Global Pesticide Use and Trade Database (GloPUT): New estimates show pesticide use trends in low-income countries substantially underestimated

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Abstract

Assessments of pesticide impacts globally and holistic policies to address them require accurate pesticide use data, but good use data are difficult to find. For comparable estimates across countries, researchers and policy makers depend upon pesticide use data collected by the UN Food and Agriculture Organization (FAO). We analyze the FAO database and find declines in data reporting and data quality since 2007. We present a novel method that uses bilateral paired mirror trade statistics and an index of reporter reliability to add, update and/or replace data for 137 countries. The resulting Global Pesticide Use and Trade (GloPUT) database shows pesticide use in low and lower-middle income countries has been substantially underestimated. Over the last decade, global pesticide use grew 20% by volume; use in low income countries grew by 153% over the same period. GloPUT estimates more accurately reflect social science findings on recent agrichemical supply chain restructuring and agrarian development, which indicate substantial increases in pesticide use. Significant issues with data reporting and quality mean that the impacts of recent changes in pesticide production, availability and adoption were not reflected in the FAO database, and, as a result, neither are they reflected in high profile environmental assessments.

Keywords: pesticides, human-environment geography, agricultural development, environmental health, pesticide trade

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Highlights

- The accuracy of the UN Food and Agriculture Organization's (FAO) data on pesticide use used for global environmental assessments is declining
- We present improved estimates for 137 countries based on mirror trade statistics and a reporter reliability index
- Global pesticide use continues to increase, contrary to recent FAO analysis
- Recent pesticide use trends have been significantly underestimated for low and lower-middle income countries
- Revised estimates more accurately reflect social science findings on agrichemical supply chain restructuring and agrarian development

Abstract

Assessments of pesticide impacts globally and holistic policies to address them require accurate pesticide use data, but good use data are difficult to find. For comparable estimates across countries, researchers and policy makers depend upon pesticide use data collected by the UN Food and Agriculture Organization (FAO). We analyze the FAO database and find declines in data reporting and data quality since 2007. We present a novel method that uses bilateral paired mirror trade statistics and an index of reporter reliability to add, update and/or replace data for 137 countries. The resulting Global Pesticide Use and Trade (GloPUT) database shows pesticide use in low and lower-middle income countries has been substantially underestimated. Over the last decade, global pesticide use grew 20% by volume; use in low income countries grew by 153% over the same period. GloPUT estimates more accurately reflect social science findings on recent agrichemical supply chain restructuring and agrarian development, which indicate substantial increases in pesticide use. Significant issues with data reporting and quality mean that the impacts of recent changes in pesticide production, availability and adoption were not reflected in the FAO database, and, as a result, neither are they reflected in high profile environmental assessments.

Introduction

In December 2022, the UN Convention on Biological Diversity adopted the Kunming-Montreal Global Biodiversity Framework, which for the first time included a quantitative commitment on pesticide pollution. To cut the risks of pesticide pollution in half by 2030, as the conference of the parties has agreed (CBD 2022), requires knowing how much pesticide is being used, and where. Accurate use data are essential for evaluating the adverse effects of pesticides on human and ecological health, and are a key part of a holistic approach to pesticide management policies (Möhring et al. 2020; Mesnage et al. 2021). Good pesticide use data are difficult to come by, however, prompting recent calls from scientists and policy makers to improve data accuracy, availability, and spatially explicit information on product use (Mesnage et al. 2021; EU 2019).

Researchers and policy makers must rely upon the pesticide use database maintained by the UN Food and Agricultural Organization (FAO) for comparable estimates across most countries. Data for the FAO's pesticide use database are drawn from surveys completed by governments, as well as import and manufacturing data that are reported annually to the FAO statistics division and made available on their database platform, FAOSTAT. Major scientific reports and papers on regional and global biodiversity loss (IPBES 2019), global environmental change drivers (Bernhardt, Rosi, and Gessner 2017), the human right to food (UN Special Rapporteur on the Right to Food 2017), human health (Sarkar et al. 2021), and risks of atmospheric, soil, surface water, and groundwater pollution (Tang et al. 2021) all draw from this database. As we detail below, reporting to the FAO has declined overall, particularly for low- and middle-income countries, but also high-income countries with pesticide-intensive agriculture (e.g., the United States). This decline in data reporting is mirrored by a decline in data quality for a substantial number of countries. Significant issues with data reporting and quality mean that the impacts of recent changes in pesticide production, availability and adoption are not reflected in the FAO database, and, as a result, neither are they reflected in high profile environmental assessments.

In the interest of improving public global data on pesticide use, we present a novel method that combines unique data records from FAOSTAT's pesticide use database with net import data derived from multilateral trade statistics, available through the UN COMTRADE database. COMTRADE offers verification opportunities within the trade data and in relation to FAO pesticide use data. We use mirror trade statistics and an index of reporter reliability to improve the accuracy of trade data, calculate an adjusted trade balance, assess the quality of pesticide use data as recorded in FAOSTAT and ultimately correct some of the inaccuracies in the FAO database. The result, the Global Pesticide Use and Trade Database (GloPUT), offers revised estimates of pesticide use for 137 countries. We share our initial findings, including a global upward trend in pesticide use and sharply rising pesticide use trends in low and lower-middle income countries, both above FAO estimates. We discuss underlying drivers behind these increases in dialogue with the social science literature on supply chain restructuring and agrarian change, which indicates major change in pesticide production, availability, and adoption in the new millennium. Political economic dimensions shaping supply and demand may also help to explain declines in data reporting and quality in some cases. GloPUT's estimates contribute towards improving pesticide use data quality and thus policies to monitor and reduce pesticide use.

Methods: Constructing the GloPUT database

Identifying missing data and non-reporting trends in the FAOSTAT pesticide use database

Pesticide use data were downloaded in bulk from the FAOSTAT Pesticide Use database for all countries (Pesticides (Total) use) for all available years (1990-2020) in tons a.i. (see databases FAOSTAT 2023). We excluded data years from our series which fall outside the time frames countries reported to UN COMTRADE (eg: South Sudan began reporting after independence in 2011, which is the first year we utilize FAOSTAT data for the country). Pesticide use is assembled and reported to the FAO by each country using official government surveys, import statistics, manufacturing data or some combination (FAOSTAT 2020). We chose to begin our series in 1995, at which point data reporting in the FAOSTAT pesticide use database was relatively consistent and widely established. Where the FAO used linear interpolation resulting in unique values or unique calculated data, we accepted FAO calculations. When gaps appear in the pesticide use data, FAO employs either linear interpolation or carries forward or backward the value from a reported year. The latter gap filling method results in repeat values across multiple years in the data set, and the former results in repeat values at the end of data series where recent data has not been reported. Repeat values can thus be used as a proxy for non-reporting. Repeat values were coded as #N/A throughout the dataset.

Trade data availability

Trade in pesticide occurs in one of two ways: as active ingredient (e.g., glyphosate technical) or as formulated product (e.g., Round Up, or glyphosate mixed with co-formulants for end use). Active ingredients are imported as inputs for domestic formulating industries. Annual trade data are available by both value and volume in the UN COMTRADE database for formulated pesticides only. The FAO also maintains a formulated pesticide trade database sourced primarily from UN COMTRADE (FAOSTAT 2021). With the exception of active ingredients that fall under the Rotterdam and Stockholm conventions, trade in active ingredients cannot be tracked because no dedicated categories exist for them (e.g., glyphosate technical is recorded within the general category “Organic chemicals: other organo-inorganic compounds”).

Pesticide trade data remains a powerful tool to supplement for gaps in country reporting of pesticide use data, and is often used by governments to estimate total national pesticide use. Data on imports of formulated pesticide in particular is occasionally used as a proxy for use in the FAOSTAT pesticides use database (FAO 2022a). Our method follows that of FAO in using trade in formulated products as a proxy for use when appropriate, but uses advanced trade data methods to address problems in the trade data before using the series to complement, verify, correct, or replace FAO pesticide use data.

Producing adjusted net import volumes using self and mirror trade reports

Data were downloaded from the UN COMTRADE database API for all trade partners in the years 1990-2020 for the HS code 3808, corresponding to trade in formulated product of all pesticide, insecticide, herbicide, rodenticide, fungicide and like products by value (nominal USD) and volume (kilograms, COMTRADE 2022).[a] Not every country reports every year to COMTRADE and there is significantly more data by value than volume in COMTRADE as a whole. Where trade data for a given country and year were available in value but not volume, the nearest available unit value (UV) -- the nearest available ratio of trade value to trade volume (quantity) -- was used to impute volumes from value (see FAO 2022a). This allowed significant gap filling in the volume data set. In addition, where a country reported pesticide trade neither in value nor volume, gaps in the data with volume reports on both sides of the data gap were filled with linear interpolation. Periods at the beginning and ends of the series' where there was no reporting remained unfilled by linear interpolation.

Partner reporting of imports and exports was used to create a mirror database of pesticide trade volumes. Mirror trade analysis is a common technique in trade statistics that takes advantage of the double accounting of each trade flow, reported by the exporter and the importer. FAO does not presently use mirror data to complement self-reported data. Reconciling mirror statistics for value must account for the gap between import values, reported as the cost, insurance and freight (CIF) price, and export values, reported as the free on board (FOB) price. But discrepancies exist for other reasons as well. Mismatches between self-reported and mirror trade data may arise due to different accounting and reporting procedures across countries, re-exports through transshipment ports, mistakes in product classification, and complexities stemming from ever more complex commodity chains (Linsi and Mügge 2019). Self-reported exports are generally higher than those recorded by importing partners because exports may be sent to non-reporters and also transshipped. In our mirror database, partners that were not also reporters were filtered out.[b] International agencies discourage mixing mirror and self-reported data in the same series because of these discrepancies (World Bank 2010). Self-reports on imports are generally more accurate since duties are applied to imports. A significant strength of our use of mirror data is that our mirror database is constructed using the sum of all bilateral pesticide trade flows reported by partners for a given country's export or import (thus minimizing reporting errors) and we exclusively use volume quantities, not value (thus eliminating the need to reconcile FOB and CIF values).

We used the pesticide trade mirror database in two ways. First, mirror import and export data closely tracks self-reported data. Therefore, where there were missing data on volume in the head or tail of the self-reported data series preventing meaningful linear interpolation, the annual rate of change in mirror exports (or imports) was applied to the missing data series in

[a] Exports include re-exports, or goods of foreign origin that are not transformed in the country recording the export. Re-exports for 3808 represented just 1% of the total for all data years and were therefore not removed. Imports include re-imports, items returned to the exporting country, for example, due to a defect or non-payment. Re-imports for 3808 were negligible and not removed from the dataset.

[b] This includes the following partners: Areas, nes; Bunkers; CACM, nes; Caribbean, nes; Europe, nes; Free Zones; LAIA, nes; Neutral Zone; North America & Central America, nes; Northern Africa, nes; Oceania, nes; Other Africa, nes; Other Europe, nes; Rest of America, nes; Special Categories; Western Asia, nes; World.

self-reported exports (or imports) to impute volume data for missing years (see Figure 1 for an illustration of our gap filling method).

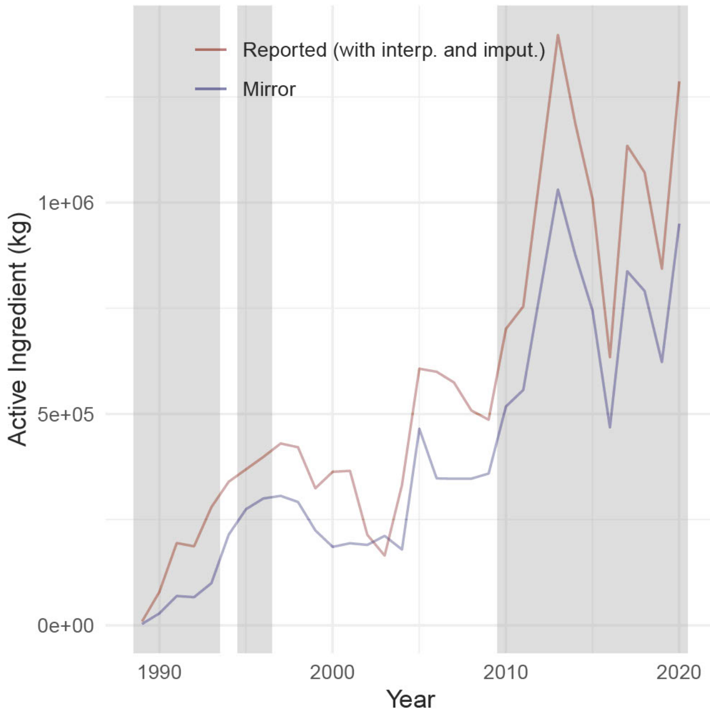

Figure 1: Example of gap filling methods for UN COMTRADE data. Self-reported and mirror imports of formulated pesticides in kg of active ingredient for Gabon. Years Gabon did not report to COMTRADE in the self-reported series are demarcated by shaded regions. Missing data in the head and tail of the self-reported series were filled by applying the annual rate of change from the closest available year in the mirror series. The gap in the self-reported series in 1995 and 1996 was filled by linear interpolation.

Second, where reporters were deemed to be unreliable, we substituted the entire self-reported series for the mirror data series. To determine reliability, we used an index for trade reporter reliability developed by the French economic research institute CEPII for their BACI database (BACI 2022). BACI uses a unique method to reconcile self-reported and mirror data reported in COMTRADE and calculates a reliability index based on a statistical analysis of the “reporting distance” between these reconciled trade values (Gaulier and Zignago 2009). Self-reported trade data for countries in the bottom quartile of corresponding BACI reporter reliability scores for importer and exporter volumes were deemed unreliable and the whole series was replaced with the mirror trade data series. In our dataset, 51 countries fell within the bottom quartile for export volumes (>1.035) and import volumes (>1.474).

Trade balances were calculated by subtracting export volumes from import volumes; a negative trade balance indicates net exports. Trade balance data were smoothed with a three-year running average to account for fluctuations attributed to stock-holding - when a large volume of pesticide purchased one year is stored to be used another year, seasonal events, and agricultural production calendars. Trade balance data for 2019 was smoothed with an average of 2018 and 2019 data due to a COVID-19 driven boom in 2020 in trade in disinfectants destined to both agricultural and non-agricultural use which is included in the HS 3808 category in COMTRADE (FAO 2022b). Finally, net imports were converted from formulated product to active ingredient using the global conversion factor for generic pesticide (.36 kg of a.i. to 1kg of formulated product) given by the FAO as discussed below.

Converting trade in formulated product to tons a.i.

The UN FAO collects data on pesticide use in tons of active ingredient of herbicide, insecticide, fungicide, rodenticide and other categories (FAOSTAT 2020). To convert data reported as formulated product to tons of a.i., the FAO uses average conversion factors by pesticide category, calculates yearly national average product mixes, and projects the average rate of change in that mix forward (FAO 2022a; FAOSTAT 2020). Given significant uneven reporting of specific pesticide classes in FAOSTAT, GloPUT focuses solely on aggregate pesticide use. This precluded the adoption of the FAO's formula for converting reports in formulated product from trade data to active ingredient, which utilizes information on the relative mix of insecticides, fungicides, herbicides and others, each with a unique conversion factor. We instead adopted the FAO's generic average conversion factor of .36 tons of a.i. to one ton of formulated product for all pesticide use totals (FAO 2022a). This global conversion factor is computed by the FAO based on a group of countries that report data in both active ingredients and formulated products (FAO 2022a). The FAO uses the standard global conversion factor when it is not possible to use conversion factors by pesticide class (FAOSTAT 2020).

Conversion factor robustness check and uncertainties

Our decision to limit GloPUT to total pesticide use estimates and not pesticide class estimates stems from clear limitations in the existing FAO database. Country-specific conversion factors would assume that the product mix is reported, the reports are accurate, and the past predicts future product mixes through substantial data gaps. We note below our findings on data reporting through an analysis of repeat data. Data accuracy is also a significant issue, with countries reporting pesticide use volumes sometimes an order of magnitude lower than their net imports. Product mix projections based on historical patterns for data series with large missing sequences may be inaccurate. The documented rapid uptake of herbicides since the mid-2000s in countries as diverse as China, India, Ethiopia and Mali (Haggblade et al. 2017), for example, means that herbicides have become a more important part of overall product mixes over time. This occurred disproportionately during the period when FAO data quality declined. Given long pesticide use data series with no reporting during which key changes occurred in both industry and agricultural systems, potential reliability issues with existing data, and changes in product mixes over time, we chose to adopt the single, empirically derived conversion factor. This is one key limitation of this study, in that it cannot track changes in product mix. This likely causes our data to underestimate pesticide use variability over the study time series, while nonetheless offering an important corrective to the existing data.

To check the potential skew attributable to our method, pesticide use in kg formulated product was calculated for 2019 (as reported to FAO in tons a.i.), using individual conversion factors for reported product mixes for each country and compared to values using the general conversion factor. The mean ratio of values using individual conversion factors to the values using a general conversion factor was .947, indicating that the standard conversion factor offers a reasonable proxy at the global level. Using a single standard conversion factor, as we do, likely underestimates pesticide use for countries that use more fungicides (which are 60% active ingredient on average) than other products, as is the case in Bangladesh and Algeria (FAO 2022). It may slightly overestimate for countries whose product mix is predominantly herbicide like Argentina: conversion factors would be 2% lower if all pesticides used were herbicide, and 5% lower if all were insecticide (FAO 2022a). In the absence of reliable, consistent pesticide use data that include product mixes, however, the FAO's empirically derived average global conversion factor is the most accurate figure available.

Evaluating FAOSTAT data quality using adjusted net import volumes

In GloPUT, we use calculated net import volumes as described above for every country and every year to identify and remedy low quality or missing data in the FAOSTAT pesticide use database. We calculated a ratio of net imports to pesticide use for each country and each year in tons of active ingredient to assess data quality. We then created systematic criteria to categorize, or bin, countries based on the completeness and quality of their data (see Figure 2). Data series for countries that met the criteria for inclusion in a given bin were treated uniformly. An important conceptual consideration in our method was the pesticide "commodity chain" or supply chain, and the position of different countries in that process. As we have noted, with the exception of a small number of highly hazardous pesticides regulated through the Rotterdam and Stockholm conventions and insignificant in terms of trade volume, COMTRADE measures pesticide trade in formulated product only. Pesticide use that originates from active ingredient either sourced in country or imported for domestic formulation will not be reflected in pesticide trade statistics but should be evident in reliable pesticide use reports. Thus, comparisons of net import trade balances with pesticide use can offer important insights into the presence of domestic formulation. A country with net imports that significantly exceed the pesticide use reported in FAOSTAT indicates poor reporting quality.

Our first criteria to determine treatment of the FAOSTAT data set was whether a given country series was complete. Our second criteria to determine how to treat a given series was whether or not the country was a net importer of formulated pesticides. We defined net importers as countries with a net import trade balance in formulated pesticides by volume for a majority of data years and/or not a net exporter for all of the last five years (2015-2019). This criterion put added weight on the trade balance on the tail of our series because a number of middle-income countries have become net exporters in the 2010s precisely reflecting the political economic dynamics we have explored elsewhere in our research (e.g., Costa Rica) (Castro-Vargas and Werner 2022). Data series for net exporters was left unaltered.

We coded a decision tree to evaluate FAOSTAT pesticide use records against our calculations of trade balance volumes using use:trade balance ratios for net importers. We established a test threshold ratio of .75 use:trade balance to indicate when a given FAO pesticide use record might be unreliable. Comparing pesticide trade and use can introduce some uncertainties. Annual figures for formulated pesticide trade volumes can be higher than pesticide use because they include non-agricultural uses such as lawn care, public health, or storage for future use.

Non-agricultural herbicide sales were less than 5% globally, driven by residential and commercial use in high-income countries (Passport Industrial 2016). Estimates of non-agricultural pesticide use for low- and middle-income countries are unavailable but are likely far less. While trade balance figures take into account pesticides that are imported and then exported legally to neighboring countries, annual net import figures can overestimate domestic use if illicit pesticide trade to neighboring countries is significant. Changes in the mix of products used (e.g., fungicide v herbicides) and thus conversion factors between a.i. and formulated products, could explain some amount of difference between a valid FAO pesticide use volume that appears to be below the net import volume, as could our method of smoothing for interannual variability in the COMTRADE data. Because use of domestically formulated products does not show up in trade data, net imports likely represent an underestimate for many countries, even where GloPUT data is significantly higher than FAOSTAT. The .75 ratio was thus selected inductively to present a conservative test of FAO data quality and preserve as much data reported to the FAO as reasonable.

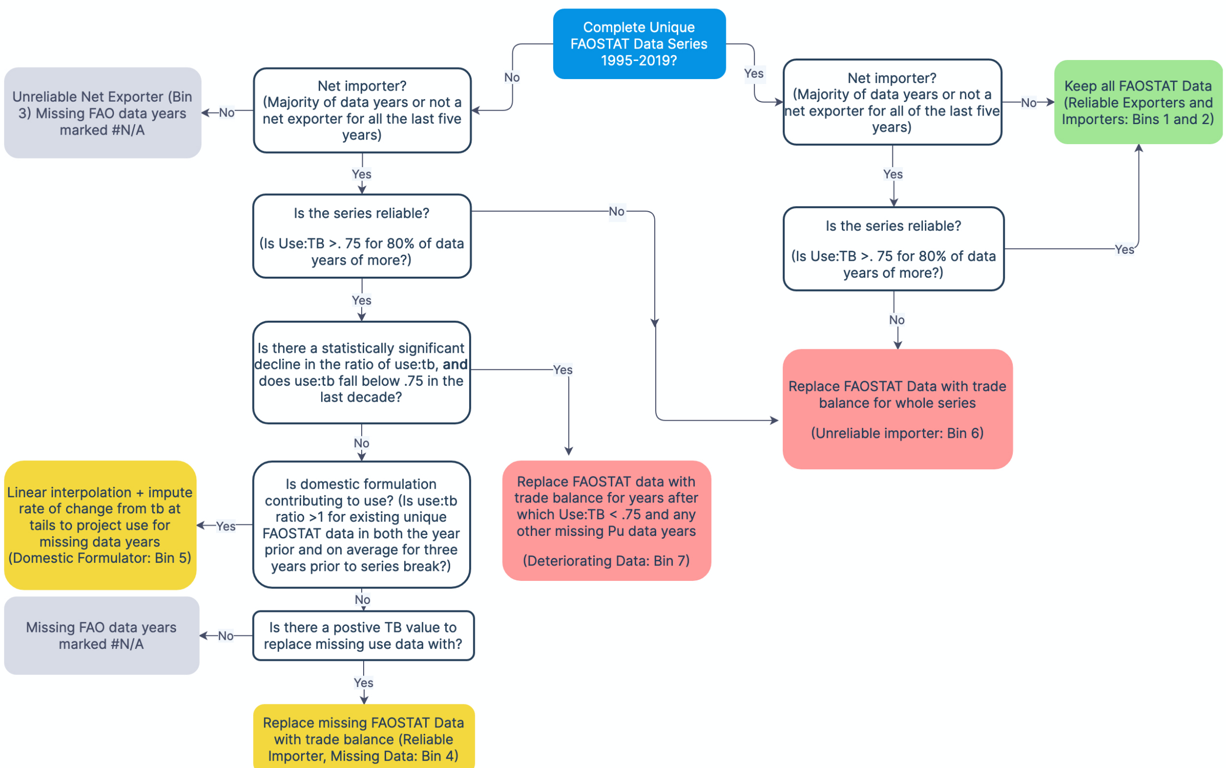

Figure 2: Decision tree for determining accuracy and treatment of FAOSTAT pesticide use data

For data series in which 80% of the use records were either repeat values or the use:trade balance ratio was <.75, the entire FAOSTAT pesticide use data series was replaced with trade balance data. To determine this threshold, we plotted all missing data years for all countries, identifying a cluster of countries with 76% and 80% missing or invalid data across the series. We chose to set the threshold at 80% as a more conservative choice to preserve more FAO data.

Because unique data reporting began to decline in the late 2000s, we tested our data series to determine if the quality of reports also began to decline during this time. For net importers we coded a test for statistically significant decline in the use to trade balance ratio for a country data series over the series as a whole. Where there was statistically significant decline and the use:trade balance ratio dropped below .75 in the last ten years, we replaced FAO pesticide use data with trade balance forward and backward to the last value that exceeded the .75 reliability threshold. This applied to nine country data series. This assumes for some countries that domestic industry disappeared during this time, which may cause underestimation. This method therefore provides a conservative correction.

Net importers where the use:trade balance ratio was greater than 1 were determined to have a domestic formulation industry contributing to supply for domestic pesticide use. Where a domestic formulator had missing pesticide use data, we used linear interpolation of existing FAO use data to fill in data gaps. Where missing data came at one end of a data series and linear interpolation would thus carry forward or backward repeat values, we imputed values assuming the ratio of domestic formulation to imported formulated products contributing to national pesticide use remains constant. Ratios are linearized and a three-year average of the net imports for the values adjacent to the data gap is calculated and used to impute missing data. For example, Brazil last reported unique data to the FAO in 2016, when pesticide use was reported as 3.96 times net imports in formulated products. Data gaps for Brazil were filled for 2017-2018 using an average of the use:trade balance ratio for 2014-2016.

Where net importers had additional missing data not covered by one of these gap-filling methods, remaining missing data were filled in with trade balance. Because trade data are available for more countries than use data, the final database covers 216 countries. The number of countries in each bin are shown in Figure 3.

Category	**Bin**	**Number of Countries**	**Treatment**
Complete, reliable net exporter	1	17	Use existing FAO data series
Complete, reliable net importer	2	38	Use existing FAO data series
Net exporter with missing FAO data	3	24	Missing FAO data years marked #N/A, data unaltered
Reliable net importer with missing FAO data	4	7	Replace missing/repeat FAO data with net imports
Domestic formulator with missing FAO data	5	27	Linear interpolation + impute missing/repeat values at end of a data series by projecting forward last known ratio of domestic production to use
Unreliable net importer	6	94	Replace entire FAO data series with net imports, create series for 20 countries not in FAOSTAT
Net importer with statistically significant deteriorating data quality	7	9	Replace FAO data with net imports for years after reliability threshold

Figure 3: Country data series in each treatment category

GloPUT replaces all or part of the FAO data series for 47.8% of high-income countries, 62.2% of upper middle-income countries (UMICs), 78% of lower-middle income countries (LMICs), and 90% of low-income countries (LICs). These replacements include 50 of 57 African countries, 33 of 51 countries in Asia, 25 of 45 countries in the Americas, 17 of 18 in Oceania, and only 12 of 45 countries in Europe.

Data Corrections for the United States

Linear interpolation of recent missing data in FAOSTAT results in repeat values for recent years in the United States, a major producer for its domestic market and a net exporter. Trade data lend no insight on domestic pesticide use for net exporters, so the above methods are inappropriate. In the FAOSTAT database, the last unique data year for pesticide use in the U.S. is 2012, meaning the US has not officially reported pesticide use data to the FAO since that time. The US Geologic Survey (USGS) Epest database provides publicly available pesticide use volume data for the coterminous states in the United States from 1992-2019 in both low and high estimates (see databases Wieben 2021). The USGS Epest low estimate for 1992-2012 is on average 1.01% of the value in FAOSTAT. (Epest low values vary from FAOSTAT values +/- 10% in any given year throughout the series.) Importantly, USGS Epest estimates do not include Hawaii, Puerto Rico and the US Virgin Islands where pesticide use is not insignificant. Epest data are thus not directly substitutable for pesticide use data reported to FAOSTAT given its different geographic coverage and methodology. Given that Epest data cannot substitute for missing FAO data due to differing methodology and geographic coverage, we calculate the annual rate of change in the USGS Epest low data, and use it to impute missing FAOSTAT data for the data years 2013-2018.[c] Epest data for 2019 was provisional at the time of writing, and 30% lower than 2018, following a slow but steady upward trend since 2012. Given this rapid drop and missing data within the 2019 provisional estimate, we chose to exclude this data year. We thus calculate global rates of change up to 2018 to accommodate for missing data from the US in 2019.

The GloPUT database and the code used to create it in R is publicly available on the Open Science Framework https://osf.io/dyu38/?view_only=7e39ab440f104ed2b61591a086f89a0b.

Initial Results

Data quality issues and non-reporting in FAO data

The FAO Statistical Yearbook (FAO 2022c) indicates that global pesticide use has leveled off over the last decade. However, this is partially an artifact of the FAO's gap filling method and a

[c] A 2017 publication from the US EPA on pesticide sales and usage from 2008-2012 utilizes multiple data sources including the National Agricultural Statistics Service and private industry data to estimate pesticide use for the entire United States, including Puerto Rico and Hawaii. The EPA estimates for 2008-2012 are 43% higher than data reported to FAOSTAT on average. However, EPA estimates are only available for those five years. Given the wide discrepancy between the EPA's estimates and that of Epest and FAOSTAT, and the geographic limitation of the Epest database, volume data for the United States in GloPUT are likely a conservative estimate (Atwood and Paisley-Jones 2017).

lack of reporting in recent years. The FAO Pesticide Use database started in 1990. The early years saw low reporting. Of 147 countries in the database in 1991, 81 did not report. Reporting improved gradually to 51 non-reporting countries in 1995, then stayed below 50 from 1997 to 2011, when non-reporting began to increase (see Figure 4).

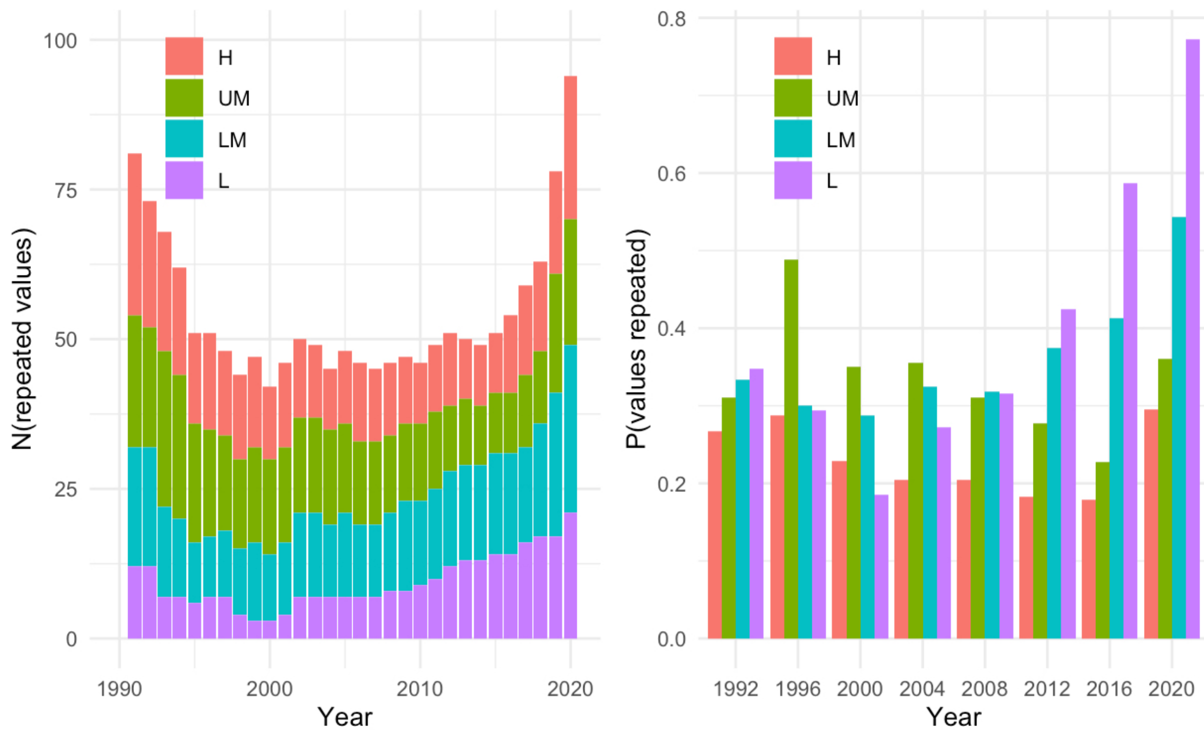

Figure 4: Trends in repeat values for total pesticide use in FAOSTAT database indicating missing data for a given year, displayed by constant 2018 World Bank income class: a) number of repeated values for high, upper-middle, lower-middle, and low-income countries, b) average percentage of repeated values for high, upper-middle, lower-middle, and low-income countries binned in four-year periods.

Lower middle income and low-income countries were more likely to have a greater number of repeat values in the data series. Between 1997 and 2009, the number of missing and repeat values was relatively stable overall. By 2020, there were 169 countries in the FAO database: more than 90% of low-income countries, 70% of lower-middle income countries, and more than 45% of upper middle-income countries had missing values. By region, countries in Africa were most likely to have a high count of repeat values. This means that net importers – those without much domestic production – were also more likely to have repeat data, although many large producing countries have not reported to the FAO for many years as well (e.g., United States and Brazil). This pattern of non-reporting introduces systematic bias in the data where pesticide use data quality is less likely to be accurate or up to date for net importing countries and lower income countries with high agricultural employment.

Rising pesticide use trends globally

Beginning in 2007, global pesticide use as calculated in the GloPUT database diverges from and exceeds estimates by the FAO, and demonstrates a steady upward global trend. Our estimates for the growth rate in global pesticide use are considerably higher than the FAO's (Figure 5, panel a). Between 2008-2018 GloPUT indicates a 20% increase in global pesticide use by volume, vs. the relative leveling off indicated by FAO This trend is confirmed when measured by use intensity, which includes areas under temporary and permanent crops as well as temporary pastures (see Schreinemachers and Tipraqsa 2012), indicating the increase is driven by intensification of use instead of expansion of agricultural production (Figure 5, panel b).

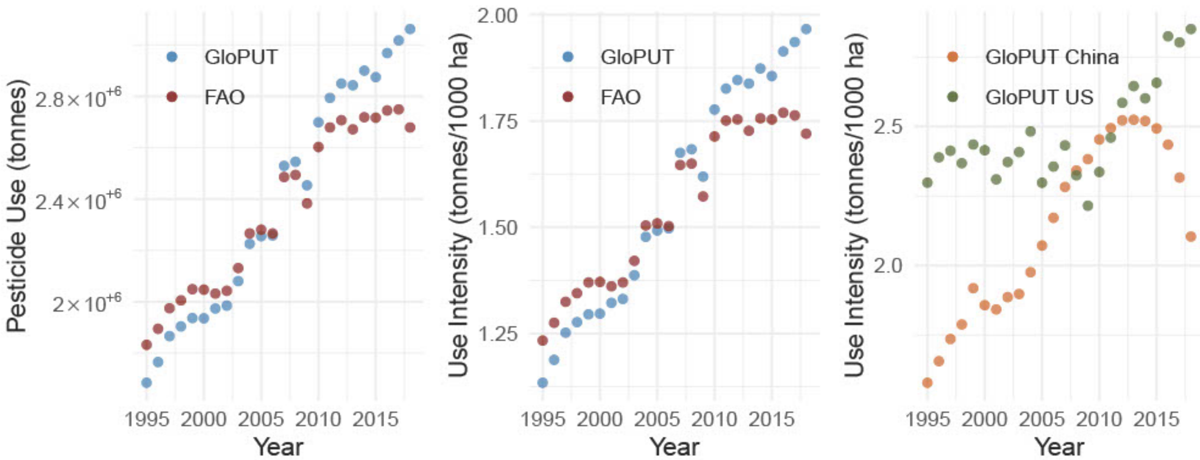

Figure 5: Trends in global pesticide use by volume in tons active ingredient (panel a) and pesticide use intensity expressed as tons active ingredient per hectare of cropland (panels b & c) in GloPUT vs FAOSTAT databases. Pesticide use intensity trends in China and the United States appear in panel (c).

Pesticide use trends underestimated in low and lower-middle income countries

The differences in pesticide use volumes reported in GloPUT are the greatest overall for low and lower-middle income countries. Growth rates in pesticide use volumes for low and lower-middle income countries between 2008-2018 are significantly higher than the FAO's estimates: 153% in low and 85.5% in lower-middle income countries in GloPUT, compared to 24.9% and 2.4% in FAO. GloPUT estimates for many country data series are likely underestimated as there is no available data on domestically formulated pesticides for countries with poor reporting to the FAO.

By income category, pesticide use intensity trends are also substantially higher in GloPUT than in FAO for LICs and LMICs, indicating again that growing volumes of pesticide use in lower income countries reflect more intensive pesticide use, rather than an expansion of the land area on which pesticides are applied.

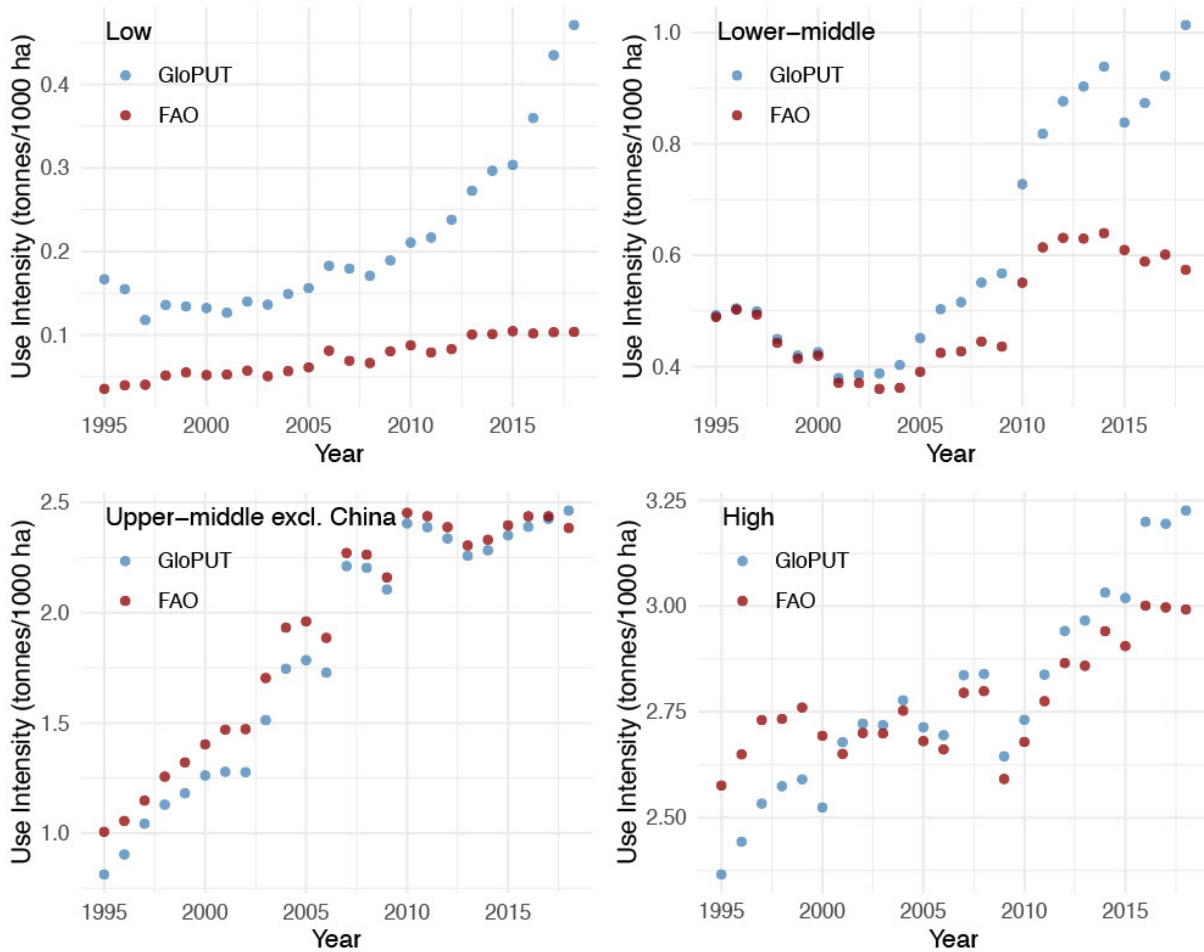

Figure 6: Pesticide use intensity by 2018 constant World Bank income class in GloPUT database vs FAOSTAT, excluding China.

Discussion

The GloPUT database presented here improves upon currently available global pesticide use data, especially for low and lower-middle income countries. Our analysis indicates current global estimates of pesticide use began undercounting volumes around 2007, which coincides with growth in the generic pesticides industry and a commodity boom in low and lower-middle income countries. In 2016, global pesticide use appears to plateau in FAO data, owing to a downward trend in pesticide use trends in China after the 2015 zero-growth in agrichemicals policy (Shuqin and Fang 2018). GloPUT indicates global pesticide use has shown no signs of a slowdown, despite the decrease in pesticide use intensity China. Below we discuss drivers of pesticide use in dialogue with the social science literature on supply chain restructuring and agrarian change, and then proceed to identify challenges of underreporting, inaccuracy, and uncertainty in relation to these drivers.

Drivers of increasing pesticide use

Country case studies indicate that massive change is afoot in the global pesticide complex (Galt 2008), that is, the dynamic interactions between pesticide production, use, regulation, and socioecological effects. Pesticide use has grown rapidly in many countries once thought to be relatively minor pesticide users like Ethiopia, Mali, and Laos (eg: Haggblade et al. 2017; Shattuck 2019). The drivers of increasing pesticide use include both supply-side factors such as the availability of lower-cost, generic pesticides, as well as changes in farming systems and rural economies that drive up pesticide demand (Shattuck 2021; Clapp 2021). To date, the drivers and effects of lower cost generics have been analyzed for herbicides (Haggblade et al. 2017). A special issue on the so-called herbicide revolution found increases of herbicides by volume since 2000 of nearly 50% in post-EU enlargement member states (Bonanno et al. 2017). Herbicide use nearly tripled in India between 2005 and 2016 (Das Gupta et al. 2017). Herbicide use intensity increased more than 6-fold in China over the same period (Huang, Wang, and Xiao 2017). Glyphosate, the world's most widely used herbicide, accelerated this trend as patent expiry lowered costs. In Argentina, for example, the price of formulated glyphosate dropped from $40 per liter in the 1980s to $10 by 1990 to $3 in the early 2000s (Trigo et al. 2003 cited in Werner, Berndt and Mansfield 2022). The total amount applied globally more than doubled between 2005 and 2014 (Benbrook 2016). New precision technologies, GE crops and other applications helped create path dependencies that "locked in" glyphosate as a key mode of weed control (Clapp 2021). With rising glyphosate use came rising weed resistance in major crop species, driving increased and diversified herbicide use (Benbrook 2016). More toxic chemicals and those prone to more drift, like 2,4-D and dicamba, are sold to farmers to deal with glyphosate-resistant weeds (Bain et al. 2017). Agrichemical firms have introduced GE crops with stacked traits to express tolerance to multiple herbicides, such as Bayer's XtendFlex soybeans with tolerance to three herbicides: glyphosate, glufosinate and dicamba.

Growing resistance and the shift towards generics were not limited to glyphosate or to herbicides. From their entry into the global market in 1991, neonicotinoids became the most used class of insecticide in the world in less than twenty years (Jeschke et al. 2011). After losing patent protections in the mid-2000s, neonicotinoid sales soared: from 2003 to 2009, sales of individual neonicotinoid insecticides increased between 1.6 and 14.6 times. (Simon-Delso et al. 2015). By 2014, neonicotinoids made up 25% of the global insecticide market, and over 500 cases of insect resistance had already been reported (Bass et al. 2015).

The pesticide industry has been transformed by a succession of mergers and acquisitions (M&As) and supply chain restructuring motivated in part by the decline in patented chemistries of major a.i.'s like glyphosate and neonicotinoids. In just eight years, from 2011 to 2019, the proportion of generic agrichemicals sold globally rose from 51 to 75% (PMD 2021). M&As and generic market increases are reflected in new geographies of outsourced production that have taken hold over the last two decades. Global supply chains offer active ingredients and formulations produced in China, India and elsewhere at lower prices to meet growing demand in much of the global South (Werner, Berndt, and Mansfield 2022; Shattuck 2021). Trade in pesticide has ballooned as a result: global imports of pesticide formulations nearly doubled in a decade and a half, from 2.5 million MT in 2005 to 4.8 million MT in 2019 (authors' analysis based on COMTRADE). Simultaneously, the regional provenance of these imports shifted over the same period: Western Europe and North America's share of exports fell from 54 to 44%, while the share from East Asia, principally China, increased from 13 to 30% (authors' analysis based on COMTRADE).

Recent studies of agrarian change indicate that higher pesticide use is linked to major social trends reconfiguring labor and knowledge in predominantly smallholder communities. Even countries where smallholder agriculture predominates, like Myanmar and Nepal, saw steep increases in overall pesticide use beginning in the late 2000s (authors' analysis of GloPUT data). Studies of agrarian change have identified drivers of increasing pesticide adoption among smallholders including circular migration, increasing feminization of agriculture, higher rural wage rates, the 'supermarket revolution', changing crop mixes for urban markets, and the replacement of effective state extension with private marketing agents (Hu and Rahman 2015; Haggblade et al 2017; Aga 2019; Stein and Luna 2021; Shattuck 2021). High commodity prices during the 2007-2008 and 2011 food crises, a boom in smallholder contract farming, and the rise of large-scale land acquisitions drove conversion of forests, pastures and peasant farms to more conventional and plantation agriculture models during this period as well (Borras et al. 2016; Borras and Franco 2012; Hurni and Fox 2018; Messerli et al. 2014). While the environmental impact of large-scale land deals and smallholder commodity booms have been debated in terms of deforestation (Liao et al. 2020; Davis et al. 2015), they likely also have had an impact on pesticide pollution and worker health and safety – impacts which are difficult to assess without quality data.

This period of transformative change in agrarian systems and the pesticide industry was not captured in FAO pesticide use data due to both underreporting overall and the poor quality of more than 100 nationally reported data series. Efforts to establish a baseline and strategy to reduce pesticide risks will have to take into account these drivers and the rapid upward trends in lower income countries.

Understanding underreporting and data quality issues

In some countries reporting has never been accurate. For example, Cote d'Ivoire last reported pesticide use to the FAO in 1996, when reported pesticide use was just 14% of its net imports of formulated pesticide, a modest increase from the 5% of net imports it reported using in 1990, suggesting consistent and significant underreporting. But the extent of underreporting was likely even more acute. A separate FAO source from 1990 estimated that as much as 80% of the pesticides used in country were formulated domestically at that time (cited in Ajayi 2020), meaning that not only did the net import balance likely reflect underreporting, but significant supply was formulated from imported active ingredient, which cannot be tracked and would not be reflected in that trade statistic. Due to consistent inaccurate reporting, GloPUT replaces the entire data series for Cote d'Ivoire with net import data. While the contribution of domestic formulation to national pesticide use is unknown at present, it is likely greater than zero given this history, meaning net import data offer a conservative estimate.

Changes in the structure of the industry may be one reason behind the recent drop in data quality in the FAO database. As the industry has shifted to a more regional production model, with local formulation of a.i. imported from China and India increasingly common in many middle-income countries (Werner, Mansfield and Berndt 2022), domestic production volumes have become more important to calculating total national pesticide use. The same firms may be involved in both domestic formulation of imported active ingredients, and trade, distribution and branding of pesticides imported as already formulated and ready to use (Werner, Mansfield and Berndt 2022). It is possible that in some places these industry changes have resulted in reduced legibility and thus, inaccurate reporting. For example, Senegal reported pesticide use greater than net imports of formulated product (and was occasionally a net exporter) in the years 1997-2010, indicating the presence of domestic formulation. In 2011, Senegal's pesticide use as reported to the FAO was 75% of the calculated net imports in formulated product. Reported pesticide use dropped to 19% of net imports in 2017, the last unique data year, indicating significant underreporting. Between 2010 and 2015 the largest pesticide producer in Senegal reduced a.i. production and formulation 80% because of environmental and regulatory issues and began importing active ingredient and formulated products from China instead (Spradley 2015). GloPUT data for Senegal uses net imports to replace FAOSTAT data from 2012-2019. Given the continued presence of some domestic formulation in Senegal (Spradley 2015), this is likely an underestimate as it does not include any pesticide imported as active ingredient. Despite not accounting for domestic formulation, the most recent pesticide use figure for Senegal is four times higher in GloPUT than FAOSTAT.

Industry changes are unlikely to explain underreporting and data quality issues in lower-income countries with no domestic formulation. Reasons for data quality issues and underreporting very likely differ by place as well. Detailed pesticide use data, including by product category, is critical for pesticide and agricultural policy development (Mesnage et al 2020). Further research to understand why reporting and data quality issues persist, and to improve pesticide use data including by product category, is urgently needed.

Limitations and uncertainty

The GloPUT database is a significant improvement on the best available data, but it too has limitations. Notably there is little difference between GloPUT and FAO estimates for upper middle-income countries. The relatively higher percentage of replaced data in LICs and LMICs reflects the lower reporting rates in those countries, and the fact that LICs and LMICs are less likely to be net exporters, thus allowing for our methods to be used to estimate pesticide use.

While our methods allow us to interpolate data gaps, we have no method to validate unique data reported to the FAO by countries with significant domestic industry. This is likely to affect UMICs more than other income groups, and may account for some of the agreement between GloPUT and FAOSTAT for these countries. For example, pesticide use in Thailand as reported to the FAO from 1995-2012 ranged from 3.5 to 1.5 times its net imports reflecting its strong domestic industry. In 2013, that ratio drops to .13 and never increases past the reliability threshold, indicating reporting was inaccurate over that period. However, since the declining trend was not statistically significant before 2013, we do not replace or impute data for Thailand. In another example, South Africa stopped reporting to the FAO in 2001, when it was a net exporter. Net import data for South Africa in 2001-2019 are highly variable and never reach the figure reported for pesticide use in 2001; there is no alternative accurate available data source. Future analyses of this dataset, depending on the research questions, may also choose to exclude some countries in this category for lack of quality data due to these issues.

The trends we outline are conservative for LMICs for many of the same reasons. Indonesia for example has not reported to the FAO since 1993. Data for Indonesia in GloPUT are sourced entirely from net imports of formulated products; by 2019 the pesticide use figure for Indonesia in GloPUT is 16x that in FAOSTAT. While more accurate than available data, the GloPUT estimate for Indonesia is also unlikely to capture actual pesticide use. After deregulation in the late 1990s, the number of companies selling local formulations of imported active ingredients proliferated (Thorburn 2015). By 2012 in one estimate, 384 companies were importing more than 50,000 tons of generic a.i. to Indonesia, none legible as pesticides in international trade statistics because a.i. cannot be disaggregated from chemical shipments writ large (Thorburn 2015). This figure alone, if accurate, is 28x higher than the GloPUT figure for 2012.

Countries with domestic industries and relatively complete data in FAOSTAT may also suffer from reliability issues which our methods cannot assess. Data included in GloPUT for India, which relies on relatively complete data as reported in FAOSTAT, officially indicated a 32% increase in herbicide use between 2006 and 2016. An analysis using multiple sources of government data found herbicide use almost tripled between 2005/2006 and 2015/2016 (Das Gupta et al. 2017), indicating there may be reliability issues for that data as well. Pesticide use trends in Colombia, a country that has reported unique data to the FAO every year, declined between 2008 and 2016 according to FAOSTAT, but a separate analysis of government data found pesticide sales by volume nearly doubled over this time (Valbuena, Cely-Santos, and Obregón 2021).

Conversion between trade data reported in formulated product and use as reported in active ingredient depends on a single conversion factor, which precludes including data on product mixes and how they change over time. This single conversion factor likely causes underestimation in tropical and other countries with high fungicide use, and slight overestimation in countries whose pesticide product mix is overwhelmingly insecticide. There are uncertainties too in interpreting the environmental and social consequences of pesticide volume data. Volumes of pesticide in aggregate alone cannot predict changes in total acute toxicity, potential long term public health consequences of exposure, or ecological impact. Some insecticide classes, such as neonicotinoids and pyrethroids, may drive pesticide use volumes lower, even while increasing impacts on pollinators and aquatic invertebrates (Schulz et al. 2021). For herbicides, in contrast, total acute toxicity to humans in the US has been decreasing while total volumes increase as glyphosate replaced more acutely toxic products (Kniss 2017). While changes in aggregate volumes are the only data available for many countries, more accurate detailed data broken down by product type could allow for more finely tuned environmental assessment.

While GloPUT significantly improves upon existing public global pesticide use data, the remaining limitations point to the need for improved data collection and reporting, as well as detailed country-based research on pesticide use, production, and trade networks, including for countries with relatively complete reporting to FAO. As we have demonstrated here, case study research can complement large-scale global databases in the continued absence of reliable and detailed data on product categories for many countries, and identify the social drivers of increasing pesticide use in each case.

Conclusions

The apparent plateauing of global rates of pesticide use identified by the FAO (2022c) does not reflect major changes in the agrichemical industry and rural development. Instead, a levelling off of global pesticide use appears most likely to reflect a combination of poor quality data and gaps in country-level data. Our estimates better reflect industry and rural dynamics. Global pesticide use is increasing steadily. Pesticide use in low and lower-middle income countries has been increasing particularly rapidly since 2009. Significant uncertainties as to the accuracy of use data for many middle-income countries both in the FAO database and in GloPUT remain because of supply chain restructuring, which has seen more domestic formulation of generic a.i. in some of these countries, a change not legible in trade statistics.

Over the last fifty years, the quantity of synthetic chemicals released into the environment has been increasing at rates surpassing other drivers of global change, including greenhouse gas emissions, despite attracting a tiny fraction of the research effort and funding as other drivers (Bernhardt, Rosi, and Gessner 2017). Pesticide use is one of the primary sources of synthetic chemical inputs to the environment by volume (Bernhardt, Rosi, and Gessner 2017). Publicly available data on what is being used where, in what volumes, and by whom is essential for environmental assessment and risk reduction, including the COP 15 Global Biodiversity Framework's target to reduce pesticide risks by 50% by 2030. Recent calls to improve pesticide use data in Europe note that these data are critical in order to target specific harms from pesticides – like drift, water pollution, residential exposures, and harms to pollinators – and to understand when and why a certain policy has been effective (Möhring et al. 2020; Mesnage et al. 2021). Yet, as we have shown, even the most basic aggregate data have serious accuracy problems for most of the world, if they are available at all.

Assessments of the impacts of pesticides on human health and the right to food (Sarkar et al. 2021) and the risk of surface water, groundwater, atmospheric and soil pollution (Tang et al. 2021) that draw on FAO data thus likely also underestimate the effects of pesticides significantly for most of Africa and South and Southeast Asia, as well as most low-income nations in general. Underestimates make it more difficult to assess the potential effects of rising pesticide use on ecosystems, human health, water quality, and occupational safety, and make it difficult to establish a baseline for global targets to reduce pesticide pollution risks. This knowledge gap, most acute in low-income in lower-middle income countries, is especially important because of the high numbers of agricultural workers and significant biodiversity in these areas. Better global use estimates, along with detailed data on which pesticide classes are used, on what crops and where, could help build adequate regulatory structures (Möhring et al. 2020; Mesnage et al. 2021), especially where such structures are either weak or do not exist.

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