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Special Section:
Geospatial data applications for environmental justice

Key Points:

- Close to 30% of the population in Ecuador lives in areas with high pesticide application rates
- High pesticide use areas create risks for human populations, biodiversity and protected ecosystems within national parks
- The accessible, modular, and scalable methods developed facilitate reproducing population-level assessments across the world

Supporting Information:

Supporting Information may be found in the online version of this article.

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Mapping Potential Population-Level Pesticide Exposures in Ecuador Using a Modular and Scalable Geospatial Strategy

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Abstract

Human populations and ecosystems are extensively exposed to pesticides. Most nations lack the capacity to control pesticide contamination and have limited availability of pesticide use information. Ecuador is a country with intense pesticide use with high exposure risks to humans and the environment, although relative or combined risks are not well understood. Here, we analyzed the distribution of application rates in Ecuador and identified regions of concern because of high potential exposure. We used a geospatial analysis to identify grid cells (∼8 km × 8 km) where the highest pesticide application rates and density of human populations overlap. Furthermore, we identified other regions of concern based on the number of amphibian species as an indicator of ecosystem integrity and the location of natural protected areas. We found that 28% of Ecuador's population dwelled in areas with high pesticide application rate. We identified an area of ∼512 km^2 in the Amazon region where high application rates, large human settlements, and a high number of amphibian species overlapped. Additionally, we distinguished clusters of pesticide application rates and human populations that intersected with natural protected areas. Ecuador exemplifies how pesticides are disproportionately applied in areas with the potential to affect human health and ecosystems' integrity. Global estimates of population dwelling, pesticide application rates, and environmental factors are key in prioritizing locations to conduct further exposure assessments. The modular and scalable nature of the geospatial tools we developed can be expanded and adapted to other regions of the world where data on pesticide use are limited.

Plain Language Summary

Pesticide exposures are a concerning issue that threatens ecosystem integrity and human health. However, most countries cannot assess, monitor, and control pesticide contamination. We studied this threat in Ecuador, a country with one of the highest application rates of pesticides worldwide, an export-bound agricultural industry, a large population at risk, remarkable biodiversity, and a limited understanding of the nationwide extent of pesticide contamination. We assessed the geographic distribution of pesticide application rates and identified regions where the potential risk of exposure to human populations and ecosystems requires detailed exposure assessments. Using publicly available global data sets that locate human populations, biodiversity, natural parks, and pesticide use rates, we mapped areas where high levels of pesticide use and high density of human population overlap. We also assessed areas where natural parks and amphibian species may be threatened. Around 28% of Ecuador's population lived in areas with a high pesticide application rate. We found widespread intensive use of pesticides in Ecuador in regions that overlap with human populations and ecosystems at risk of exposure. The methods developed relied on open-source software and publicly available data. Thus, our approach can be applied to other regions where data on pesticide use are limited.

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1. Introduction

The extensive and increasing application of pesticides in agriculture is receiving more recognition as a major chemical pollution challenge due to its severe impacts on human health and ecosystems' ecological integrity (Landrigan et al., 2018; UNEP, 2019). Non-occupational exposures through agricultural drift are a major source of contamination, particularly for populations living near agricultural land (Dereumeaux et al., 2020; Deziel Nicole et al., 2017; K. Larsen et al., 2020; Wan, 2015). In addition to acute poisoning (Mew et al., 2017), recurring exposures to low-doses of pesticides have been associated with negative health outcomes such as non-Hodgkin lymphoma (Zhang et al., 2019), Parkinson's disease (Tangamornsuksan et al., 2019), neuropsychological effects (Muñoz-Quezada et al., 2016), Type 2 diabetes (Evangelou et al., 2016), and Alzheimer's diseases (Yan et al., 2016). Prenatal and young children are particularly sensitive to pesticide pollution and are at a higher risk of early death and developing disease across their lifespan (Suk et al., 2016; Vrijheid et al., 2016). Different perinatal outcomes have been found to be associated with prenatal exposure to pesticides, including prematurity, low birth weight, and birth anomalies (Jaacks et al., 2019; A. E. Larsen et al., 2017; Ling et al., 2018; Toichuev et al., 2018; Yang et al., 2020). Besides their impacts on human health, pesticides have consequences on wildlife population decline (e.g., amphibians, bees), changes in microbial communities, and alteration of ecosystems that ultimately support the wellbeing of humans (Köhler & Triebskorn, 2013; Springborn et al., 2022; UNEP, 2019; Whitmee et al., 2015).

Although there is growing awareness of this planetary health issue among researchers, most countries lack the capacity to assess and control the contamination risk of novel chemical exposures (Persson et al., 2022). This is particularly true in low- and middle-income countries (LMICs), where regulation enforcement, chemical contamination monitoring, banned pesticide control, disease surveillance and risk, and control management strategies are limited (González-Andrade & López-Pulles, 2012; Naidoo et al., 2010; Ngowi et al., 2020). In addition, LMICs carry the double burden of having some of the highest pesticide application rates globally while also having limited data on distribution and contamination (Ferlay et al., 2015; Landrigan et al., 2018).

South America is the fastest growing pesticide market globally, fueled partly by a sharp increase in export-bound crops that have replaced traditional farming with intensive agricultural practices that rely heavily on chemical use (Müller et al., 2021; UNEP, 2019). For example, Ecuador is the largest banana exporter in the world, the third largest exporter of cut flowers, and the fourth largest exporter of cacao (Datawheel, 2020; Simoes & Hidalgo, 2011). Export-bound agricultural industries drove the country's rapid expansion of intensive agriculture, making it the second largest pesticide user per land area worldwide in 2018 (FAOSTAT, 2020). The rapid environmental and land cover changes caused by the expansion of agricultural production have severe negative impacts on human health, biodiversity, and the functioning of ecosystems (Calderón Rios & Sarango Flores, 2015; Deknock et al., 2019; Friedman et al., 2020; Handal et al., 2015; Hutter et al., 2020; Ortega-Andrade et al., 2021; Suarez-Lopez et al., 2017, 2019; Tapia-Armijos et al., 2015). Moreover, Ecuador has a relatively large rural population (~34%) when compared with its neighboring countries (e.g., Colombia and Peru) (Royuela & Ordóñez, 2018) and a relatively small land mass area compared to other top countries for pesticide use in the Americas (i.e., USA, Brazil, Argentina, and Canada) (FAOSTAT, 2020). In other words, a disproportionately large proportion of the population of Ecuador resides in areas where there is agricultural production and potential for pesticide exposure.

A confluence of factors has resulted in high levels of human and environmental exposures to pesticides in Ecuador. A recent study identified a ~1,300 km^2 area as one out of the seven global hotspots where high levels of pesticide pollution risk, water scarcity, and biodiversity overlap (Tang et al., 2021). Although there is emerging evidence of increasing occupational acute pesticide poisoning in Ecuador (Andino Padilla, 2021; González-Andrade et al., 2010; Solís Gordon, 2021), no nationwide assessment of populations at risk of pesticide environmental exposures has been conducted. Moreover, data on pesticide application rates in Ecuador are fragmented, and affected by missing information or aggregation at the provincial level.

One strategy to overcome the challenges in estimating potential exposure to pesticides in the environment is to use geospatial data sciences (A. E. Larsen et al., 2020; K. Larsen et al., 2020; VoPham et al., 2015; Wan, 2015). This approach has been used elsewhere to prioritize specific regions of concern where further environmental assessments are needed to evaluate the risk of pesticide exposures in human and wildlife populations (A. E. Larsen et al., 2020; K. Larsen et al., 2020). However, these population-level studies were based on comprehensive pesticide application rates data from regional or national surveys and guidelines. In the absence of detailed high-resolution pesticide use inventories, one promising alternative is the recently developed PEST-CHEMGRIDSv1 gridded maps, which can estimate application rates globally (Maggi et al., 2019).

1.1. Aims

The aim of this study is to overcome challenges in data availability to assess the distribution of pesticide use rates in Ecuador and to estimate the total population living in areas with a greater risk of exposure. To this end, we used freely available data on exposure rates and population density and developed a modular and scalable method to prioritize areas where further exposure assessments and interventions are required. We also aimed to identify areas where high human population density and high pesticide application rates overlap, including a disaggregated assessment of overall pesticide application, glyphosate (a common herbicide), and chlorothalonil (a common fungicide) due to their widespread use in Ecuador and their high toxicity. Given the particularly high sensitivity of children to environmental pollution and previous studies linking pesticide exposure to adverse birth outcomes, we conducted a specific analysis for children under five and females between 20 and 29 years of age (i.e., highest birth rate age group in Ecuador). This study also aimed to identify areas of particular concern where pesticides may be used in the vicinity of large human populations and high diversity of amphibians, leading to a risk to human health and ecosystem integrity. Our approach was based on publicly available global databases and used open-source software to process and analyze the data. Thus, this method is readily available for application to other regions worldwide.

2. Methods

2.1. Study Area

Ecuador is located on the northwest coast of South America, and its landmass of 256,369 km^2 is the fourth smallest on the subcontinent. The geographical and natural diversity of Ecuador is remarkable, making it the smallest of the 17 mega-diverse countries on Earth (Cuesta et al., 2017; Mittermeier et al., 2011; Ortega-Andrade et al., 2021). The country has 83 natural protected areas comprising ~23% of the landmass and ~13% of the marine territory (UNEP-WCMC, 2022). Ecuador is divided into four natural regions: the Pacific Coast (Coast) located to the west, the Andean mountain range (Inter-Andean), the Amazon rain forest (Amazon) to the east, and the Galapagos Islands (Ilbay-Yupa et al., 2021) (Figure 1). Close to 4% of the Ecuadorian landmass is considered arable land and the agricultural sector represents ~9% of the GDP and ~55% of the total exports (Juca et al., 2021; World Bank, 2021). Moreover, the agricultural sector is the major source of jobs in the country employing ~30% of the economically active population (Juca et al., 2021).

Ecuador had an estimated population of ~17.5 million people in 2020 and half of the population is concentrated in three out of 24 provinces: the coastal provinces of Guayas and Manabí, and the Pichincha province in the northern Andes (Instituto Nacional de Estadísticas y Censos [INEC], 2020). Although seasonal internal migration has historically characterized the rural areas—driven by agricultural and construction employment (Bernard et al., 2017)—there has been a drastic reduction in the last two decades (Pontarollo & Segovia, 2019; Royuela & Ordóñez, 2018).

2.2. Pesticide Application Rates

PEST-CHEMGRIDSv1 is a global database that provides annual application rate estimates at a 5 arc-minute resolution (~8 km at the equator) for 20 pesticides, including chlorothalonil and glyphosate (Maggi et al., 2019, 2020). The PEST-CHEMGRIDSv1 database includes 1,037 application rate grids with high and low estimates for the years 2015, 2020, and 2025. It also contains data on six individual crops (i.e., corn, soybean, wheat, cotton, rice, alfalfa) and four crop groups (i.e., vegetable and fruit, orchards and grapes, pastures and hay, and other crops). Global pesticide application rate estimates were calculated based on current pesticide global inventories per country and 25-year historical application rates trends in the USA in combination with ancillary data on agricultural land distribution, hydro-climatic variables, soil physical properties, and socioeconomic variables (Maggi et al., 2019). We used the overall pesticide application rates (i.e., the sum of all pesticide ingredients available in the database for this region) for all crops. We also conducted separate analyses specifically for glyphosate and chlorothalonil. These two were chosen because they are included in a high number of pesticides

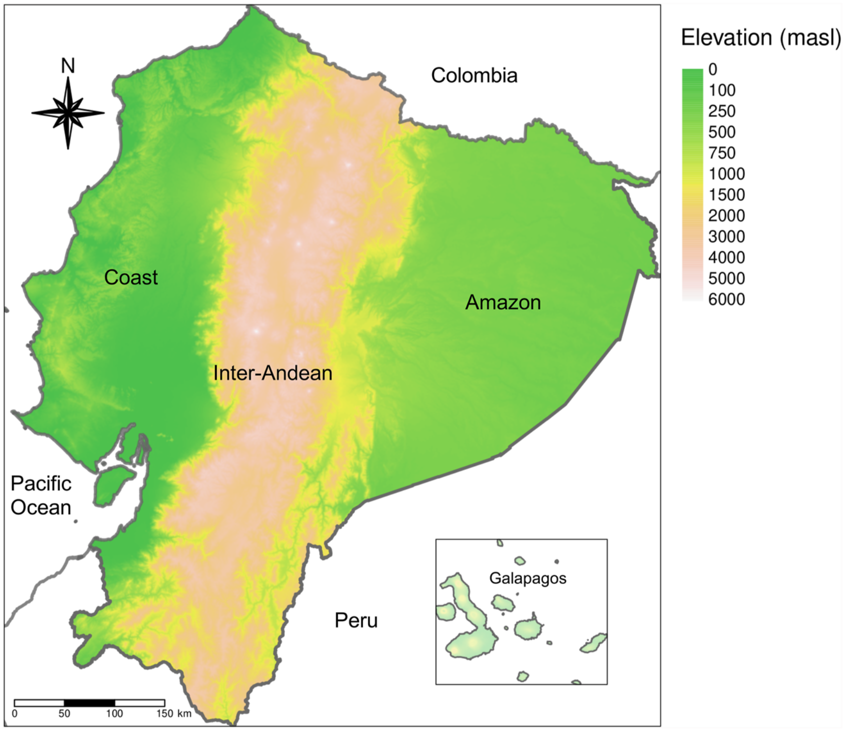

Figure 1. Elevation in meters above the sea level (masl) in Ecuador. The country is divided into four natural regions known as Coast, Inter-Andean, Amazon, and Galapagos Islands.

registered in Ecuador (Rivera, 2015), their IARC classification as probably and possibly carcinogenic, respectively (IARC, 2017), and past evidence of reproductive health effects (Ling et al., 2018; Milesi et al., 2021).

A grid with a spatial resolution of approximately 8 km × 8 km was generated to match PEST-CHEMGRIDSv1. The grid covered Ecuador and some regions from the neighboring countries (i.e., Perú and Colombia). A total of 6,560 grid cells, or "pixels" were used as the unit of analysis. We excluded the Galápagos islands as estimates of pesticide application rates were not available.

2.3. Population Data, Number of Amphibian Species, and Protected Areas

Estimates of population counts for 2010, 2015, and 2020 (e.g., Figure 2a) were derived from the Gridded Population of the World Version 4 (GPWv4) data collection produced by the US National Aeronautics and Space Administration (NASA) Socioeconomic Data and Applications Center (SEDAC) (Center for International Earth Science Information Network [CIESIN]-Columbia University, 2018). These population count grids provide information on the number of persons per pixel (30 arc-second resolution, ~1 km at the Equator), based on national-level census data, population registries, ancillary data on administrative units, and the distribution of land and water areas (CIESIN-Columbia University, 2018). Prior to the data analysis, we added the population counts of the GPWv4 pixels to a coarser spatial resolution of 8 km × 8 km.

To examine more age- and sex-specific exposures, we extracted data on the proportions of males and females in each 5-year age group (0–4 to 85+ years) for 2010. Age- and sex-specific data were not available for 2015 and 2020. Thus, to calculate population counts disaggregated by sex and age group for 2015 and 2020, we assumed that the age and sex proportions remained constant and multiplied total populations per pixel by the proportions of 2010. In addition, we estimated the total population count per pixel for 2025 assuming that the growth rate in population per pixel was constant between the periods 2015–2020 and 2020–2025.

To map areas where pesticide contamination may affect ecosystems' integrity and biodiversity, we used the number of amphibian species as a proxy indicator (Figure 2b). Amphibian species are suitable as ecosystem indicators in general (Waddle, 2006) and have been used as indicators of environmental pollution and restoration success in tropical forests (Díaz-García et al., 2017; Hamer et al., 2004). In addition, this indicator is particularly relevant for this study as

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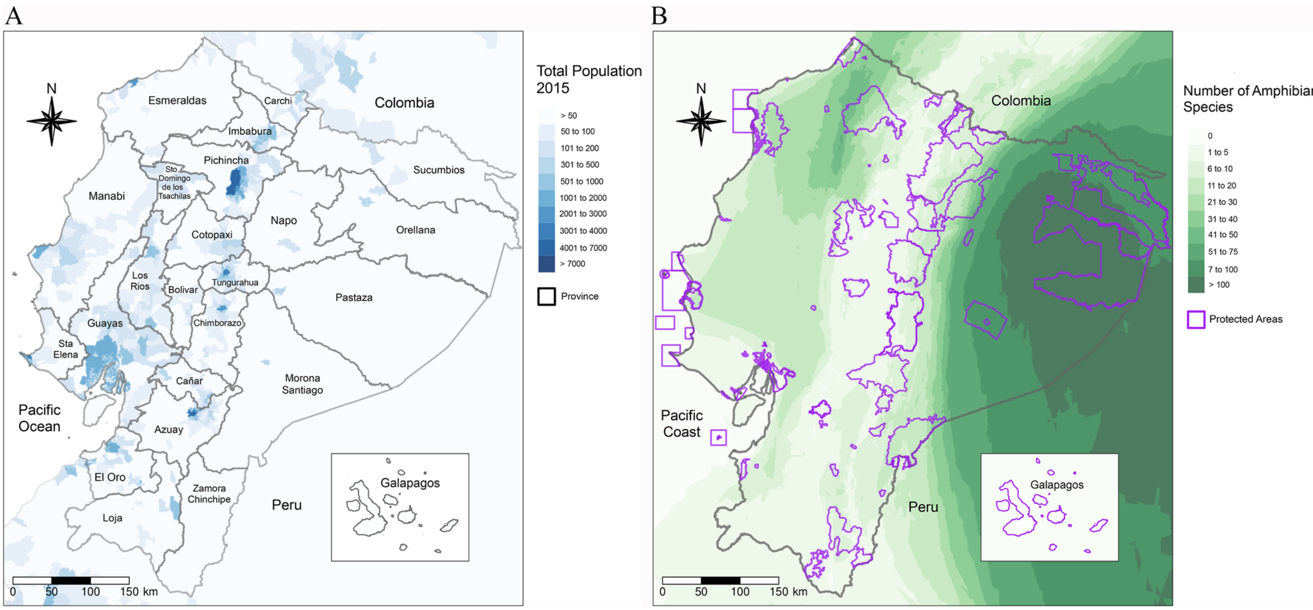

Figure 2. (a) Total human population of Ecuador in 2015 per pixel (~1 km resolution at the equator). Based on the Gridded Population of the World (GPWv4); (b) Number of amphibian species based on the Global Amphibian Richness Grids 2015 (~1 km resolution at the equator) and protected areas borders in Ecuador.

amphibian species in Ecuador are considered among the most threatened in South America, partly due to deforestation, agriculture, and oil and mining industries (Ortega-Andrade et al., 2021). Species counts were derived from the Global Amphibian Richness Grids 2015 release available at a 30 arc-second resolution (~1 km at the equator) (International Union for Conservation of Nature [IUCN] & CIESIN—Columbia University, 2015). These grids were developed as part of a comprehensive assessment of the 5,918 currently known amphibian species against the International Union for Conservation of Nature Red List Categories and Criteria (IUCN & CIESIN—Columbia University, 2015).

Global Amphibian Richness Grids raster was aggregated to a spatial resolution of 8 km × 8 km by calculating the mean number of amphibian species. To account for the effect of elevation on species richness of amphibians, we ran a linear regression predicting amphibian species richness with elevation as an explanatory variable. Elevation data in meters were extracted from the Global Multi-resolution Terrain Elevation data 2010 (GMTED2010) (Danielson & Gesch, 2011). We extracted the statistical model's residuals for each pixel as an indicator of amphibian species richness that is not explained by elevation (e.g., a large residual indicates that the number of species in the pixel is large even after accounting for elevation), and used such residuals in subsequent analyses. Finally, natural protected areas boundaries were obtained from the United Nations Environment Program World Database on Protected Areas for the year 2020 (UNEP-WCMC, 2022). We included 71 protected areas as spatial polygons in the analyses, excluding those that only provided a spatial point location (Figure 2b).

2.4. Data Analysis

The three databases (i.e., PEST-CHEMGRIDSv1, GPWv4, and Global Amphibian Richness Grids) were integrated into a geospatial database that was used for assigning values to each of the 6,560 grid pixels (8 km × 8 km spatial resolution). To assess the number of people who live in areas of potential concern for pesticide exposures, we identified pixels with high application rates (i.e., top 20%, excluding cells with zero values and no agricultural land). Then, we calculated the total counts for each population of interest (i.e., total population, children under five, females between 20 and 29) within high application rates pixels. Children under five were included in the analyses because of their particular vulnerability to pollution contamination. In addition, we included a separate analysis for females between 20 and 29 because pollution affects perinatal health outcomes, as this age group presented the highest birth rate in Ecuador (INEC, 2020).

To assess areas of potential exposure, we calculated five quantiles for each of the following variables: total population count, children count (<5 years), females between 20 and 29 years old, and number of amphibian species adjusted for elevation (i.e., residuals of the model using elevation as an explanatory variable). For these variables, we classified pixels in the highest quantile (i.e., 20%) as "high." Next, we identified pixels where "high" values for each of the variables overlapped in three separate analyses: (a) human populations (total, children, or females between 20 and 29 years) and pesticide application rates (overall, glyphosate, or chlorothalonil); (b) human populations, pesticide application rates, number of amphibian species adjusted for elevation; and finally, (c) overall pesticide application rates and protected areas borders.

In addition, we assessed the spatial autocorrelation of the pesticide application rates, using the Getis-Ord Gi* statistic to identify high-value clusters. These hotspots of high application rates are defined as areas with higher concentration of events compared to the expected number under the assumption of a random distribution of the events. The Gi* statistic measures the extent to which neighboring points in a grid cell have similar low or high values, by comparing local associations against the global average (Anselin, 1995; Chainey et al., 2002). The Gi* statistic is applied to a grid cell and calculates a z-score and a p-value for each pixel, which provides information on the intensity of the clustering. This provides a quantitative measurement that complements the visual inspection of areas with high application rates. We set the statistical significance at 99.9%, meaning that pixels with z-scores greater than 3.29 were considered hotspots of high pesticide application rates.

No major differences were observed between the spatial distribution of the PEST-CHEMGRIDSv1 pesticide application rates in Ecuador for 2015, 2020, and 2025. In addition, the areas of potential concern (i.e., overlap between application rates and human density) presented similar spatial patterns when comparing the three populations of interest (i.e., children under five, females between 20 and 29, and total population) (Figures S1 and S2 in Supporting Information S1). Hence, to identify areas where there is an overlap between high application rates and high human density, we primarily focused our analyses on the year 2015 and the total human population density. However, to better understand the extent of potential pesticide exposures in Ecuador across population type, we conducted an additional analysis where we counted the number of people living within areas of high application rates for the three populations of interest. For the total population, we conducted this calculation for all years (i.e., 2015, 2020, and 2025). However, for children under five and females between 20 and 29, we only did this calculation for 2015 and 2020 due to the lack of projected disaggregated data for 2025. The R statistical computing environment (version 4.1.1) was used to extract, process, analyze and visualize all data, and the code was developed in RStudio (version 1.4.1717) (R Core Team, 2021; RStudio Team, 2021).

3. Results

3.1. Pesticide Application Rates Distribution

For the overall pesticide application rates in 2015, we observed exceptionally high rates along the coastal provinces. The central part of Ecuador's Coast (Manabí Province) presented both the highest per province mean application rate and included the pixel with the maximum application rate, estimated at 64.0–81.4 kg/ha per year. Other areas of high overall pesticide application rates were located in the Inter-Andean region both in the north (border with Colombia) and south (border with Peru), and in scattered areas in the central Amazon region. The lowest mean application rate for all pesticides was observed in the northeast, neighboring Colombia and Peru (Table 1; Figure S3 in Supporting Information S1).

Glyphosate application rates were exceptionally high in the west-central part of the Coast and Inter-Andean regions (Figure S4 in Supporting Information S1). In addition to all pesticides, the Manabí province had the highest per province mean application rates for glyphosate, which was estimated at 6.3–8.6 kg/ha per year. However, the provincial ranking for glyphosate application rates was distinct compared to all pesticides. For chlorothalonil, the distribution of application rates followed a similar pattern compared with all pesticides, with relatively high rates in the south part of the Coast region and some high-rate areas in the Amazon provinces. The highest per province chlorothalonil mean application rate was in the coastal province of Santa Elena and estimated to be 4.2–4.4 kg/ha per year (Table 1). Although some Amazonian provinces did not have relatively high mean chlorothalonil application rates, they contained areas with high application rates (e.g., Orellana, Morona Santiago) (Table 1; Figure S5 in Supporting Information S1).

3.2. Total Human Population Living in Areas of High Pesticide Application Rates

The number of people, children under five, and females between 20 and 29 living in areas with high application rates of all pesticides, glyphosate, or chlorothalonil are projected to increase by approximately 20% between 2015 and 2025. We estimated that in 2015 between 4.3 and 4.6 M people lived in areas with high overall pesticide

Table 1
Summary Statistics Per Province of Pesticide Application Rates in Ecuador for the Year 2015

Province	Overall pesticide application rates high estimate (kg/ha per year) mean (min–max)	Overall pesticide application rates low estimate (kg/ha per year) mean (min–max)	Glyphosate application rates high estimate (kg/ha per year) mean (min–max)	Glyphosate application rates low estimate (kg/ha per year) mean (min–max)	Chlorothalonil application rates high estimate (kg/ha per year) mean (min–max)	Chlorothalonil application rates low estimate (kg/ha per year) mean (min–max)
Manabi	56.2 (0–81.4)	41.0 (0–64.0)	8.6 (0.0–12.7)	6.3 (0.0–9.8)	3.7 (0.0–6.4)	3.3 (0.0–6.0)
Loja	47.4 (14.3–65.8)	33.4 (11.4–51.0)	5.1 (1.0–6.0)	3.5 (0.7–4.3)	3.2 (1.6–5.7)	2.82 (1.3–5.4)
El Oro	47.1 (0.0–70.0)	33.4 (0.0–53.8)	4.6 (0.0–5.7)	3.1 (0.0–4.0)	3.3 (0.0–6.2)	3.0 (0.0–5.7)
Carchi	44.8 (15.1–58.7)	31.2 (11.9–43.8)	4.9 (3.1–5.7)	3.3 (2.1–4.0)	2.7 (0–4.8)	2.4 (0–4.4)
Santa Elena	43.0 (0.0–71.2)	33.5 (0.0–55.9)	3.9 (0–6.1)	2.8 (0.0–4.5)	4.4 (0.0–7.2)	4.2 (0.0–6.8)
Esmeraldas	42.5 (0–73.2)	32.5 (0–58.8)	4.2 (0–10.4)	3.04 (0–7.8)	4.1 (0–7.2)	3.8 (0–6.8)
Cañar	42.2 (30.0–47.3)	25.1 (20.2–29.8)	8.0 (5.8–8.9)	5.7 (3.9–6.6)	1.2 (0.7–2.0)	0.8 (0.4–1.5)
Los Ríos	42.0 (38.8–45.9)	26.2 (23.2–30.0)	7.5 (6.8–7.9)	5.2 (4.7–5.7)	2.0 (1.4–2.6)	1.6 (1.1–2.2)
Bolívar	42.0 (17.1–45.6)	25.7 (10.1–28.1)	7.3 (2.3–8.5)	5.1 (1.7–6.2)	1.6 (1.2–2.1)	1.2 (0.9–1.6)
Imbabura	40.8 (19.0–51.8)	27.2 (11.8–36.8)	4.7 (2.1–5.8)	3.2 (1.6–4.2)	2.4 (1.7–3.7)	2.1 (1.3–3.2)
Cotopaxi	40.2 (16.7–44.3)	24.3 (10.1–28.0)	5.3 (2.2–7.8)	3.6 (1.7–5.6)	1.6 (1.3–2.1)	1.2 (0.9–1.6)
Chimborazo	37.6 (15.3–44.0)	22.0 (8.4–28.2)	5.4 (2.4–8.7)	3.6 (1.8–6.4)	1.3 (0.9–2.1)	0.9 (0.5–1.6)
Azuay	37.1 (0.1–48.0)	22.7 (0.1–31.0)	5.3 (0.0–8.7)	3.6 (0.0–6.4)	1.5 (0.0–2.8)	1.1 (0.0–2.4)
Tungurahua	36.9 (17.6–45.4)	22.6 (10.4–29.3)	4.3 (1.8–5.6)	2.9 (1.4–3.9)	1.7 (1.2–2.2)	1.3 (0.9–1.8)
Napo	35.3 (5.4–44.9)	22.8 (4.5–32.9)	4.0 (1.8–5.6)	2.9 (1.5–3.9)	2.1 (0.0–3.9)	1.8 (0.0–3.5)
Santo Domingo de los Tsachilas	35.1 (16.9–53.4)	22.6 (11.1–37.0)	5.4 (2.1–10.2)	3.9 (1.6–7.6)	2.1 (1.6–2.8)	1.7 (1.2–2.4)
Guayas	34.1 (0.0–58.7)	23.0 (0.0–44.6)	5.2 (0.0–10.0)	3.7 (0.0–7.2)	2.3 (0.0–6.1)	2.0 (0.0–5.7)
Pichincha	31.6 (14.6–46.7)	20.3 (8.9–32.4)	3.8 (0.6–5.8)	2.7 (0.3–4.2)	2.0 (1.3–3.3)	1.6 (1.0–2.9)
Zamora Chinchipe	31.5 (0.0–50.1)	20.4 (0.0–34.6)	4.00 (0.0–5.7)	2.7 (0.0–4.0)	1.6 (0–3.1)	1.3 (0–2.6)
Morona Santiago	29.7 (0.0–56.9)	19.9 (0.0–42.8)	3.7 (0.0–6.4)	2.7 (0.0–5.0)	2.0 (0.0–5.1)	1.7 (0.0–4.7)
Orellana	17.6 (0.0–49.8)	12.9 (0.0–37.7)	2.0 (0.0–4.8)	1.6 (0.0–3.8)	1.5 (0.0–5.4)	1.3 (0.0–5.2)
Pastaza	9.2 (0.0–46.6)	6.8 (0.0–34.7)	1.1 (0–4.8)	0.9 (0.0–3.8)	0.9 (0.0–4.7)	0.8 (0.0–4.4)
Sucumbios	6.3 (0.0–48.3)	4.6 (0.0–36.4)	0.8 (0.0–4.8)	0.6 (0.0–3.7)	0.6 (0.0–4.4)	0.5 (0.0–4.2)
Galapagos	–	–	–	–	–	–
National	6.4 (0.0–81.4)	4.4 (0.0–64.0)	0.8 (0.0–12.7)	0.6 (0.0–9.8)	0.4 (0.0–7.2)	0.4 (0.0–6.8)

Table 2
Number of People in Ecuador Living in Areas With High Pesticides Application Rates

	Year	Total population	Children under 5 years of age	Females in the 20–29 age group
All pesticides	2015	4.33–4.55 M	451k–471k	185k–195k
	2020	4.76–5.06 M	497k–524k	203k–216k
	2025	5.29–5.52 M	–	–
Glyphosate	2015	5.09–5.41 M	534k–565k	219k–233k
	2020	5.61–5.89 M	5.89k–617k	241k–254k
	2025	6.11–6.37 M	–	–
Chlorothalonil	2015	3.23–3.29 M	332k–340k	141k–144k
	2020	3.58–3.64 M	369k–377k	157k–160k
	2025	3.97–4.00 M	–	–

application rates, and this will increase approximately to 5.3–5.5 M by 2025. These populations correspond to ~28% of the total population in Ecuador in 2015 and 2025. Approximately between 5.1 and 5.41 M people lived in areas with high glyphosate application rates in 2015, and this figure can be projected to exceed 6 million people by 2025. The total population of people living in areas with high application rates of chlorothalonil in 2015 was 3.2–3.3 M, and we estimate this number to rise to 4 M by 2025 (Table 2).

To assess populations that are particularly sensitive to environmental pollution, we also estimated the numbers of children under five and females between 20 and 29 years of age living in areas with high pesticide application rates. In 2015, between 451k and 471k children under 5 years of age (~30% out of the total) lived in areas with high application rates of all pesticides. Furthermore, on average 336k and 550k children under five resided in areas with high application rates of chlorothalonil and glyphosate respectively. For the same year, an average of 190k females between 20 and 29 years of age (~15% out of the total) lived in areas with high application rates of all pesticides, 226k for glyphosate, and 143k for chlorothalonil (Table 2).

3.3. Human Populations and Pesticide Application Rates Spatial Distribution

In addition to calculating the population count in areas with high pesticide application rates, we also spatially analyzed regions where high human population and high application rates overlapped. We identified four key areas in the coastal region and one in the northern interior for overall pesticide application rates. Two additional smaller areas were located in the central part of the Inter-Andean region and the northern Amazon (Figure 3a). The regions of high glyphosate application rates were mostly located in the western part of the country, with a few other areas in the southern interior (Figure 3b). For chlorothalonil, the areas identified are concentrated on the west Coast, with an additional area in the northern Amazon region (Figure 3c).

Based on the Gi* statistic, most areas where the highest quantiles of the pesticide application rates and total population count overlapped were statistically significant clusters (Figures 4a–4c). For the three pesticides, the median and mean Gi* statistic z-scores were above the 99.9% level of significance for clustering (z-score ≥ 3.3), and at least 75% of the pixels in the highest application rates and total population quantile were above the 99% level of significance (z-score ≥ 2.6). We also identified regions in the northern and southern part of the Inter-Andean region, however they may not be significant clusters given the relatively low Gi*.

3.4. Pesticide Application Rates, Number of Amphibian Species, and Protected Areas

We explored regions of particular concern due to an intersection of high pesticide application rates, large human populations, and high number of amphibian species adjusted for elevation (i.e., potential clusters with high risk to both humans and valuable ecosystem). We also identified a 512 km^2 area in northern Amazon where these three variables overlapped (Figure 5a). As an illustrative example of this intersection, the satellite image of one pixel shows a mixture of agricultural, urban, and natural vegetation land covers (Figure 5b). Out of the 71 natural protected areas included in this study, 11 intersected with pixels in the highest quantile of overall pesticide application rates (Figure 6). In addition, some of these areas were also in the highest quantile of total human

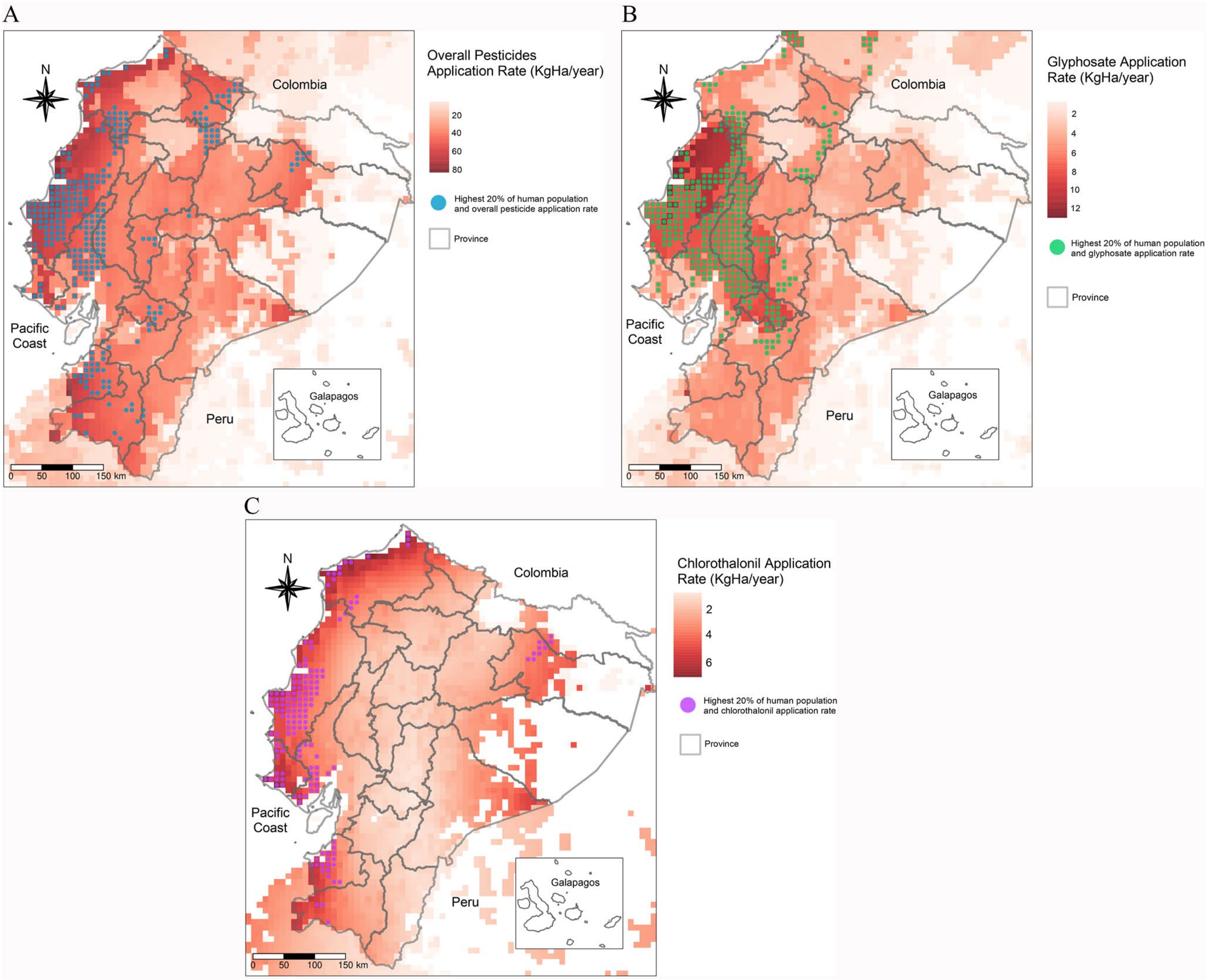

Figure 3. (a) Overall pesticide application rates in Ecuador. Dotted areas indicate where the highest 20% application rates and highest 20% population density overlapped; (b) Glyphosate application rates in Ecuador. Dotted areas indicate where the highest 20% application rates and highest 20% population density overlapped; (c) Chlorothalonil application rates in Ecuador. Dotted areas indicate where the highest 20% application rates and highest 20% population density overlapped. Note: Data on pesticide application rates were extracted from PEST-CHEMGRIDSv1 (~8 km resolution at the equator) for the year 2015. Application rates were not available for the Galapagos Province.

population, as is the case of locations identified in the northeastern part of the Inter-Andean region. While some areas of concern were located on the border of protected areas, others lie entirely inside national parks as it was observed in the central and southern part of the Inter-Andean region (Figure 6).

4. Discussion

In this population-level study, we provide nationwide evidence of the extent of potential pesticide exposures in Ecuador. We developed a modular and scalable strategy and found that close to 30% of the total population lives in areas with high pesticide application rates. In addition, we identified regions with a high potential of harmful exposures to large populations, mainly along the central Coast of Ecuador. Moreover, we found a hotspot area with high risk both to humans and valuable ecosystem located in the Amazon region (Figures 5a and 6). Finally, we located regions where high pesticide use areas may affect protected ecosystems within national parks borders.

Our methods build on previous approaches applying geospatial tools to assess human and wildlife exposures to pesticides. Prior research has assessed potential pesticide exposures to humans at the state level in the United States (VoPham et al., 2015; Wan, 2015) and at the national level in Canada (K. Larsen et al., 2020). In addition,

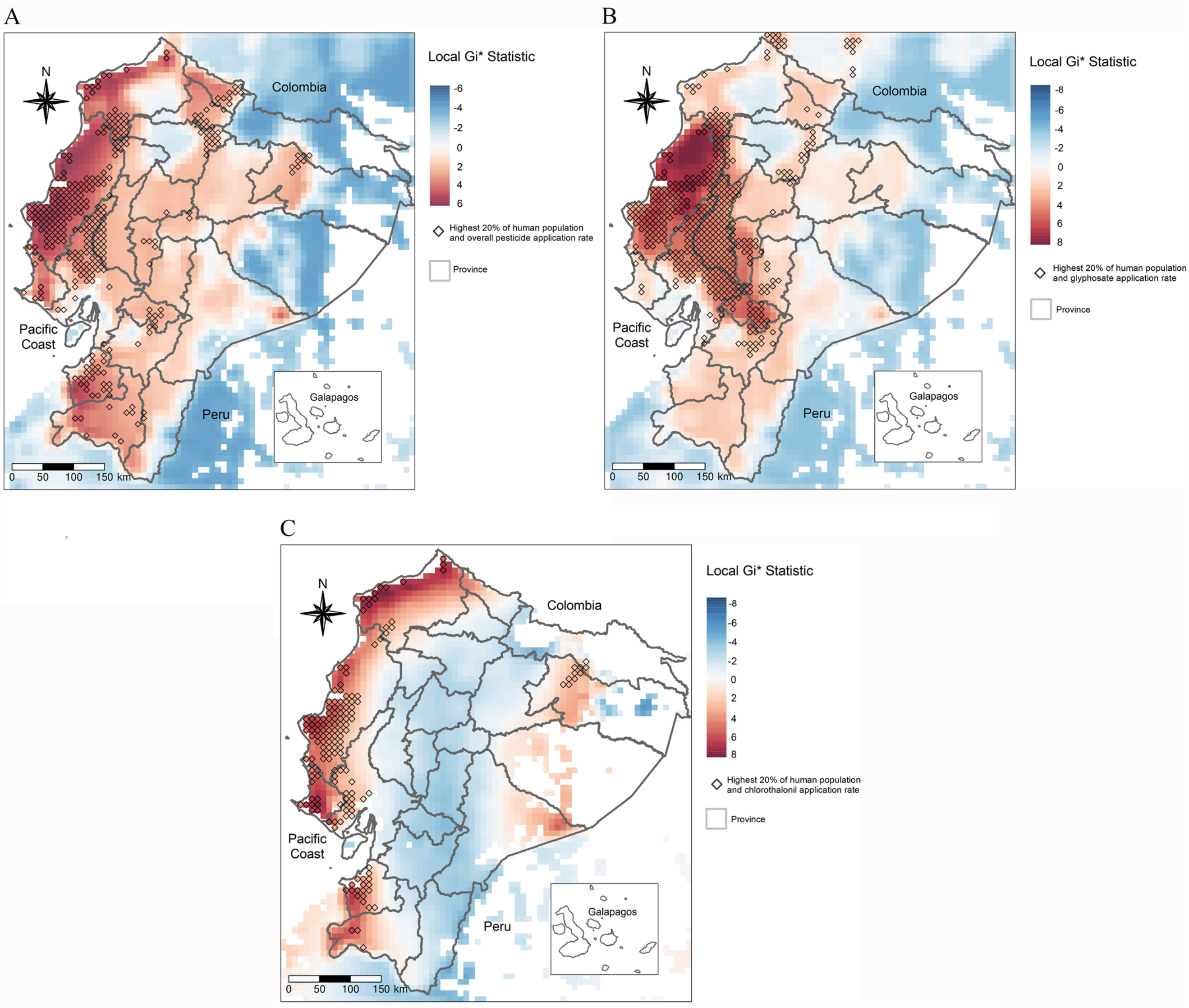

Figure 4. (a) Getis-Ord Gi* statistic for overall pesticide application rates. Diamonds indicate areas where the highest 20% of human population density and the highest 20% of pesticide application rates overlap; (b) Getis-Ord Gi* statistic for glyphosate application rates. Diamonds indicate areas where the highest 20% of human population density and the highest 20% of pesticide application rates overlap; (c) Getis-Ord Gi* statistic for chlorothalonil application rates. Diamonds indicate areas where the highest 20% of human population density and the highest 20% of pesticide application rates overlap. Note: The Getis-Ord Gi* statistic *z*-score provides information on the intensity of the data clustering. Statistical significance was set to 99.9% for pesticide application rates hotspots (*z*-score > 3.29). Application rates were not available for the Galapagos Province.

recent studies have examined hotspots where pesticide use and species richness overlap both at the state level in the United States and globally (K. Larsen et al., 2020; Tang et al., 2021). Our approach adds to the current literature by focusing on a middle-income country, while including analyses that account for potential exposures to human populations, vulnerable ecosystems, and animal species. Previous studies examining human population exposures were based on state-level use data (VoPham et al., 2015; Wan, 2015) or used the United States pesticide application rates as a proxy (K. Larsen et al., 2020). Our study relied on the recent development of pesticide application rate estimates that were validated with global and country-specific data (Maggi et al., 2019). Moreover, our analysis for Ecuador used continuous pesticide application rates data not bounded to administrative units, in contrast to a prior assessment conducted in Canada where potential exposure was calculated per census subdivision ($n = 5{,}054$) (K. Larsen et al., 2020). In addition, this study adds to previous approaches the flexibility of using exclusively global databases and open-source software, facilitating reproducing population-level assessments of potential pesticide exposures across the world, including in areas with limited resources.

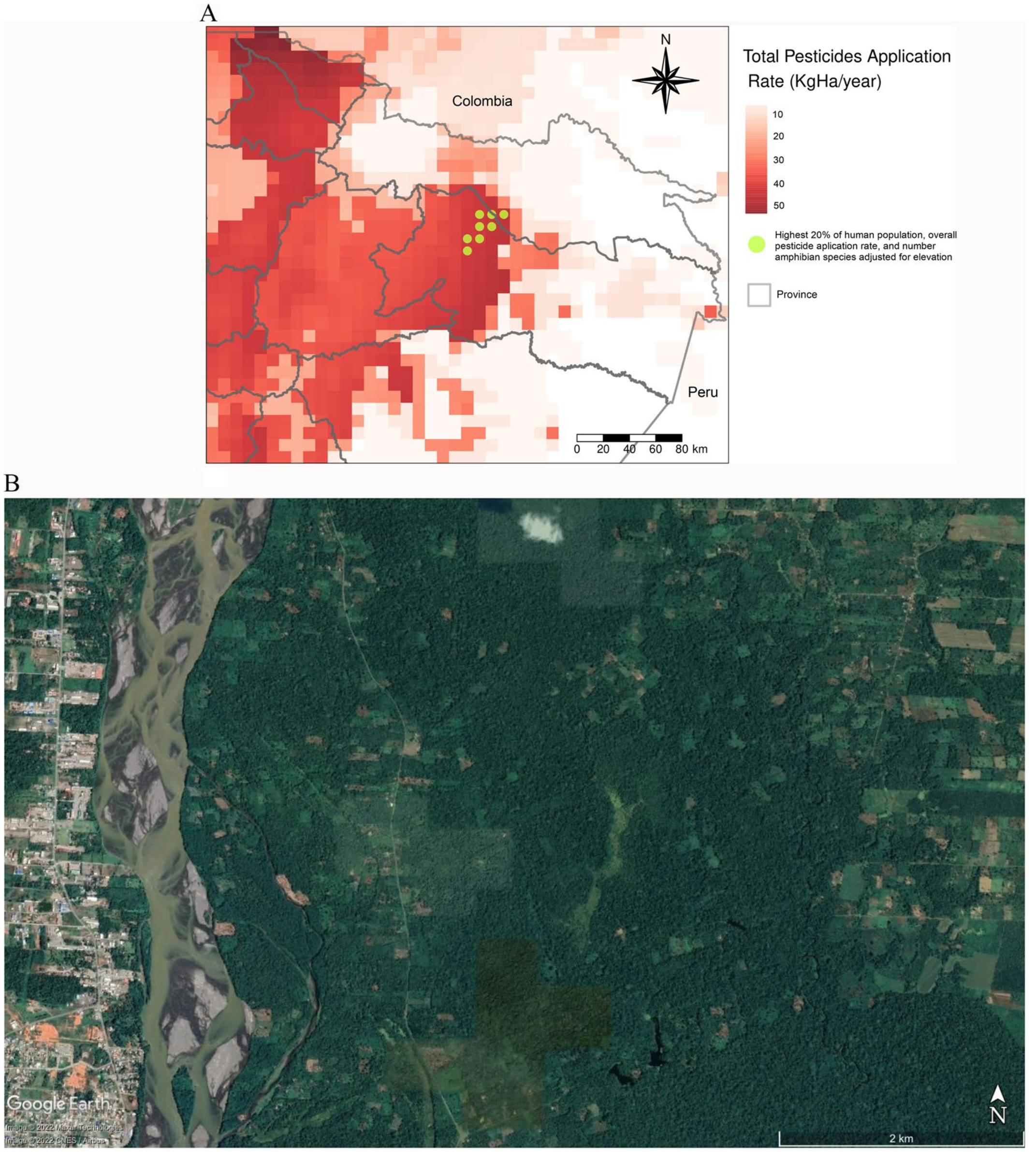

Figure 5. (a) Overall pesticide application rates in Ecuador. Data were extracted from PEST-CHEMGRIDSv1 (~8 km resolution at the equator) for the year 2015. Dotted areas indicate where the highest 20% application rates, highest 20% population density, and the highest 20% number of amphibian species adjusted for elevation overlapped; (b) Satellite image illustrating part of one of the eight 8 km × 8 km where the highest 20% application rates, highest 20% population density, and the highest 20% number of amphibian species adjusted for elevation overlapped. Note: CNES/Airbus image extracted from Google Earth v. 7.3.4 for 20 September 2018. Geographic coordinates: 0°24′36.07″S, 76°57′33.37″W. Eye altitude: 8.4 km.

Based on the Gi* statistic results, we found that most areas with high application rates for the three types of pesticides studied were spatially clustered, that is, not randomly distributed. The spatial distribution of individual pesticides does not necessarily follow the same pattern as the sum of all pesticides, but is dependent on the specific type. Due to the range of toxicity levels of pesticides and their different effects on the health of humans and the environment, our analysis highlights the importance of disaggregated information on different types of pesticides to prioritize areas for further exposure assessments. The types of crops partly determine the type of pesticide and rates used. Although PEST-CHEMGRIDSv1 estimates offer application rates for some individual crops (i.e., corn, soybean, wheat, cotton, rice, alfalfa), major Ecuadorian agricultural products such as banana, flowers, and cacao are aggregated into broad groups. However, we observed that areas with high application rates varied geographically and corresponded to regions dedicated to different agricultural products. This suggests that

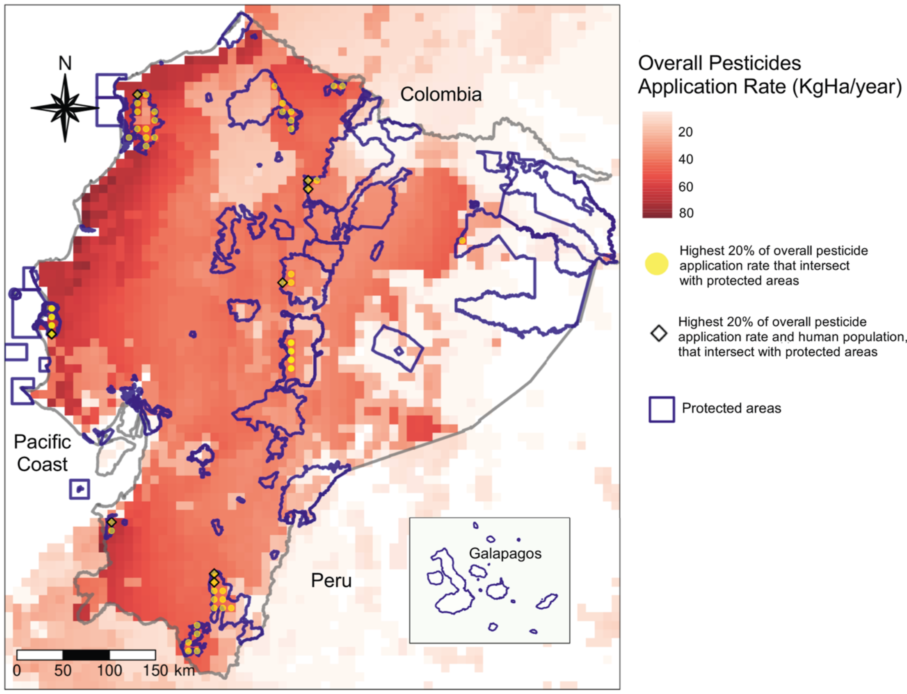

Figure 6. Overall pesticide application rates in Ecuador. Data were extracted from PEST-CHEMGRIDSv1 (~8 km resolution at the equator) for the year 2015. Dotted areas indicate where the highest 20% application rates, and highest 20% population density overlapped. Diamonds indicate areas where the highest 20% of human population density and the highest 20% of pesticide application rates intersect with protected areas. Note: Application rates were not available for the Galapagos Province.

the widespread use of pesticides and areas classified as having high application rates in Ecuador are associated with several agricultural industries and cannot directly be attributed to a single product. Disaggregated data on application rates for major Ecuadorian crops could better support targeted interventions or policies to control pesticide exposures that account for practices associated with specific agricultural industries.

Application rates were particularly high in the coastal provinces where export-bound bananas, oil palms, rice, sugar cane, and cacao are cultivated (INEC, 2021). Our results align with previous research raising concerns about pesticide contamination in this region. Widespread contamination has been previously reported in Guayas province, where pesticide residues were linked to industrial agricultural activity, mainly banana and rice, in the Guayas River basin (Deknock et al., 2019). Moreover, two other river basins in this region were identified in previous studies as areas of significant concern globally based on pesticide pollution risk, water scarcity, and biodiversity threats (Tang et al., 2021). The contamination of water environments on the Coast is concerning, as these provinces are leading producers of farmed shrimp which could be exposed to pesticide residues and lead to bioaccumulation. Contamination of shrimp aquaculture systems with pesticides from agricultural production has been previously reported (Braun et al., 2019; Khatun et al., 2020). Some argue that the availability of pesticide residues in shrimp farm water does not necessarily translate to widespread bioaccumulation in shrimp tissue (Boyd et al., 2021). However, assessments of shrimp bioaccumulation in Ecuador are limited, and further attention to potential cross-contamination of local human populations and mangrove ecosystems are needed.

The results of pesticide application rates per province (Table 2) provide valuable insights for national and regional policymakers and resource allocation strategies aligned with relevant administrative units within the country. For example, there is limited research on pesticide exposure in Manabí Province, and most studies are focused on the central and southern Coast (Calderón Rios & Sarango Flores, 2015; Deknock et al., 2019; Hutter et al., 2020). However, our results showed exceptionally high pesticide use rates and populations at risk on the northern Coast and prior studies documented elevated acute occupational poisoning in Manabi (Andino Padilla, 2021; Solís Gordon, 2021). This evidence should translate into detailed local assessments and interventions to reduce exposures. In addition, descriptive statistics of pesticide distribution and populations at risk at the provincial level must be paired with a broader holistic understanding that also considers ecosystem distribution and watersheds. Agricultural land distribution and chemical use intensity are not limited to provincial or national borders and respond to other dynamics such as available land, geographical characteristics (e.g., river basins), and socioeconomic factors (Maggi et al., 2019). Moreover, small areas within provinces with a relatively low mean application rate may be relevant due to potential exposure to human populations and natural ecosystems, as in areas with high application rates located in the Amazon provinces (Figures 5a and 6).

To our knowledge, only one other study has examined the national-level proportion of people living in areas of high pesticide use, and this was conducted in Canada (K. Larsen et al., 2020). We calculated that the proportion of people in Ecuador living in areas with high glyphosate use was ~30%, five times more than in Canada. For Chlorothalonil, about 18% of the population of Ecuador lived in areas of high use compared to 5% in Canada. In addition to having a larger proportion of people exposed to the highest quantile of pesticide use compared to Canada, Ecuador also has a higher rate of overall pesticide use per cropland area. These alarming comparisons must also account for the likely reduced capacity of LMICs to control, regulate, and monitor chemical contamination, and the limitations of disease surveillance systems in these countries (González-Andrade & López-Pulles, 2012; Naidoo et al., 2010; Ngowi et al., 2020). Although the application of pesticides does require human activity, and this partly explains that human populations are found in agricultural areas, the association between agricultural areas and human density likely varies across countries depending on the social and environmental context and the agricultural practices and technologies implemented.

Our results showed that the estimated human populations (i.e., total, females between 20 and 29 years of age, and children under five) living in areas with high pesticide application rates increased over time. This trend is due mainly to predicted population growth, but other factors could influence changes in the proportion of human populations living in areas with high application rates, such as internal migration and changes in agricultural practices. However, there has been a drastic reduction in internal migration in Ecuador, and this factor may not have a large effect in this case. Further analyses are needed to assess the factors influencing the estimated increase in population living in high-risk areas beyond population growth.

One relatively large region along the central Coast raised particular concerns as we found an overlap between high application rates for all pesticides analyzed and high population counts. Depending on the pesticide analyzed, different regions on the Coast region were identified, and together they covered a large proportion of the coastal territory (Figure 3). The large population potentially exposed to pesticides in the Coast region, together with previous studies confirming widespread pesticide pollution in several rivers' watersheds (Deknock et al., 2019; Tang et al., 2021), highlight the urgency of local exposure assessments and control strategies to prevent impact on human health and the environment. In addition, export-bound banana production dominates the agricultural sector in several regions of the Coast, and accumulation of pesticide residues from these plantations has been documented (Deknock et al., 2019). This raises concerns, as previous studies conducted in Ecuador have shown that environmental exposures to pesticides from banana plantations have a negative effect on birth weight (Calzada et al., 2021) and are linked to indicators of genotoxicity in farmers (Hutter et al., 2020).

Other relatively large areas of concern were identified in the northern part of the Inter-Andean region and the central part of the country in the Coast and Inter-Andean regions (the latter exclusively for glyphosate). The province of Pichincha (northern Inter-Andean region) contains the sixth-largest agricultural land in the country, and its main products are palm oil and cut flowers (INEC, 2021). Most of the export-bound cut-flower production in Ecuador comes from this region, where 60%–70% of the workforce is female, many of childbearing age (Handal & Harlow, 2009; Handal et al., 2016). Previous research in the region has confirmed the exposure of children to pesticides due to agricultural drift from flower plantations and parental occupational residues, which has negative neurobehavioural and physiological impacts in young adolescents and children (Friedman et al., 2020; Suarez-Lopez et al., 2017, 2019).

Our results showed other scattered areas of concern across the country that warrant further analysis. For example, an area in the northern Amazon region presented high application rates of all pesticides and chlorothalonil overlapping with human populations. Despite a relatively low population density, Ecuador's Amazonian provinces are home to a vast diversity of human populations (e.g., Indigenous Peoples), ecosystems, wildlife, and plants, which are important reasons to consider further localized contamination assessments. Beyond the direct negative impacts of pesticide pollution on human and wildlife health, ecosystems provide wellbeing and economic development to Ecuador, and contamination may affect their integrity. For example, it has been shown that the decline of amphibian abundance is linked to an increased incidence of vector-borne infectious diseases (Springborn et al., 2022). Amphibian species prey on insect vectors, contributing to regulating the transmission of infectious diseases, which are a major public health concern in Ecuador.

Moreover, we identified an area of concern of 512 km^2 in the watershed of the Napo River, one of the main tributaries of the Amazon River, located in the Orellana Province. In this area, we observed high application rates, large population density, and a high number of amphibian species. As an illustrative example, a satellite image of one of the pixels identified shows that several land cover types (e.g., urban, forest, water) are mixed with agricultural land, which indicates the close proximity of the source of contamination and populations and ecosystems at risk (Figure 5b). This spatial configuration suggests the need for localized pesticide exposure assessments to inform intervention and controls.

We identified several natural protected areas that intersect with pixels with the highest pesticide application rates. This included the Sangay National Park, located in the central part of the country across the Inter-Andean and Amazon regions, which is also designated as a UNESCO Natural World Heritage Site as it contains one of the world's most complex series of ecological habitats (UNEP-WCMC, 2022). In addition, some of these areas of concern also present a high density of human populations, creating a potential threat to both ecosystems' integrity and human health. This can particularly affect populations that rely directly upon harvesting natural areas (e.g., Indigenous Peoples) and may also face the secondary effects of pollution on the integrity of their supporting ecosystems (e.g., biodiversity loss, wildlife population decline).

Altogether, our findings highlight the urgency for regional and local pesticide exposure assessments that account for local use practices while expanding the analysis to include social and environmental factors that influence pesticide exposures (e.g., socioeconomic status and climate conditions). Beyond informing preventive isolated practices to reduce exposures at the local level, these assessments should be considered collectively to impact policies and strategies at broader scales that target structural drivers of intensive pesticide use and widespread high risk of exposures in Ecuador.

4.1. Limitations and Strengths

This study has several limitations that should be considered when interpreting our results. Due to the relatively coarse resolution of the PEST-CHEMGRIDSv1 application rates, the distances between the sources of contamination and the population, ecosystems, or organisms at risk within identified pixels may exceed the distance of agricultural drift. On the other hand, our analysis could miss areas with a relatively low population density but still at high risk of pesticide exposure due to their proximity to agricultural areas and potential occupational safety issues. Moreover, pesticide exposure pathways are varied, and this study exclusively focused on potential environmental exposures due to living in proximity to agricultural areas. In addition, PEST-CHEMGRIDSv1 estimates were based on international data on pesticide use practices and crops that may not fully characterize the contamination in Ecuador. Nonetheless, these pesticide use rates accounted for local environmental and social variables and were validated using comprehensive information on the total mass of pesticides per country (Maggi et al., 2019).

Finally, biodiversity and ecosystem integrity indicators to identify areas of convergence of public health and environmental threat need to be further developed in future studies. For example, the IUCN layer of amphibian species richness could be refined by using land cover and ecosystems distribution from remotely sensed data (Ocampo-Peñuela et al., 2016) and including other animal classes (e.g., mammals and birds). Note that pesticide application rates were not available for the province of Galapagos. This region warrants exposure assessments due to its great environmental value worldwide and previous reports of pesticide residues from local crops, including banned pesticides (Riascos-Flores et al., 2021).

Despite these limitations, our study has several strengths and provides an accessible and reproducible methodology for assessing pesticide exposure risk. We relied on publicly available global databases and open-source software. This makes our approach readily available to assess risk in countries or regions where detailed high-resolution pesticide use data is lacking. This is particularly important in countries like Ecuador, where there is an urgency for further assessments and strategies to prioritize actions to reduce exposures while dealing with limited national-scale pesticide use data. Our approach can be adapted to account for additional data that responds to local priorities and criteria to assess potential pesticide exposures. Moreover, the databases used are not restricted to administrative boundaries, allowing for analyses at multiple spatial scales that account for factors that are not bounded to national or regional sociopolitical boundaries.

The results of this study should not be interpreted as an exact exposure assessment but as a strategy to further identify, categorize, and prioritize regions where the potential of harmful exposures to large populations is high.

5. Conclusion

The widespread concerns raised by researchers on pesticide adverse effects contrast with the limited global information on application practices and potential contamination. Our study is a step toward understanding this planetary health threat in a country with one of the highest application rates of pesticides worldwide, an export-bound agricultural industry, a large population at risk, remarkable biodiversity and ecosystems, and a limited understanding of the nationwide extent of pesticide contamination. We found widespread and alarming intensive use of pesticides in Ecuador in regions that overlap with human populations and ecosystems at risk of exposure.

While our study focused on Ecuador, it is unlikely that the widespread risk of exposure in this country is an isolated case. Countries may have different spatial and temporal arrangements of agricultural production where human populations and natural ecosystems are at differential risk of exposure to pesticides. This study's accessible, modular, and scalable methods can be adapted to local priorities, and additional data (e.g., water scarcity, malnutrition) could be integrated to identify areas of concern based on multiple criteria.

From a health equity and environmental justice perspective, the potential exposures caused by global food systems must be included when assessing the benefits and challenges of agricultural development projects and when exploring alternative food production systems with different requirements for chemical inputs. Concerns raised about adverse pesticide effects are yet to be paired with strategies that strengthen global and national capacities to assess and control agrochemical contamination and to improve the availability, harmonization, and access to pesticide use data. Global food systems are increasingly relying on intensive agricultural practices in LMICs. Therefore, there is a need for policies that control and prevent potential transboundary pesticide pollution affecting populations and ecosystems already threatened by other social and ecological challenges.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

All the geospatial databases used in this study (i.e., PEST-CHEMGRIDSv1, GPWv4, and Global Amphibian Richness Grids Elevation, GMTED2010, and UNEP World Database on Protected Areas) are publicly available (CIESIN-Columbia University, 2018; Danielson & Gesch, 2011; IUCN & CIESIN—Columbia University, 2015; Maggi et al., 2020; UNEP-WCMC, 2022). We analyzed data using open-source software. We used the R statistical computing environment (version 4.1.1) to extract, process, analyze, and visualize all data (R Core Team, 2021). The code was developed in RStudio (version 1.4.1717). To conduct the geographical calculations, we used the *rgdal*, *rgeos*, *sp*, *sf*, and *raster* packages (Bivand et al., 2015, 2017; Hijmans & van Etten, 2016; E. J. Pebesma, 2018; E. Pebesma & Bivand, 2005). In addition, the *tidyverse* collection of packages was used for data processing and analysis (Wickham et al., 2019), and *tmap* for data visualization (Tennekes, 2018).

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