim of the present study was to assess the concentration of pesticide residues in water in rice ecosystems and discover their potential impacts on both environmental health and the most common fauna groups across a cropping year in Sri Lanka. A total of 270 water samples from waters associated with paddy fields within a watershed were analyzed for 20 commonly used pesticides; in addition, local farm holders were surveyed to assess pesticide usage details in three selected paddy tracts. We then used the Cornell University environmental impact quotient (EIQ) calculator and the ECOTOX Knowledgebase to determine the exposure risk associated with individual pesticides relative to their application rates and aquatic concentrations. Survey results demonstrate that several pesticides were overapplied at rates 1.2–11 times the recommended application, and the EIQ demonstrated high environmental risk of two of the agrochemicals detected, 2-methyl-4-chlorophenoxyacetic and diazinon. Fish, amphibians, insects, and beetles were found to have a wide range of potential adverse outcomes from exposure to diazinon, captan, thiamethoxam, and chlorantraniliprole. To balance the trade-offs between food security and ecosystem sustainability, the present study recommends that adoption of quantifiable environmental health indicators be considered as part of the national policy regulating pesticide use. Environ Toxicol Chem 2022;41:343–355. © 2021 The Authors. Environmental Toxicology and Chemistry published by Wiley Periodicals LLC on behalf of SETAC.

Keywords: Ecotoxicology; Pesticides; Water quality; EIQ; ECOTOX; Rice ecosystem

INTRODUCTION

Rice cultivation occurs on >162 million ha of land worldwide and produces >755 million tons of grain (Food and Agriculture Organization of the United Nations, 2021), providing a staple food resource for half of the world’s population. To feed the growing population, sustaining rice production is therefore a critical element of food security in many countries. Sri Lanka is no exception, rice being a staple food in the country. Paddy cultivation is a prominent farming activity in Sri Lanka and occupies 15% of the land area (Department of Agriculture, 2019). Because opportunities to further expand the land area available for paddy cultivation are limited, the government is giving priority to increasing production and productivity through rice intensification. The country actively promotes agrochemicals to boost rice production (Weerahewa et al., 2010). Despite the banning of many pesticides by the country and the introduction of World Health Organization (WHO)
guidelines recommending restrictions on their use, excessive pesticide application and ineffective policy enforcement have resulted in severe environmental pollution (World Bank, 2013). In fact, agricultural pesticide uses in Sri Lanka increased 43% from 1991 to 2018 (Food and Agriculture Organization of the United Nations, 2020). In addition, there have been several reports of pesticide misuse, including overapplication, in paddy cultivation in the country (Aravinna et al., 2017; Horgan & Kudavidanage, 2020). Also, widespread pesticide advertising and marketing campaigns by industry contribute to farmers’ perception of pesticides as a means to improve their harvests (Aravinna et al., 2017).

Sri Lanka, together with the Western Ghats, forms one of the world’s 34 biodiversity hotspots. Of the nation’s documented species, 28% of its flora and 16% of its terrestrial vertebrates are endemic to the island, while invertebrates are understudied (Edirisinghe et al., 2016). Rich agro-biodiversity is one of the key features of the rice cultivation landscape in Sri Lanka (Bambaradeniya et al., 2004; Marambe et al., 2012). The diversity led by environmental features (wet-to-dry conditions, irrigation systems, elevations, soil conditions) and management interventions has created a dynamic ecosystem that generates rich biodiversity. The flood cycles of the irrigated rice fields provide the base for the system’s resilience through several regulatory ecosystem functions supporting this biodiversity (Horgan, 2017). Bambaradeniya et al. (2004) reported 494 species of invertebrates, 103 species of vertebrates, 89 species of macrophytes, and three species of macrofungi in intermediate-zone rice ecosystems in Sri Lanka. Of these taxa, arthropods were the most prominent group, with 405 species in intermediate-zone irrigated rice ecosystems. In addition, a wide spectrum of freshwater invertebrates across different taxonomic classes (Bambaradeniya et al., 2004) and a high density of water birds (Bellio et al., 2009) are associated with Sri Lankan rice ecosystems.

Pesticide pollution of irrigation water can negatively impact biodiversity (Pandey et al., 2020), and direct contact with applied pesticides can adversely affect nontarget species, soils, and waterways (Barbieri et al., 2021). Some examples of harmful impacts of pesticides on nontarget species include inhibition of enzyme functions, bioaccumulation in and damage to fish tissues (Clasen et al., 2018; Gao et al., 2020; Rossi et al., 2020), disturbances in the swimming behaviors of fish and amphibians (Shuman-Goodier et al., 2017), hormonal disruption in frogs (Shuman-Goodier et al., 2017), the restriction of development and biological activities of beetles (Khan et al., 2018), mortality and changed feeding behavior of spiders (Tahir et al., 2019), mortality of bees and wasps (Cheng et al., 2018; Yasuda et al., 2017), weight loss and shifts in enzymatic activity of earthworms (Rico et al., 2016), and reduction of soil microbe populations (Nicomrat et al., 2016). Optimal use of pesticides in paddy farming supports beneficial species, leading to ecosystem services that limit pests, while maximizing production (Horgan, 2017). Out of the 800 insect species observed in rice ecosystems worldwide, only approximately 20 are economically damaging rice pests. Moreover, humans are also vulnerable to the impacts of pesticides via occupational exposure, spray drift, and food chains (Blair et al., 2015); exposure of this kind can cause short-term to chronic health effects, including skin and eye irritation, headaches, dizziness, nausea, cancer, respiratory disorders, reproductive disorders, neurological dysfunction, and diabetes (Kim et al., 2017; Rani et al., 2021).

Considering the increasing agrochemical usage within the country, there is considerable potential to damage existing biodiversity in Sri Lankan rice fields. However, pesticide residues in rice ecosystems and their ecological impacts are still not widely studied in Sri Lanka, so there is a knowledge gap that needs to be bridged. To gain an understanding of the ecotoxicological and environmental impacts of pesticides used in Sri Lankan rice cultivation, the present study was designed to (1) determine the pesticide application status of agrochemicals used in rice cultivation, (2) study the adverse impact of field-scale pesticide application on the environment, and (3) investigate the potential impact of pesticide residues at the landscape scale including adverse impacts to the most common faunal groups in rice ecosystems.

**METHODOLOGY**

**Study area**

The present study was conducted in the Deduru Oya River basin, the fourth largest river basin in Sri Lanka (Figure 1). The Deduru Oya reservoir project, the largest irrigation project in the basin, feeds a command area of 11 115 ha. The study focused on the command area of the Deduru Oya reservoir, where paddy cultivation is the prominent agricultural activity. Vegetables, coconut, and other field crops are also grown in the basin. There are generally four rainfall seasons in Sri Lanka, including two monsoons, the northeast (December–February) and southwest (May–September) monsoons, and two intermonsoonal seasons (March–April and October–November). Based on Sri Lanka’s annual rainfall, the island has been divided into three zones: wet (>2500 mm/year), intermediate (1750–2500 mm/year), and dry (<1750 mm/year). A major portion of the Deduru Oya basin area (>90%) is located in the intermediate zone.

**Data collection**

The fieldwork consisted of water sample testing for agricultural pesticide residues and a questionnaire survey (Supporting Information, Annex S1) undertaken with local farm holders to assess pesticide application practices. The survey was carried out from March to July 2020 to capture details of pesticide application in relevant cropping seasons, including pesticide type, active ingredients, application dose, and timing.

The questionnaire survey was carried out at the parcel scale rather than at the farmer level because cultivators often cultivate more than one parcel in different locations of a paddy tract, and they perform different management practices in these scattered parcels within the same paddy tract. For the
The present study, “paddy parcel” is defined as an adjacent and contiguous set of paddy plots cultivated by a cultivator. The questionnaire survey was designed to cover all the cultivators \((n = 84)\) in the three selected paddy areas at different toposequence positions and to capture parcel-based pesticide application information. The areas of the selected upstream, midstream, and downstream paddy fields were 13, 7, and 34 ha, respectively. The rates of pesticide application in each parcel were then compared with the pesticide application rates recommended by the Department of Agriculture (2015), Sri Lanka, to determine deviations in pesticide usage.

To address non-point-source water pollution by pesticides, 20 pesticides were selected based on their wide use within the study area in previous seasons, pesticide import details, and expert opinion: 2-methyl-4-chlorophenoxyacetic (MCPA), pretilachlor, bispyribac sodium, propanil, glyphosate, fenoxaprop-p-ethyl, oxyfluorfen, cyhalofop butyl, thiamethoxam, chlorantraniliprole, fenobucarb, carbosulfan, fipronil, diazinon, carbofuran, etofenprox, carbandazim, hexaconazole, tebuconazole, and captan. Water samples were collected from irrigation inlets and drainage outlets of three selected paddy tracts along the left bank canal of the Deduru Oya irrigation scheme (Figure 1). Water samples were collected in 1-L glass bottles via grab sampling. A total of 270 water samples were collected biweekly over the course of one cropping year, April 2019 to March 2020. The collected water samples were conditioned with dichloromethane in the field (amylene as stabilizer; 99.8%). Samples were transported to the laboratory at 4 °C on the day of collection. In the laboratory, samples were frozen until further analysis. Samples were analyzed for pesticide contamination using an in-house liquid chromatographic–tandem mass spectrometric method (limit of quantification = 0.01 mg/L) at an accredited laboratory, the Bureau Veritas Sri Lanka, located in Katubedda, Sri Lanka. Details of the water sampling methodology are presented in Jayasiri et al. (2022).

Environmental impact determination

To assess the environmental impact of the pesticides applied to each paddy parcel, we used the environmental impact quotient (EIQ), a composite hazard indicator developed by Cornell University (Kovach et al., 1992). This measure was designed to determine the environmental impact of commonly used agricultural pesticides by making the published data available in a usable format so that farmers can choose pesticides with lower environmental impacts. The EIQ value is a constant for a particular active ingredient and is estimated based on its impact on farmworkers, consumers (nontarget applications), and ecology as per the formula given in Equation 1:

\[
\text{EIQ} = \left\{ \left[ C(DT \times 5) + (DT \times P) \right] + \left[ (C \times (S + P)2 \times SY) + (L) \right] + \left[ (F \times R) + (D \times (S + P)2 \times 3) + (Z \times P \times 3) \right] + (B \times P \times 5) \right\} / 3
\]

In Equation 1, \(C\) is the chronic toxicity, \(DT\) is the dermal toxicity, \(P\) is the plant surface half-life, \(S\) is the soil half-life, \(SY\) is the...
systemicity, $L$ is the leaching potential, $F$ is the fish toxicity, $R$ is the surface loss potential, $D$ is the bird toxicity, $Z$ is the bee toxicity and $B$ is the beneficial arthropod toxicity.

While the EIQ explains the inherent toxicity of specific pesticides, the EIQ-field use rate (EIQ-FUR) explains the true impact of an applied pesticide. The EIQ-FUR can be estimated using Equation 2:

$$
\text{EIQ-FUR} = \text{EIQ of pesticide} \times \text{Percentage of active ingredient} \times \text{Application rate (formulated product dose/hectare)}
$$

(2)

The EIQ-FUR equation provides a sensible numerical value which can be used to compare the environmental impact of different pesticide-based pest-management practices. The EIQ-consumer component explains the impact on nontargets (soil, plants, and groundwater), while the EIQ-worker and EIQ-ecology components explain the impact on farmworkers and the ecological impact, respectively. Values of EIQ-FUR >20 are considered high environmental impact, while values between 10 and 20 are considered moderate environmental impact and values <10, low environmental impact (Beckie et al., 2014).

The EIQ values of pesticides and their FURs were computed using the online calculator developed by Cornell University (2021). The EIQ values of three commonly applied pesticides (pretilachlor, fenobucarb, phenthoate) were absent from the database of the online calculator; these were computed manually using Equations 1 and 2. The EIQ value of a pesticide with more than one active ingredient was computed by summing the relative proportions of EIQ-FUR values similar to Beckie et al. (2014). The EIQ-FUR was calculated for all of the applied pesticides during the cropping year studied. Each paddy parcel’s contribution to the overall environmental impact was mapped using ArcMap 10.5, and other analyses were run using Minitab 17 software. The data were analyzed using descriptive statistics.

To determine the landscape-level environmental impact, the ecotoxicity of detected pesticides in water samples was assessed using a five-step approach. (1) A complete list of flora and fauna species observed in Sri Lankan intermediate-zone rice ecosystems was compiled from the literature. (2) All flora species, protozoa species, and other microorganisms (Cnidaria, Ectoprocta, Gastrotricha, and Rotifera taxonomic groups) were excluded; and the study was confined to macrofauna species. Selected species were categorized based on their taxonomic rank to the family level, and families that consisted entirely of rice pests were also excluded. (3) The ecotoxic threshold data for detected pesticides of each family were collected through the Ecotoxicology Knowledgebase (ECOTOX), which provides chemical toxicity data for aquatic life, terrestrial plants, and wildlife based on peer-reviewed literature (US Environmental Protection Agency, 2017). (4) The collected ecotoxicology data set was further filtered, retaining the data for active ingredient concentrations in water (excluded concentrations per body weight, etc.) and for the endpoints of no-observed-effect level (NOEL), lowest-observed-effect level (LOEL), and 50% lethal concentration (LC50; mortality only) associated with behavior, growth, reproduction, and mortality. (5) The maximum concentration of each detected pesticide was compared with the toxicity threshold levels for vertebrates and invertebrates observed in the irrigated paddy ecosystems of the intermediate zone of Sri Lanka.

**RESULTS AND DISCUSSION**

**Pesticide application and water pollution**

**Status of pesticide application pattern.** Farmers in the area mainly applied two herbicides (pretilachlor and MCPA) and eight insecticides (carbosulfan, thiamethoxam, diazinon, a mixture of chlorantraniliprole and thiamethoxam, etofenprox, tebufenozide, lambda-cyhalothrin, and phenthoate) to their rice fields during the cropping year studied (Table 1). Among them, three insecticides (tebufenozide, lambda-cyhalothrin, and phenthoate) are not recommended for use on rice fields. Pretilachlor, used by 97.6% of the surveyed farmers, was the most widely used preemergence herbicide. Farmer preferences in the use of preemergence herbicides for weed control in paddy cultivation in Sri Lanka have also been previously reported (Munaweera & Jayasinghe, 2017). In addition, the herbicide MCPA and the insecticides carbosulfan, chlorantraniliprole, and thiamethoxam were applied widely. During the study period, only one farmer applied fungicide to his paddy parcels. However, the active ingredient in that particular fungicide could not be identified based on the information provided by the farmer. Greater use of insecticides than fungicides is a common pesticide application pattern in Sri Lanka (Horgan & Kudavidanage, 2020). Aravinna et al. (2017) also observed higher insecticide selection compared to fungicide as well as misuse of pesticides in the Mahaweli River basin in Sri Lanka. However, they observed a broader range of pesticide preferences, possibly with a higher number of farmers in Mahaweli schemes compared to our study area.

Of all farmers surveyed, 95.2% applied the pesticides at rates above the recommended levels at least once during the cropping year. Figure 2 shows the overapplication of the recommended pesticides for rice over the cropping year. The highest overapplication was observed for the insecticide with two active ingredients, chlorantraniliprole and thiamethoxam; application doses were 11.5 times (median) higher than the recommended (Department of Agriculture, 2015). The insecticides carbosulfan, etofenprox, and thiamethoxam, were overapplied at 2.25, 2.54, and 3.95 times (median) the recommended rate, respectively. When compared to other overapplied pesticides, diazinon application rates were closest to the recommended application rates (1.28 times [median]). The pesticides thiamethoxam, chlorantraniliprole, and etofenprox were overapplied by all farmers. Thiamethoxam application rates were highly variable compared to the other pesticides, with a standard deviation of 4.33. This trend was also observed for herbicides, but the degree of overuse was lower than with insecticides, at a rate of 1.57 times for pretilachlor and 1.12 times (median) for MCPA.
The main factors leading to pesticide overapplication include limited awareness among farmers of the environmental and health risks associated with high pesticide use and the perception that increased pesticide use improves harvests (Aravinna et al., 2017). Other influencing factors for farmers’ decisions related to pesticide type and quantity could include type of irrigation, area under cultivation, land ownership of the cultivator, household size, farming experience, and age and gender of the farmer (Munaweera & Jayasinghe, 2017).

### Pesticide residues detected in water

Of the 20 pesticides tested to assess water quality, 10 were detected in the collected water samples, including two herbicides (pretilachlor and oxyfluorfen), six insecticides (thiamethoxam, chlorantraniliprole, fenobucarb, fipronil, diazinon, and etofenprox), and two fungicides (tebuconazole and captan). The maximum reported concentrations of the pesticides are presented in Table 2, and all detected concentrations are presented in Supporting Information, Table S3. Remarkably high concentrations of captan were observed, and diazinon was frequently detected. Among the pesticides detected in water, some were not applied to the rice fields evaluated in the present study. Detection of these pesticides is perhaps due to non-point-source pollution from surrounding agricultural activities, including nearby rice and vegetable cultivation. Pesticide overapplication and several other misuses in intensively cultivated vegetables have been reported in Sri Lanka (Padmajani et al., 2014).

### Field-level environmental impact of pesticides

#### Contribution of applied pesticides to environmental impact

Assessing the impact of broad mixes of pesticides across scales of time and concentration is challenging. However, the EIQ is a useful indicator and tool for predicting environmental risks associated with pesticide use. Despite some critiques of the EIQ (Kniss & Coburn, 2015), it has been widely used as a reasonable indicator of environmental impact in different agrosystems worldwide (Arora et al., 2019; Beckie et al., 2014; Biddinger et al., 2014; Gaona et al., 2019). Kromann et al. (2011) emphasized the lack of effective resources available to predict the environmental impacts of pesticides, especially when there are environmental mixes across landscapes. Considering the potential of versatile usability of the EIQ hazard indicator across many agricultural land uses and its wider range of environmental considerations, we used the EIQ hazard indicator in the rice systems of the present study.

#### Table 1: Environmental impact quotient values of applied pesticides

| Pesticide                          | Toxic class | EIQ<sub>C</sub> | F%    | Dosage | EIQ<sub>W</sub> | EIQ<sub>E</sub> | EIQ-FUR |
|------------------------------------|-------------|-----------------|-------|--------|-----------------|-----------------|---------|
| Pretilachlor (300 g/L)              | U           | 13.11           | 97.6% | R      | 1600 ml/ha      | 2.8             | 12.9    |
| MCPA (60%)                         | II          | 36.7            | 47.6% | R      | 1800 ml/ha      | 13.2            | 100.9   |
| Carbosulfan (200 g/L)              | II          | 47.3            | 52.4% | R      | 1200 ml/ha      | 1.7             | 26      |
| Thiamethoxam (25%)                 | II          | 33.3            | 29.8% | R      | 600 ml/ha       | 1.5             | 9.9     |
| Diazinon (500 g/L)                 | II          | 44              | 2.4%  | R      | 1600 ml/ha      | 1.7             | 84      |
| Chlorantraniliprole thiamethoxam (20%)+ (20%) | II+U       | 18.33 + 33.33   | 20.2% | R      | 100 g/ha        | 0.2             | 1.1     |
| Etofenprox (100 g/L)               | II          | 22.22           | 3.6%  | R      | 600 g/ha        | 0.3             | 2.0     |
| Phenthoate (500 g/L)—NRR           | II          | 30.33           | 7.1%  | R      | 867 g/ha        | 21.2            | 75.5    |
| Lambda-cyhalothrin (50 g/L)—NRR   | II          | 44.2            | 6.0%  | R      | 663 g/ha        | 0.0             | 0.3     |
| Tebufenoxid (200 g/L)—NRR          | U           | 16.4            | 2.4%  | R      | 5903 g/ha       | 5.5             | 37.3    |

EIQ<sub>C</sub> = environmental impact quotient value of the active ingredient; F% = percentage of farmers who applied relevant pesticides; EIQ<sub>W</sub> = EIQ consumer component; EIQ<sub>E</sub> = EIQ ecology component; EIQ <sub>FUR</sub> = EIQ-FUR = EIQ field use rate; MCPA = 2-methyl-4-chlorophenoxyacetic; NRR = applied but not recommended for rice; R = recommended dosage; A<sub>med</sub> = median values of applied dosage; II = moderately hazardous; U = unlike to present acute hazard.

*Toxic class is according to the World Health Organization classification.

**FIGURE 2:** A comparison of pesticide application rates by 84 farmers in the Deduru Oya irrigation scheme over the recommendation rates of use for each pesticide. Vertical shaded bars indicate 25th–75th percentiles; black solid straight line inside the box indicates the median; values beyond the whisker range are presented as asterisks. MCPA = 2-methyl-4-chlorophenoxyacetic.
| Pesticide         | Detected maximum concentration (mg/L) | LOEL (mg/L) | LC50 (mg/L) | Study duration (days) | Neg. impact | Median Range | No. of publications | No. of studies of impact data | Fauna group | No. of concen-range of impact studies | No. of concen-range of impact studies of effect category | Effect | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range | Median | Range |Median |
| Pesticide         | Detected maximum concentration | Fauna category | No. of species | Effect | Range   | Median | Range   | Median | Range | Median | Study duration range (days) | No. of publications | Negative impact (YN) | No. of studies–impact | No. of data |
|-------------------|--------------------------------|----------------|----------------|--------|---------|--------|---------|--------|-------|--------|-----------------------------|---------------------|---------------------|----------------------|------------|
| Beetles 2         |                                |                | 2              | Be     | 0.053–0.78 | 0.78   | 0.53–0.78 | 0.655  | 2.43–788.5 | 124.03 | 1–7                           | 2                   | N                   | 0                    | 3          |
| 8 Mo              |                                |                | 0.0053–50      | 50     | 0.005–750 | 2.34   | 24.10265 | 24.10265 | 2–140 | 2      | 1                           | 7                   | Y                   | 1                    | 31         |
| 2 Re              |                                |                | 0.0053–48.2    | 86     | 0.0075–86 | 135    |                      |         | 1–3               | 2      | 1                      | 1                   | N                   | 0                    | 13         |
| Spiders and other arthropods 2 |                | 1 Be          | 37–135        | 86     | 135     | 37     |                      |         | 2–5             | 2      | 0                    | 0                   | N                   | 0                    | 5          |
| Oxyfluorfen 0.242 mg/L Fish  |                | 1  Gr         | 0.0047        |        | 0.0047  |        |                      |         | 0.4985 | 0.104 | 1–3 | 2      | 1                           | 33                  | Y                   | 1                    | 1          |
| 1 Mo              |                                |                | 0.0013        |        | 0.0024  |        |                      |         | 0.0845 | 0.0845 | 0–10 | 10                | 1                   | N                   | 0                    | 2          |
| 1 Re              |                                |                | 0.0047        |        | 0.0047  |        |                      |         | 0.4985 | 0.104 | 1–3 | 2      | 1                           | 33                  | Y                   | 1                    | 1          |
| Insects 0.036 mg/L Fish  |                | 2              | 200           | 200    | 200     | 200    | 0.00018–790.48 | 0.127  | 1–7               | 13                 | Y                   | 8                    | 60         |
| 1 Mo              |                                |                | 0.4845        |        | 0.4845  |        |                      |         | 0.0833 | 0.0833 | 1–10 | 10                | 1                   | N                   | 0                    | 2          |
| Insects 12 Mo     |                                |                | 200           | 200    | 200     | 200    | 8.8–790.48 | 72.71  | 1–7               | 13                 | Y                   | 8                    | 60         |
| Insects 1 Re     |                                |                | 0.05–0.92     |        | 0.05–0.92 | 0.18   | 4.07–40.8 | 11.56  | 1–60              | 9                  | N                   | 1                    | 57         |
| Crustacea 1 Mo    |                                |                | 0.18          |        | 0.18    |        |                      |         | 0.0017–5 | 0.0017–5 | 4–27 | 28–60               | 1                   | Y                   | 1                    | 23         |
| Mollusks 1 Be    |                                |                | 0.01          |        | 0.01    |        |                      |         | 11.395 | 11.395 | 1–40 | 4                   | 1                   | N                   | 0                    | 1          |
| Annelids 1 Mo    |                                |                | 0.18          |        | 0.18    |        |                      |         | 1.245–1.899 | 1.572  | 4–14 | 4                   | 1                   | N                   | 0                    | 1          |
| Insects 3 Mo     |                                |                | 11.395        |        | 11.395  |        |                      |         | 1.245–1.899 | 1.572  | 4–14 | 4                   | 1                   | N                   | 0                    | 1          |
| Captan 686.51 mg/L Fish  |                | 1 Be          | 3.14          | 3.14    | 3.14    | 3.14    | 0.065–0.89 | 0.29  | 1–4               | 3                  | Y                   | 3                    | 9          |
| Insects 1 Mo     |                                |                | 3.14          | 3.14    | 3.14    | 3.14    |                      |         | 0.65–0.89 | 0.29  | 1–4 | 3                  | 1                   | Y                   | 1                    | 12         |

**Effect** = expected feature that changes because of a toxic effect of the relevant pesticide; Be = behavior; Gr = growth; Mo = mortality; Re = reproduction; NOEL = no-observed-effect level; LOEL = lowest-observed-effect level; LC50 = lethal concentration for 50% of the population. **"No. of studies–impact"** = number of studies that demonstrate the presence of a negative impact under detected pesticide concentrations.
study to evaluate whether usage was above the recommended levels to protect environmental and human health. The EIQ indicator highlights the environmental impact of many of the pesticides used in the study area.

The EIQ-FUR is a measure of overall environmental impact that can be broken down into three components: consumer, farmworker, and ecology impacts (Table 1). Values of EIQ-FUR were determined for recommended rates and applied rates (median) of each of the pesticides recommended for rice. The ecological impacts of all the applied pesticides are higher than those on consumers and workers (Table 1).

Used by almost half of the farming community, MCPA has remarkably high environmental impact scores (72.4) compared to all the other pesticides examined. High variability (standard deviation = 23.0) was observed in EIQ-FURs of MCPA, which was due to the varying herbicide application rates (Figure 3). Also, MCPA has a high EIQ value for workers and ecology, meaning it is likely to have significant adverse impacts on those who apply it and on ecological systems. Gaona et al. (2019) also observed high environmental risk associated with herbicides, especially MCPA, in an agricultural water basin in Argentina. The herbicide MCPA is used to control annual broadleaf and sedge weed species infestations, which can also be controlled using alternative herbicides, currently registered and available in Sri Lanka, which have a much lower EIQ-FUR (0.1–0.5), such as bensulfuron-methyl + metsulfuron-methyl, carfentrazone, ethoxysulfuron, and azimsulfuron, compared to MCPA (53.6 of EIQ-FUR based on recommended rate; Supporting Information, Table S1). Moreover, herbicide resistance to MCPA has been reported recently in Cyperus difformis, and an annual sedge weed of rice was effectively controlled by carfentrazone (Herath et al., 2017). These results highlight the importance of replacing MCPA with alternative herbicides to reduce environmental impacts and achieve effective weed control.

Pretilachlor, the most widely used herbicide, has a low environmental impact, both in recommended and in field application scenarios. The results clearly showed the need to increase farmers’ awareness of applying pesticides at the recommended rates to reduce EIQ-FUR, as well as to avoid phytotoxicity, because greater-than-recommended herbicide doses can adversely impact crops.

Diazinon has a high environmental impact, especially under the ecological index, despite the limited nature of its reported proportional overuse (1.28 times) by farmers. However, it is possible that farmers outside the study zones were using diazinon because it was frequently detected in the water samples (61.5%) over the cropping year. Considering the low solubility of diazinon in water (National Center for Biotechnology Information, 2021), its frequent detection in water samples, and its environmental impact, this pesticide has great potential to produce ecotoxicity. Carbosulfan is another recommended insecticide with a high environmental impact and a very high ecological impact but lower health impacts on workers. Because 52.4% of farmers were using carbosulfan, its use may cause considerable harm to the paddy field ecology. The pesticide with two active ingredients, thiamethoxam and chlorantraniliprole, shows the lowest environmental impact, even though it is the most overapplied pesticide, indicating a lower ecotoxicity potential.

Two registered insecticides that are not recommended for rice, phenthoate and tebufenozide, showed high environmental impacts; however, these pesticides are used by only 7.1 and 2.4% of the farmers in the study area, respectively. Phenthoate has very high ecological impacts, second only to MCPA; and it also has the highest potential impacts on consumer health across all pesticides in the present study. Tebufenozide has high ecological impacts and comparatively high worker and consumer impacts. Lambda-cyhalothrin, used by 6.0% of the farmers, is also a nonrecommended pesticide for rice; but its environmental impact is very low. Previous studies reported that application rate creates greater pressure on the environment than the inherent characteristics of individual pesticides (Arora et al., 2019; Deihimfard et al., 2014; Gaona et al., 2019). Our findings are consistent with these studies (Table 1) because they demonstrated that the pesticide application rate has a greater impact on the EIQ-FUR than the toxicity of a pesticide (Supporting Information, Figure S1).

Use of MCPA and diazinon led to the highest environmental impacts, including high ecological impacts, among all the registered pesticides in Sri Lanka that are recommended for rice (Supporting Information, Table S1). Overall, our results demonstrate that the ranking of environmental risk of applied pesticides in the Deduru Oya irrigation scheme, from highest to lowest, is as follows: MCPA > phenthoate > diazinon > tebufenozide > carbosulfan > pretilachlor > thiamethoxam > etofenprox > chlorantraniliprole, with thiamethoxam formulation > lambda-cyhalothrin. The ranking of the ecological risk of the pesticides examined follows the same pattern.
Paddy parcels’ role in pesticide-related environmental risk. The ultimate decision about which pesticide to apply is made by the farmer, depending on the location, elevation, water availabilities, and pest attacks. Therefore, studying the parcel-level contribution to environmental impacts can lead to precision management of pesticide application in line with environmental impact reduction. Values of EIQ are useful indicators for identifying farmer- or field-level contributions to environmental impact through pesticide use.

Our results demonstrate that each paddy parcel contributes different levels of environmental impact (Figure 4A–C). Pest- and disease-management practices vary with weed and pest damage characteristics, water availability and hydrological characteristics, land leveling and water stagnation, parcel size, economic and social factors, individual knowledge levels, and knowledge transfer mechanisms (Sharma et al., 2015). Highest environmental impacts (consumer + worker + ecological) were observed in upstream parcels, while lowest impacts were in midstream (Figure 4).

The ecological impact of applied pesticides from all the parcels is higher than that on consumers and workers. Accordingly, the pest-management practices of each parcel also contribute to further ecological impacts (Figure 4D–F). Therefore, ecological impacts beyond the field level are worth studying to gain a more complete picture of the true ecological impacts of pesticide usage.

Landscape-level ecological impacts of pesticides
Effect of pesticides on observed fauna groups. A total of 552 species from phyla Chordata, Mollusca, Nematoda, Annelida, and Arthropoda were observed in rice ecosystems in Sri Lanka’s intermediate zone. These species belong to 227 taxonomic families (Bambaradeniya et al., 2004). The ecotoxicology data in the ECOTOX Knowledgebase for the detected pesticides are available for 18 taxonomic families out of 227 observed families in Sri Lankan rice ecosystems (Supporting Information, Table S2). Detected pesticide concentrations are presented in Supporting Information, Table S3.

The existing fauna in nine higher-level taxonomic groups were studied: amphibians (class Amphibia), birds (class Aves), fish (class Pisces), mollusks (phylum Mollusca), worms (phylum Annelida), insects (class Insecta excepting order Coleoptera), crustaceans (class Crustacea), beetles (order Coleoptera), and spiders and other arthropods (class Arachnida and other arthropods). The threshold levels (i.e., NOEL, LOEL, and LC50) of pesticides affecting growth, behavior, mortality, and reproduction across all taxa are presented in Table 2. These results demonstrate that the recorded maximum level of pesticide pollution during the studied cropping year has the potential to negatively affect many faunal groups—namely, amphibians, beetles, crustaceans, fish, insects, mollusks, and spiders—at least once during the cropping year.

Many taxa were identified as sensitive to a number of pesticides. For fish across all studies in the ECOTOX database, the threshold values for adverse outcomes on growth, reproduction, behavior, or mortality were lower than the observed concentrations in water for diazinon, tebuconazole, fenonil, oxyfluorfen, thiamethoxam, captan, etofenprox, and fenobucarb, suggesting that fish are at risk in the waters evaluated in the study. The database suggested that amphibian growth and mortality levels may be affected by diazinon exposure at the levels found in the tested water systems. Beyond diazinon, amphibian research in relation to other pesticides is limited, making evaluations of their potential toxicity to this group of vertebrates difficult. Crustaceans were also sensitive to diazinon and fenobucarb. Similar to fish, and not surprisingly, insects are the most widely studied fauna group in terms of pesticide ecotoxicity. Behavior, growth, reproduction, and mortality of insects in the study area are at risk with the detected concentrations of diazinon, captan, chlorantraniliprole, fipronil, thiamethoxam, and etofenprox. Furthermore, beetles are at risk at the thiamethoxam levels found. Chlorantraniliprole and tebuconazol at the concentrations detected in the study area have been shown to threaten mollusks and spiders, respectively.

The landscape-level environmental impact analysis (eco-toxicity) results are in agreement with and highlight the results of paddy field–level environmental impact analysis (EIQ–FUR).

The most toxic effects of pesticide usage. Diazinon appeared in 61.5% of the collected water samples and has a high environmental impact. Therefore, fauna groups with thresholds below the maximum detection concentrations are at risk (Table 2). The growth and mortality of amphibians; the mortality of crustaceans; the growth, reproduction, and mortality of fish; and the growth and mortality of insects are all potentially threatened by diazinon pollution. Captan was detected at extremely high concentrations (686.5 mg/L) and with a high detection frequency (49.3%). Therefore, fish and nontarget insects are at risk from captan pollution. Though chlorantraniliprole has a lower overall environmental impact, a high percentage of farmers reported applying it (20.2%); and its detection frequency (26.3%) and highest recorded concentration (34.4 mg/L) were both high. As a result, some species of insects and spiders may be at risk of negative effects from chlorantraniliprole toxicity. Thiamethoxam also had a lower environmental impact quotient value compared to some of the other pesticides; however, it had a high detection frequency (18.5%), and a high percentage of farmers reported using it (29.8%). The higher application rates may lead to accumulated toxic environmental impacts, and hence, beetles, fish, and nontarget insects may be at risk of adverse outcomes from thiamethoxam pollution, as indicated in the ECOTOX Knowledgebase. Because fenobucarb was detected at high concentrations (15.5 mg/L) and had a high detection frequency (16.3%), the potential mortality threat to fish and crustaceans should be considered.

Some compounds were not represented in the database for the evaluated taxa. The pesticides MCPA and phenthoate were found to have very high environmental impacts and high EIQ values; MCPA is also used by a high percentage of farmers (47.6%). Both carbosulfan and pretilchlor have
moderate environmental impacts and are used by a high percentage of farmers (52.4 and 97.6%), respectively. Carbosulfan is listed as a highly hazardous pesticide according to its WHO classification and is overapplied at 3.3 times the recommended concentration. Therefore, these four pesticides may have considerable impact on faunal species in rice ecosystems.

**Limitations of the study and the adopted ecotoxicity approach**

Based on data available in the ECOTOX Knowledgebase, this research only addressed 8% of the observed fauna families, and the risk of all detected pesticides was not studied for all of those observed. However, the potential impact of pesticides should
not be underestimated, especially those that are detected frequently (e.g., diazinon) or at very high concentrations (e.g., captan) and have high environmental impacts (e.g., MCPA), though the present study provides limited information identifying the fauna groups affected by the detected pesticides.

In general, ecotoxicity studies are confined to broadly used and/or heavily regulated pesticides, such as diazinon, and more sensitive, beneficial, or readily available laboratory species (Tilli & Mouneyrac, 2021). Furthermore, most of the ecotoxicity research is laboratory-based and focuses on only a few species; pesticide dissipation and other environmental fates are not considered (Godfray et al., 2014). In addition, the ecotoxicological threshold levels can be affected by a variety of factors such as species sensitivity, reported exposure time, pesticide formulations, standards of laboratories, toxicity assessment methods, and climate, especially when they are considered in the context of real-world ecosystems (Thore et al., 2021).

Considering the wide ecotoxicological knowledge gap in low- and middle-income countries the ECOTOX Knowledgebase can be considered an important platform for collecting a wide range of pesticide ecotoxicology data published worldwide.

CONCLUSION AND WAY FORWARD

The present study identified common malpractices in pesticide application for rice such as overapplication and usage of insecticides that are not recommended for rice. Carbosulfan, which is classified as a highly hazardous pesticide, was the most widely applied insecticide in the study area. One of the most popular weedicides used by local farmers, MCPPA showed a high level of environmental impacts, followed by diazoin. Strong ecological impacts of all the pesticides were consistently demonstrated through EIQ indicators over impacts on farmworkers and nontargets. These finding highlighted that the EIQ approach can be used to help target change at the individual level or farmer level to support improved environmental outcomes. The data from the ECOTOX Knowledgebase indicate that fish, amphibians, insects, and beetles face potential adverse outcomes from exposure to diazinon, captan, thiamethoxam, and chlorantraniliprole. We propose that highly toxic pesticides like MCPPA and diazinon be replaced with alternative herbicides with lower environmental impacts. Furthermore, increasing farmer awareness of the recommended dosage of agrochemicals should be considered as a foremost need for reducing environmental impacts.

The results of the present study suggest that environmental impact-based national regulatory actions for pesticide regulation should be established. The national policy actions should be based on the use of a wide array of environmental health impact-assessing approaches using direct resources, such as bridging ecotoxicological knowledge gaps at the national level through research, and more convenient indirect resources, such as the EIQ and EXOTOX. Because the EIQ-FUR allows for the capture of season-specific pesticide application practices, this tool may be a good option for timely field-level monitoring of environmental impacts. Embedding the results from research studies (like this one) in long-term planning and effective implementation of integrated pest-management programs, field-level precision agriculture, and farmer assistance can promote realistic solutions to pesticide reduction in rice agroecosystems.

Furthermore, we underline the global importance of bridging the information gap that exists in regard to the ecotoxicity of pesticides, particularly across a broad variety of species; and research efforts are required, particularly in developing countries, to address this gap.

Supporting Information—The Supporting Information are available on the Wiley Online Library at https://doi.org/10.1002/etc.5261.

Acknowledgment—The Swiss Agency for Development and Cooperation provided funding for the present study through the project “Closing Rice Yield Gaps in Asia with Reduced Environmental Footprint (CORIGAP)” (grant 81016734). The authors also recognize the support and cooperation of the Department of Agriculture and Professor Buddh Marambe of the University of Peradeniya, Sri Lanka, who provided advice on pesticide usage.

Disclaimer—The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in the present study.

Author Contributions Statement—Maveekumbure M. J. G. C. N. Jayasiri conducted field experiments, investigated, curated data, analyzed and visualized the data, wrote the manuscript, and prepared the original draft. Sudhir Yadav conceptualized the research, supervised, administrated the project, and wrote, reviewed, and edited the manuscript. Catherine R. Proper and Virender Kumar conceptualized the research and, wrote, reviewed, and edited the manuscript. Nandani D. K. Dayawansa wrote, reviewed, and edited the manuscript. Grant R. Singleton acquired the funding and wrote, reviewed, and edited the manuscript.

Data Availability Statement—Data, associated metadata, and calculation tools are available from the corresponding author (s.yadav@irri.org).

REFERENCES

Aravinna, P., Priyanthu, N., Pitawala, A., & Yatigammana, S. K. (2017). Use pattern of pesticides and their predicted mobility into shallow groundwater and surface water bodies of paddy lands in Mahaweli River basin in Sri Lanka. Journal of Environmental Science and Health, 52(1), 37–47. https://doi.org/10.1080/03601234.2016.1229445

Arora, S., Sehgal, M., Srivastava, D. S., Arora, S., & Sarkar, S. K. (2019). Rice pest management with reduced risk pesticides in India. Environmental Monitoring and Assessment, 191, 241. https://doi.org/10.1007/s10661-019-7384-5

Bambaradeniya, C. N. B., Edirisingle, J. P., De Silva, D. N., Gunatilleke, C. V. S., Ranawana, K. B., & Wijekoon, S. (2004). Biodiversity associated with an irrigated rice agro-ecosystem in Sri Lanka. Biodiversity and
Barbieri, M. V., Peris, A., Postigo, C., Moya-Garcés, A., Monllor-Alcaraz, L. S., Rambla-Alegre, M., Eljarrat, E., López, & de Alda, M. (2021). Evaluation of the occurrence and fate of pesticides in a typical Mediterranean delta ecosystem (Ebro River delta) and risk assessment for aquatic organisms. Environmental Pollution, 274, 115813. https://doi.org/10.1016/j.envpol.2020.115813

Beckie, H., Sikkema, P., Soltani, N., Blackshaw, R., & Johnson, E. (2014). Environmental impact of glyphosate-resistant weeds in Canada. Weed Science, 62(2), 385–392. https://doi.org/10.1614/WS-D-13-00093.1

Bellio, M. G., Kingsford, R. T., & Kotagama, S. W. (2009). Natural versus artificial wetlands and their water birds in Sri Lanka. Biological Conservation, 142(12), 3076–3085. https://doi.org/10.1016/j.biocon.2009.08.007

Biddinger, D. J., Leslie, T. W., & Joshi, N. K. (2014). Reduced-risk pest management programs for eastern U.S. peach orchards: Effects on arthropod predators, parasitoids, and select pests. Journal of Economic Entomology, 107(3), 1084–1091. https://doi.org/10.1603/ec13441

Blair, A., Ritz, B., Wesseling, C., & Freeman, L. B. (2015). Pesticides and risk from insecticide use at the field and regional scales in Iran. Crop Protection, 65, 29–36. https://doi.org/10.1016/j.cropro.2014.06.028

Department of Agriculture. (2015). Pesticide recommendations. Retrieved June 1, 2020, from https://doa.gov.lk/naiccoo-books/#1588567423836-1174ee8c-3e6a

Department of Agriculture. (2019). Agstat—Agricultural statistics (Vol. XVI). Retrieved June 25, 2020, from https://www.doa.gov.lk/SEPC/images/ PDFs/Agriculture.pdf

Edirisinghe, J. P., Karunaratne, W. A. I. P., Hemachandra, I. I., Jayasiri, M. M. J. G. C. N., Yadav, S., Dayawansa, N. D. K., Propper, C. R., Kumar, V., & Singleton, G. R. (2022). Spatio-temporal analysis of water quality for pesticides and other agricultural pollutants in Deduru Oya river basin of Sri Lanka. Journal of Cleaner Production, 330, 129897. http://doi.org/10.1016/j.jclepro.2021.129897

Kim, K., Kabir, E., & Jahan, S. A. (2017). Exposure to pesticides and the associated human health effects. Science of the Total Environment, 575, 525–535. https://doi.org/10.1016/j.scitotenv.2016.09.009

Kiss, A. R., & Coburn, C. W. (2015). Quantitative evaluation of the environmental impact quotient (EIQ) for comparing herbicides. PLoS One, 10(6), e0131200. https://doi.org/10.1371/journal.pone.0131200

Kovach, J., Petzoldt, C., Degni, J., & Tette, J. (1992). A method to measure the environmental impact of pesticides. New York’s Food and Life Sciences Bulletin, 139, 1–8.

Kromann, P., Pradel, W., Cole, D., Taipe, A., & Forbes, G. A. (2011). Use of the environmental impact quotient to estimate health and environmental impacts of pesticide use in Peruvian and Ecuadorian potato production. Journal of Environmental Protection, 2(5), 581–591. https://doi.org/10.4236/jep.2011.25067

Kumar, V. & Singleton, G. R. (2022). Spatio-temporal analysis of water quality for pesticides and other agricultural pollutants in Deduru Oya river basin of Sri Lanka. Journal of Cleaner Production, 330, 129897. http://doi.org/10.1016/j.jclepro.2021.129897

Khan, M. M., Nawaz, M., Hua, H., Cai, W., & Zhao, J. (2018). Lethal and sublethal effects of emamectin benzoate on the rove beetle, Paederus fuscipes, a non-target predator of rice brown planthopper, Nilaparvata lugens. Ecotoxicology and Environmental Safety, 165, 19–24. https://doi.org/10.1016/j.ecoenv.2018.08.047

Lamas, E., Rojas, E., Santana, R. C., & Elías, E. (2017). Impact of pesticides on aquatic organisms..retrieve doa.gov.lk/ 10.1016/j.scitotenv.2018.01.154

Kumar, V. & Singleton, G. R. (2022). Spatio-temporal analysis of water quality for pesticides and other agricultural pollutants in Deduru Oya river basin of Sri Lanka. Journal of Cleaner Production, 330, 129897. http://doi.org/10.1016/j.jclepro.2021.129897

Marambe, B., Pushapakumara, G., & Silva, P. (2012). Biodiversity and agrobiodiversity in Sri Lanka: Village tank systems. In S. Nakano, T. Yahara, & T. Nakashizuka (Eds.), The biodiversity observation network in the Asia-Pacific region (Ecological research monographs, pp. 403–430). Springer. https://doi.org/10.1007/978-4-314-54032-8_28

Munaweera, T. P., & Jayasinge, J. A. U. P. (2017). Farmer perception and demand for pesticide in rice cultivation of Sri Lanka (Research report 212). Hector Kobekaduwa Agrarian Research and Training Institute.

National Center for Biotechnology Information. (2021). PubChem: Diazinon. Retrieved May 30, 2021, from https://pubchem.ncbi.nlm.nih.gov/compound/Diazinon#section=Information-Sources

Nicomrat, D., Tharajak, J., & Kanthang, P. (2016). Pesticides contaminated in rice paddy soil affecting on cultivated microorganism community. Applied Mechanics and Materials, 848, 135–138. https://doi.org/10.4028/www.scientific.net/amm.848.135

Padmaji, M. T., Aheeyar, M. M. M., & Bandara, M. A. C. S. (2014). Assessment of pesticide usage in up-country vegetable farming in Sri Lanka (Research report 164). Hector Kobekaduwa Agrarian Research and Training Institute.

Pandey, N., Rana, D., Chandrakar, G., Gowda, G. B., Patil, N. B., Pandi, G., Guru, P., Annamalai, M., Pokhare, S. H., Rath, P. C., & Adak, T. (2020). Role of climate change variables (standing water and rainfall) on dissipation of chlorantraniliprole from a simulated rice ecosystem. Ecotoxicology and Environmental Safety, 205, 111324. https://doi.org/10.1016/j.ecoenv.2020.111324

Rani, L., Thapa, K., Kanoja, N., Sharma, N., Singh, S.,rewal, A. S., Srivastav, A. L., & Kaushal, J. (2021). An extensive review on the consequences of chemical pesticides on human health and environment. Journal of Cleaner Production, 283, 124657. https://doi.org/10.1016/j.jclepro.2020.124657

Rico, A., Sabater, C., & Castillo, M. Á. (2016). Lethal and sub-lethal effects of five pesticides used in rice farming on the earthworm Eisenia fetida. Ecotoxicology and Environmental Safety, 127, 222–229. https://doi.org/10.1016/j.ecoenv.2016.02.004

Rossi, A. S., Fantón, N., Michlig, M. P., Repetti, M. R., & Cazenave, J. (2020). Fish inhabiting rice fields: Bioaccumulation, oxidative stress and neurotoxic effects after pesticides application. Ecological Indicators, 113, 106186. https://doi.org/10.1016/j.ecolind.2020.106186
Sharma, R., Peshin, R., Shankar, U., Kaul, V., & Sharma, S. (2015). Impact evaluation indicators of an integrated pest management program in vegetable crops in the subtropical region of Jammu and Kashmir, India. *Crop Protection, 67*, 191–199. https://doi.org/10.1016/j.cropro.2014.10.014

Shuman-Goodier, M. E., Singleton, G. R., & Propper, C. R. (2017). Competition and pesticide exposure affect development of invasive (*Rhinella marina*) and native (*Fejervarya vittigera*) rice paddy amphibian larvae. *Ecotoxicology, 26*, 1293–1304. https://doi.org/10.1007/s10646-017-1854-8

Tahir, H. M., Basheer, T., Ali, S., Yaqoob, R., Naseem, S., & Khan, S. Y. (2019). Effect of pesticides on biological control potential of *Neoscona thesi* (Araneae: Araneidae). *Journal of Insect Science, 19*(2), 17. https://doi.org/10.1093/jisesa/iez024

Thore, E. S. J., Philippe, C., Luc Brendonck, L., & Pinceel, T. (2021). Towards improved fish tests in ecotoxicology—Efficient chronic and multi-generational testing with the killifish *Nothobranchius furzeri*. *Chemosphere, 273*, 129697. https://doi.org/10.1016/j.chemosphere.2021.129697

Tilli, S., & Mouneyrac, C. (2021). New challenges of marine ecotoxicology in a global change context. *Marine Pollution Bulletin, 166*, 112242. https://doi.org/10.1016/j.marpolbul.2021.112242

US Environmental Protection Agency. (2017). ECOTOX Knowledgebase. Retrieved June 5, 2021, from https://cfpub.epa.gov/ecotox/

Weerahewa, J., Kodithuwakku, S., & Ariyawardana, A. (2010). The fertilizer subsidy program in Sri Lanka. In P. Pinstrup-Andersen & F. Cheng (Eds.), *Food policy for developing countries: Case studies*. Cornell University Press. https://ecommons.cornell.edu/handle/1813/55709

World Bank. (2013). Pest management plan—Second community development and livelihood improvement project. Retrieved February 2, 2021, from: https://documents1.worldbank.org/curated/en/416161468303014589/pdf/E21470v20E0P00C0disclosed040160130.pdf

Yasuda, M., Sakamoto, Y., Goka, K., Nagamitsu, T., & Taki, H. (2017). Insecticide susceptibility in Asian honey bees (*Apis cerana* (Hymenoptera: Apidae)) and implications for wild honey bees in Asia. *Journal of Economic Entomology, 110*(2), 447–452. https://doi.org/10.1093/jee/tox032