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Pesticide Toxicity Hazard of Agriculture: Regional and Commodity Hotspots in Australia

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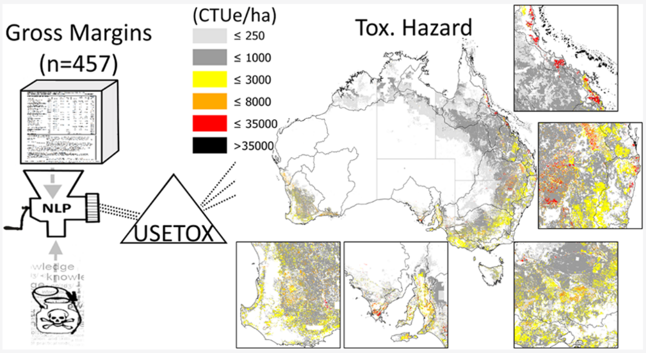
ABSTRACT: While the need to reduce the impacts of pesticide use on the environment is increasingly acknowledged, the existing data on the use of agricultural chemicals are hardly adequate to support this goal. This study presents a novel, spatially explicit, national-scale baseline analysis of pesticide toxicity hazard (the potential for chemicals to do harm). The results show an uneven contribution of land uses and growing regions toward the national aggregate toxicity hazard. A hectare of horticultural crops generates on average ten times more aquatic ecotoxicity hazard and five times more human toxicity hazard than a hectare of broadacre crops, but the higher yields and incomes in horticulture mean that both sectors are similar in terms of environmental efficiency. Livestock is the sector with the least contribution to overall hazard, even when the indirect hazard associated with feed is considered. Metrics such as pesticide use (kg/ha) or spray frequency (sprays/ha), commonly reported in highly aggregated forms, are not linearly related to toxicity hazard and are therefore less informative in driving reductions in impact. We propose toxicity hazard as a more suitable indicator for real-world risk than quantity of pesticide used, especially because actual risk can often be difficult to quantify. Our results will help broaden the discussion around pathways toward sustainability in the land-use sector and identify targeted priorities for action.



INTRODUCTION

Reducing agricultural emissions of substances that are toxic to humans and the environment is one of the targets of the UN's Sustainable Development Goal (SDG) 12 Responsible Consumption and Production (SDG 12.4).[1,2] Reducing pesticide reliance while maintaining or growing overall productivity and profitability in croplands is a challenge, but it is considered possible.[3] Advancing toward these targets will require careful, science-backed planning to avoid hindering progress toward "no poverty," "zero hunger," and "full and productive employment and economic growth" (SDGs 1, 2, and 8). Regulatory agencies need a comprehensive baseline of pesticide use and impacts to track performance toward SDG 12.4, but a baseline with extensive coverage of chemicals, agricultural commodities, and management regimes and accounting for regional diversity is lacking.

Past studies have firmly established the link between pesticides and their impacts on biodiversity and human health. Two European studies quantified around 30−45% of loss in aquatic invertebrates[4,5] due to chemical pollution. Pesticide overuse is a significant problem,[5−8] but biodiversity impacts still occur with use at regulatory levels.[5] Recent studies on neonicotinoid insecticides reveal significant impacts on beneficial species even at low levels of concentrations of low persistence chemicals.[9,10] Widely used chemicals such as chlorpyrifos and copper pose high risks of acute toxicity and chronic effects in aquatic systems,[11,12] and legacy pesticides present in contaminated groundwater contribute significantly to total toxicity.[13] The impact of toxic emissions from agriculture on human health is also a significant cause of concern[14] due to a variety of potential physiological[15] and neurological[16] effects and the emergence of fungicide resistance.[17]

Obtaining a baseline of pesticide use and toxicity across agriculture and the food system is difficult because of a scarcity of relevant data. Even where data are available, they are provided in highly aggregated form both spatially and categorically. The Food and Agriculture Organization Corporate Statistical Database (FAOSTAT) provides total pesticide use as kg of active ingredient (a.i.) per country and year and as kg per hectare. The Australian Pesticide and Veterinary Medicine Authority (APVMA) provides national pesticide sales per year and type of chemical (e.g., herbicide, fungicide, and insecticide).[18] The Australian Department of Environment's Agricultural Chemical Usage Database[19] provides average

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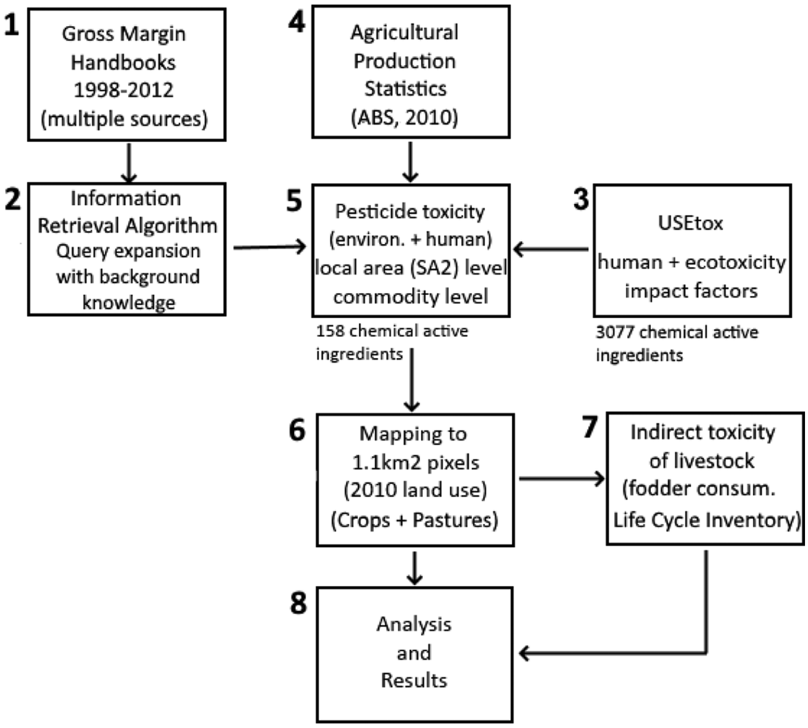

Figure 1. Method summary.

chemical application rates per active ingredient for large portions of Australia and up to 2006. The problem with highly aggregated data is that pesticide fate and transport are highly dependent on the specific active ingredient, its physicochemical properties, and local landscape and weather conditions. Aggregating otherwise rich data renders it inadequate for the assessment of toxicity impacts. FAOSTAT shows that the average pesticide use in Australia has more than doubled since 1990, from less than 0.4 kg/ha on average to over 1.0 kg/ha in 2016 across all cropland,[20] but it is unclear how much toxicity hazard has changed, for a few reasons: first, since 1990, some chemicals have been banned or superseded by new ones; second, the spatial distribution of Australian croplands (both the crops produced and their location/extent) has changed; and third, it is unclear how a doubling of total pesticide use per hectare translates to growth in the use of individual chemicals. Furthermore, there is little information on the extent of resistance by the various weeds, pests, and disease organisms against the chemicals used to control them.[21]

The last comprehensive assessment of pesticide use in Australia occurred in 2002.[22] The authors used the trend in total $ value of sales between 1996 and 1999 as a proxy of change in impact for cotton, potato, apple/pear, and winter cereals production systems. This simplifying assumption was acceptable because, over such a short period, substantial changes in which chemicals are used by producers were unlikely. Despite their achievement, the authors were unable to assess the use of individual chemicals or pesticide products because no such data were available. One of the main recommendations of their report was the need for a more comprehensive and integrated pesticide reporting and monitoring programs.

This study presents the first comprehensive national-scale baseline of the pesticide toxicity hazard (the potential for chemicals to do harm) of agriculture, based on 457 expert assessments of typical farm management practices spanning the most important[23] agricultural commodities in Australia. The results pinpoint the locations and commodity sectors with higher aquatic ecotoxicity and human toxicity hazard. The data includes 158 chemicals (86 herbicides, 42 insecticides, and 32 fungicides) to produce 75 agricultural commodities categorized into 25 classes, mapped at a spatial resolution of 1.1 km^2 across Australia. The results include a spatially resolved baseline aquatic ecotoxicity map for the entire continent, enabling the identification and visualization of regional hotspots. We discuss how this information is crucial for the assessment of policy interventions aimed at reducing pesticide use and its impacts.

■ METHODS

Study Area. Agriculture covers over half of Australia's landmass. As of 2010, the main agricultural land uses by area were grazing in natural vegetation and modified pastures (45 and 9%), followed by dryland cropping (3.6%) and agroforestry (1.6%).[24] The Murray–Darling Basin (MDB—Figure S1) is Australia's food bowl, and it occupies 14% of Australia's land mass.[25] From an economic perspective, the MDB is a powerhouse, hosting 48% of total revenues and profit in 2010.[26] The MDB is of crucial environmental importance, as it is home to 30% of Australia's bioregions[27] (15 out of 50).[25]

Agriculture employs approximately 304,000 people directly across 86,000 farms and contributes about 3% of Australia's GDP or AUD 60bn.[26,28] The top ten contributors to agricultural revenues in 2010 (beef cattle, sheep, dairy cattle, winter cereals, grapes, vegetables, cotton, winter oilseeds, winter legumes, and stone fruit) contributed AUD 55.4 bn or 92% of total revenues (Table S1). Irrigated agriculture occupied 0.66% of the land in 2010 but raised 26% of total revenue.[26] Drought years exacerbate the relative contribution of irrigated agriculture: in 2005, irrigated agriculture occupied 0.6% of the land and contributed 34% of total revenue.[29]

Method Description. The method extends previous work[30] to extract knowledge from hundreds of gross margin handbooks and store it in a relational database for further analysis. Pesticide use data were retrieved via natural language processing and combined with USETox impact factors[31] to estimate aquatic ecotoxicity and human toxicity. Toxicity values were distributed to statistical areas using official agricultural production statistics and mapped at 1.1 km^2 resolution using a national land use map for Australia.[32] The indirect toxicity hazard of livestock feed rations was quantified using a previously published life cycle inventory analysis.[33] Figure 1 shows the different elements of the method and their interconnection. The numbers at the top left of each box represent the order in which these elements will be described below.

Gross margin handbooks are agricultural extension documents produced by government district agronomists and are used by farmers as economic planning tools. A single handbook (example in Table S2) describes the operations that a typical farmer would undertake to grow a specific crop (e.g., wheat, apples, etc.) in a particular growing region [similar in size to ABS' SA4 regions[34] (Figure S2)] and year. The handbooks describe a growing season's calendar in detail, including what type of operations a typical farmer would perform in which month (e.g., tilling, sowing, application of fertilizers, pesticides, harvesting), the rate of application of specific products, machinery hours, and costs of labor and inputs. The handbooks specify fertilizer and pesticide inputs down to commercial name or active ingredient, which is crucial information that other sources very rarely provide.

This analysis used a collection of 457 gross margin handbooks[35−40] covering an extensive range of crops and growing regions.[23] Previous studies have relied on this data source as a quantitative expert opinion to produce national-scale and high-resolution baselines for agricultural profits and water use,[23,29] or GHG emissions and the use of fertilizers and pesticides.[30] Some of these baselines have recently informed essential studies on the future sustainability of Australian agriculture.[41−44]

The group of handbooks is highly heterogeneous: table structures differ, the naming of farm operations and inputs are not standardized and can contain spelling mistakes, and the units of application rates vary. On top of this, the volume of data to interpret and standardize is vast at close to 70,000 data points. For these reasons, we used an information retrieval (IR) algorithm known as query expansion with background knowledge[30] to parse all handbooks and store them in a relational database. In this study, we improve the information extracted from the gross margin handbooks by incorporating the latest gross margin handbooks available for horticultural crops at the time of writing (covering the period between 2010 and 2012).[35,37] For perennial crops, pesticide use for years before maturity was collected to represent better the variability of pesticide use over the entire life cycle of tree crops.[37] We substituted rates of application of endosulfan [banned by the Australian Pesticides and Veterinary Medicine Authority (APVMA) in 2010[45] with application rates of trichlorfon as specified by Nufarm Australia in a public notice to growers (one of the leading Australian distributors of endosulfan-based pesticides at the time) (Table S3).

Gross margin handbooks sometimes do not specify pesticides by product name or chemical name, instead opting to simply state the chemical's group (insecticide, fungicide, or herbicide) and rate of application. This is a problem because, without a specific chemical name, we cannot assess toxicity. To fill this information gap, we looked at which chemicals are mentioned most frequently within the commodity groups cereals, fruit, legumes, oilseeds and vegetables and calculated weights based on the relative number of mentions. Then, the estimated toxicity of an unspecified chemical is determined as the weighted average of toxicity for the specified chemicals of cereals, fruit, legumes, and so forth (Supporting Information data tables). The number of times chemical applications are unspecified hovers around 10% of total mentions for the land uses cereals, fruit, legumes, and oilseeds (Table S4). Although the proportion is higher for vegetables (28%), it is still low enough that this method can be applied with reasonable reliability.

For this study, the result of applying the IR algorithm is a spatial table of pesticide use (kg/ha) by active ingredient, commodity, and area (standardized to SA4 regions[34]) (Figure S2). For grasslands and pastures, gross margin handbooks do not include data on inputs use. To fill this gap, we inferred pesticide application rates from a report on weed control in pastures and lucerne for the state of New South Wales,[46] which encompasses the subtropical and temperate climate areas of the MDB. The MDB, being Australia's most productive region, offers a good representation of pastures practices in other intensively managed parts of the country. The report contains data on the variety of chemicals that could be applied based on different pasture types and different pest species and diseases, as well as rates of application. Here, we assume that all the combinations of chemicals and application rates are equally likely, which means that the toxicity of pastures is uniformly distributed. The pasture types in the report were reclassified to fit the categories in the Australian Land Use Map (ALUM)[32] (Table S5).

The pesticide use values are converted to pesticide toxicity values using characterization factors (CFs) published in USEtox[31] (the UNEP−SETAC toxicity consensus model) for the regions of "Northern Australia" and "Southern Australia & New Zealand".[47] USEtox assesses the toxicity hazard of different chemicals emitted into the environment by accounting for a chemical's environmental fate (FF—fate factor), exposure of human and wildlife populations (XF—exposure factor), and damage to human health or aquatic ecosystems (EF—effect factor) (eq 1). Chemical- and region-specific CFs for human toxicity (cancer and noncancer effects) and aquatic ecotoxicity (not terrestrial at the time of writing) in "comparative toxic units" (CTU) enable users to compare chemicals with one another based on their hazard. CTU of aquatic ecotoxicity and human toxicity are shortened to CTUe and CTUh, respectively.

$$\mathrm{CF} = \mathrm{EF} \times \mathrm{XF} \times \mathrm{FF} \tag{1}$$

It is important to note that CFs do not provide a measure of risk, as actual risk depends on the type of environment a chemical is used within and can be reduced by users carefully following instructions on the label. We ran USEtox for all 3077 organic chemicals for the regions of Northern Australia and Southern Australia and New Zealand. Given the lack of data on continental-scale spray drift, we assumed that all chemicals are emitted to the agricultural soils compartment, in order to avoid bias against horticultural commodities grown in closer proximity to water bodies than grains and pastures. We combined the CFs with the pesticide use table to quantify the toxicity (aquatic ecotoxicity and human toxicity) associated with growing a specific commodity in an SA4 region (eq 2). Toxicity values

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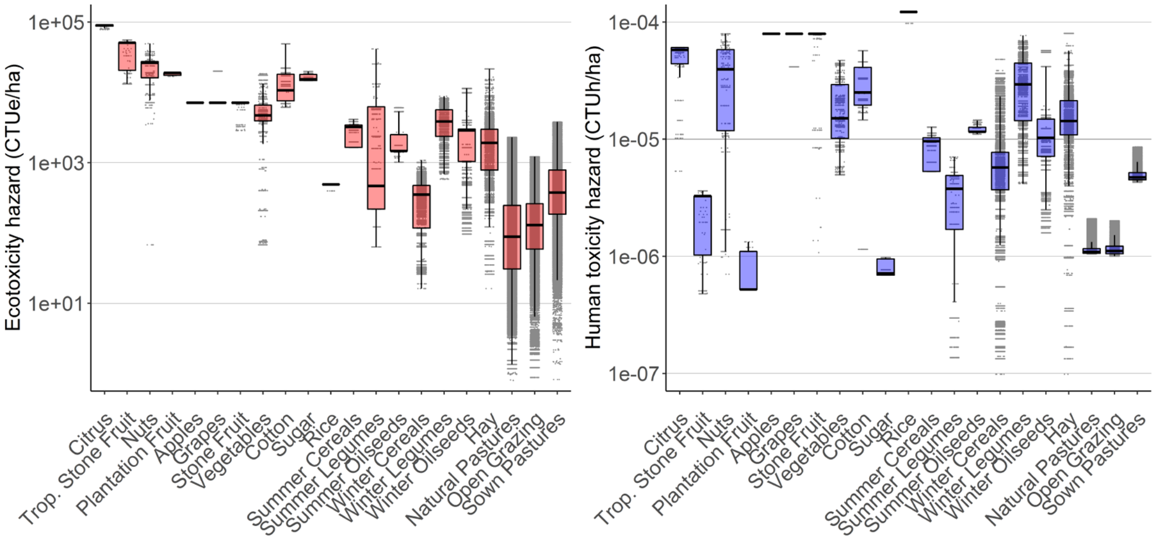

Figure 2. Boxplot of toxicity hazard per hectare by land use. Grey jittered dots show the distribution of values mapped in Figure 4. *Y*-axis in log scale.

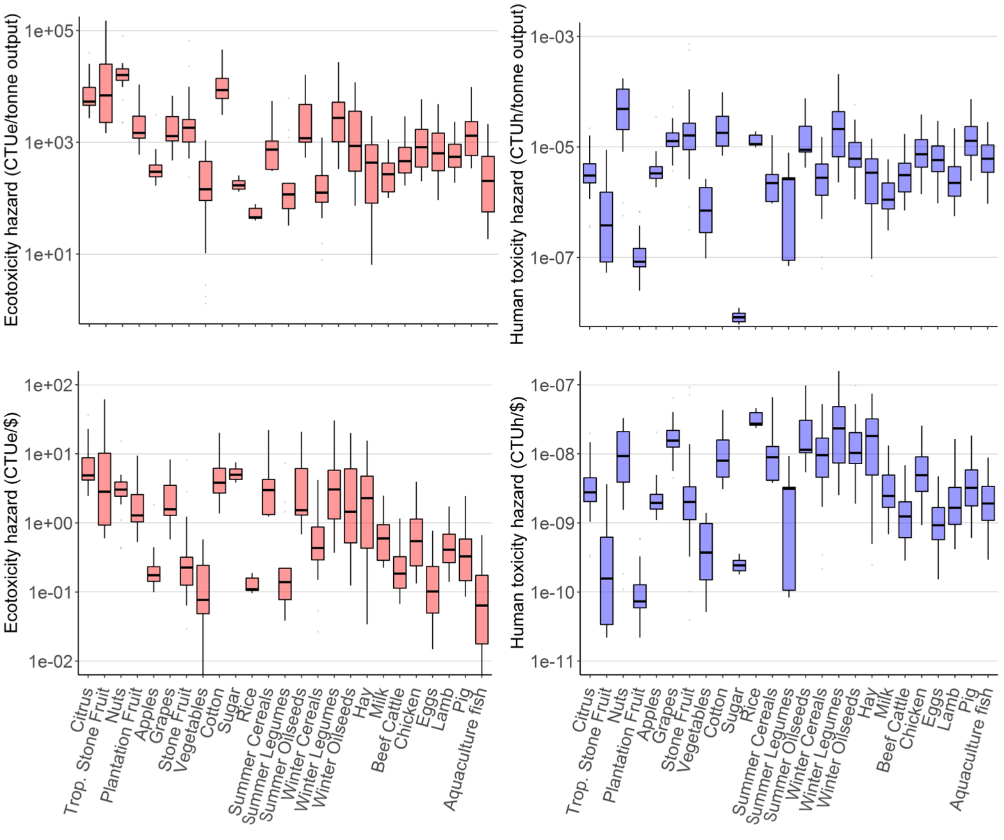

Figure 3. Toxicity hazard per tonne produced by land use (top panels) and per $ revenue (bottom panels), including livestock products and aquaculture fish. Output units are tonnes for crops and eggs, tonnes live weight for livestock meat and aquaculture fish, and 1000 L for milk—*Y*-axis in log scale.

were normalized using European toxicity emissions as a reference[48] to put the results in a broader context.[49]

$$\mathrm{TOX}_{\mathrm{comm,SA4}} = \sum_{\mathrm{comm,SA4}} (\mathrm{kg/ha}_{\mathrm{chem,comm,SA4}} \times \mathrm{CF}_{\mathrm{chem}}) \tag{2}$$

To distribute the toxicity data to the locations where specific commodities (Table S6) are grown, we use Australian agricultural production statistics[50] (from hereon AgStats) published at the SA2 region level[34] for the year 2010 (Figure S2). The spatial toxicity table covers a wide range of the commodity-SA2 pairs found in AgStats (because SA2s sit within SA4s), but not all. We filled the remaining data gaps using a rule-based approach first described in ref 23: if no pesticide toxicity data are available for a commodity within an SA2, we populate it with the average toxicity for that commodity within the same agro-ecological region (AER).[51] If no toxicity data are available for the same AER, we populate the missing value with the

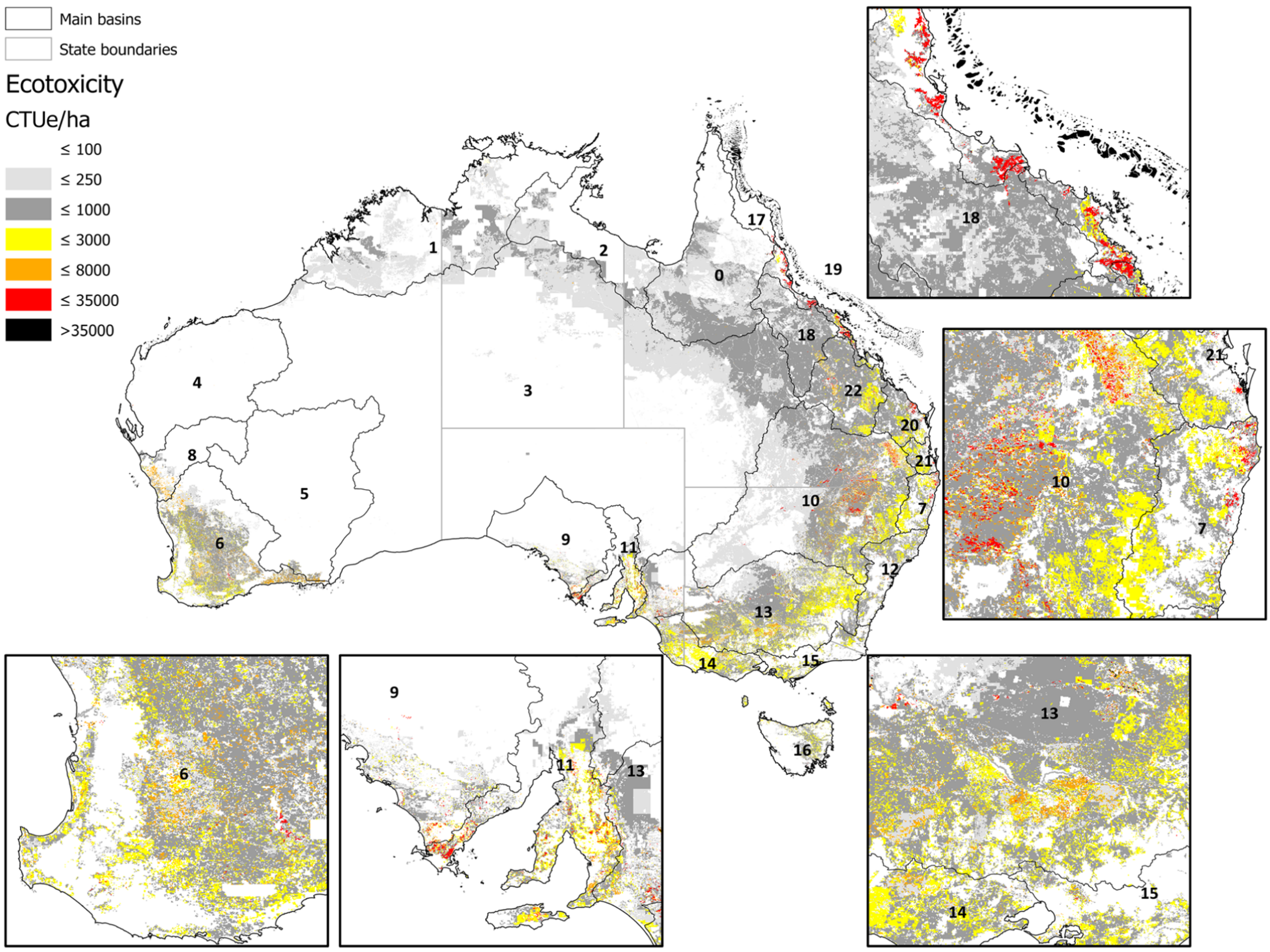

Figure 4. Australian map of aquatic ecotoxicity hazard (1.1 km^2 resolution). Main basin id links to the data in Table S7.

average toxicity for that commodity across the whole country. The pesticide use data cover 76% of the total cropland area. The rule-based approach populated 21% of the remaining cropland area using AER-level data, and 3% of the remaining cropland area using national-level averages.

Mapping Toxicity. The SA2-level information is then mapped to 1.1 km^2 pixels using the Australian Land Use Map[32] as a template. Crop toxicity values are assigned to the pixels of a local area based on each pixel's land use (a.k.a. SPREAD class, Table S6). Pasture toxicity in each pixel is scaled so that pastures with higher stocking rates incur in higher toxicity emissions because they need to be managed more intensively. First, we use the Australian Map of Profit at Full Equity[29] to calculate the distribution of livestock stocking rates (derived from livestock stocking rate maps based on previously published methods[52,53]) within the sown pastures land use category, capped at 1st and 99th percentile. Then, the average, minimum, and maximum values of toxicity are calculated using data from all SA2 regions where sown pastures are found. Finally, a lookup table of toxicity values based on stocking rate is built by tying the average, minimum, and maximum toxicity values of sown pastures to the 1st, 50th, and 99th percentiles of stocking rate. This method is generally known as quantile mapping.[54−57]

Pasture spraying constitutes a direct toxicity hazard for livestock groups such as beef cattle, dairy cattle, and sheep. On top of that, there is an indirect toxicity hazard associated with livestock products resulting from animal consumption of grain fodder. Data on the crop products that are consumed by livestock and their quantities came from life cycle inventory[33] and industry data from numerous sources.

RESULTS

A hectare of horticultural crops generates ten times more aquatic ecotoxicity hazard and five times more human toxicity hazard than a hectare of broadacre crops (Figure 2). There is a marked difference in intensity between both groups, although horticulture occupies only 0.5% of the total agricultural land compared to the 6% held by broadacre production. The aquatic ecotoxicity hazard of sown pastures is seven times lower than broadacre crops, and its human toxicity is two times lower than broadacre crops on average. Citrus, tropical stone fruit, nuts, plantation fruit, cotton, and sugar have medians at the higher end of aquatic ecotoxicity. In contrast, rice, winter cereals, summer legumes, and pastures have medians at the lower end of aquatic ecotoxicity. The relative position of commodity groups varies significantly when we focus our attention on human toxicity. Tropical stone fruit, plantation fruit, and sugar are at the lower end of human toxicity, whereas apples, grapes, stone fruit, citrus, and rice are at the top end. Rice's high human toxicity hazard is due to the use of molinate to control grass weeds post-emergence. Apples, grapes, and stone fruit appear similar because the base data available for them in the largest growing region assume identical pesticide use practices. Winter legumes and winter oilseeds display relatively high human toxicity values per hectare due to the use of simazine to treat weeds such as wild radish in lupins and ryegrass in canola.

Expressing toxicity relative to agricultural output causes the gap between horticulture and other sectors to shrink dramatically (Figure 3 top panels). A tonne of horticultural produce[29] is associated with 3.4 times more aquatic ecotoxicity hazard and two times more human toxicity hazard than a tonne of broadacre crops. Remarkably though, on average, both horticulture and broadacre crops generate the same aquatic ecotoxicity hazard per $ revenue [based on mean national farmgate price 2000−2020 (Supporting Information data tables)] (Figure 3 bottom panels). It is a similar pattern for human toxicity hazard: horticulture produces two times more human toxicity per tonne output, but nearly three times smaller human toxicity per $ revenue. This shows that the higher yields and incomes achieved in horticulture can significantly offset the higher hazard per hectare.

Relative to output, the total toxicity (direct + indirect) of livestock is lower than that for broadacre crops (about 3 and 4 times lower for human toxicity and aquatic ecotoxicity, respectively). This is due to the fact the majority of livestock fodder comes from winter cereals, hay, and silage, which generate relatively low toxicity. There are, however, examples of crops that are more efficient than livestock as a group per tonne of output (Figure 3 top panels). The toxicity per $ revenue of broadacre crops is 6.5−7 times greater than livestock's (Figure 3 bottom panels), which shows that the added value these commodities generate completely offsets their indirect impact.

A moderate resolution (1.1 km^2) map of aquatic ecotoxicity shows several spatial hotspots where aquatic ecotoxicity hazards concentrate: in coastal areas of Eastern Australia such as the sugar and horticulture growing regions from Far North Queensland and south along the Queensland and northern New South Wales coast; the north New South Wales cotton-growing region; the winter oilseed production areas in South Australia's Eyre Peninsula; and livestock production on sown pastures in northern Victoria (Figure 4). Moderate-intensity aquatic ecotoxicity areas (in yellow) are present along the entire eastern border of the MDB, south-west Victoria, the South Australian gulf, and south-west Western Australia.

The total aquatic ecotoxicity hazard for Australia is about 23 million EU27 citizen equivalents (normalized), which equates to 1.1 EU27 citizen equivalents per capita. The overall human toxicity of Australia's agricultural pesticide use totals nearly 1 million EU27 citizen equivalents or 0.045 EU27 citizens per capita. However, considering Australia feeds approximately 51 million people worldwide per year,[28] expressing toxicity relative to the total population fed may be more appropriate than relative to the Australian population alone. Normalized toxicity hazards per consumer are about 0.45 and 0.02 EU27 citizen equivalents (aquatic ecotoxicity and human toxicity, respectively), which is less than half the per capita values.

The top five land uses for overall aquatic ecotoxicity at the national level are cotton, citrus, winter legumes, sown pastures, and grapes (Table 1). For human toxicity, the top-ranked commodities are winter cereals, winter legumes, rice, grapes, and sown pastures. Sown pastures feature among the highest for total toxicity due to their extensive area coverage.

The Murray and the Darling basins contribute about 38% of overall aquatic ecotoxicity and 40% of total human toxicity (Table S7). The size of the MDB's aquatic ecotoxicity contribution is, however, smaller than the size of its economic contribution in 2010 (48% of total revenue and profit at full equity).[26] The WA South, SA Gulf, and Southern (Victoria) basins are other sizeable contributors adding up to 18% of total aquatic ecotoxicity hazard and 39% of overall human toxicity hazard.

Table 1. Sum of Aquatic Ecotoxicity and Human Toxicity (Cancer and Noncancer Effects) Hazard per Land Use for the Whole of Australia

land use	aquatic ecotoxicity (CTUe)	land use	human toxicity (CTUh)
natural pastures	1.1×10^{11}	vegetables	1.5×10^{2}
sown pastures	2.5×10^{10}	w. cereals	1.4×10^{2}
grapes	1.1×10^{10}	grapes	1.1×10^{2}
w. legumes	1.1×10^{10}	w. legumes	8.6×10^{1}
open grazing	1.0×10^{10}	hay	3.3×10^{1}
cotton	8.3×10^{9}	inter oilseeds	3.2×10^{1}
w. oilseeds	6.9×10^{9}	cotton	1.8×10^{1}
w. cereals	6.3×10^{9}	rice	1.1×10^{1}
sugar	5.6×10^{9}	s. cereals	6.5×10
hay	4.8×10^{9}	stone fruit	4.9×10
citrus	3.5×10^{9}	vegetables	3.0×10
s. cereals	2.2×10^{9}	nuts	2.2×10
nuts	1.2×10^{9}	citrus	1.6×10
trop. stone fruit	9.1×10^{8}	apples	1.1×10
vegetables	7.0×10^{8}	s. oilseeds	5.0×10^{-1}
stone fruit	4.6×10^{8}	sugar	2.7×10^{-1}
plantation fruit	4.4×10^{8}	s. legumes	9.5×10^{-2}
s. legumes	1.1×10^{8}	trop. stone fruit	5.7×10^{-2}
apples	1.0×10^{8}	plantation fruit	1.7×10^{-2}
s. oilseeds	1.0×10^{8}		
rice	4.5×10^{7}		
total	2.1×10^{11}	total	6.0×10^{2}

Comparing aquatic ecotoxicity and human toxicity with pesticide use metrics shows there is no linear relationship between chemical applied (kg/ha) and chemical applications (sprays/ha) on the one hand and toxicity on the other (Figure 5). Even when separating agriculture into the broadacre and horticulture sectors, the correlation coefficient remains weak.

■ DISCUSSION

This study presents the first comprehensive national-scale baseline of pesticide toxicity in agriculture, covering an extensive range of commodities and growing regions. This method can be applied in other countries which lack official, comprehensive, and spatially explicit pesticide use data. For example, in the USA and some European countries, similar gross margin handbooks are available. The results show how different land uses and geographical areas contribute to national toxicity hazards and enable the identification of priorities for action. Land uses that have higher levels of toxicity per hectare may be good starting points because research and development efforts would need to target smaller areas and enable more significant toxicity reductions. Similarly, geographical hotspots of toxicity hazard could be seen as national priorities: The Great Barrier Reef catchments, the Murray−Darling Basin, and the WA South, SA Gulf, and Southern (Victoria) basins.

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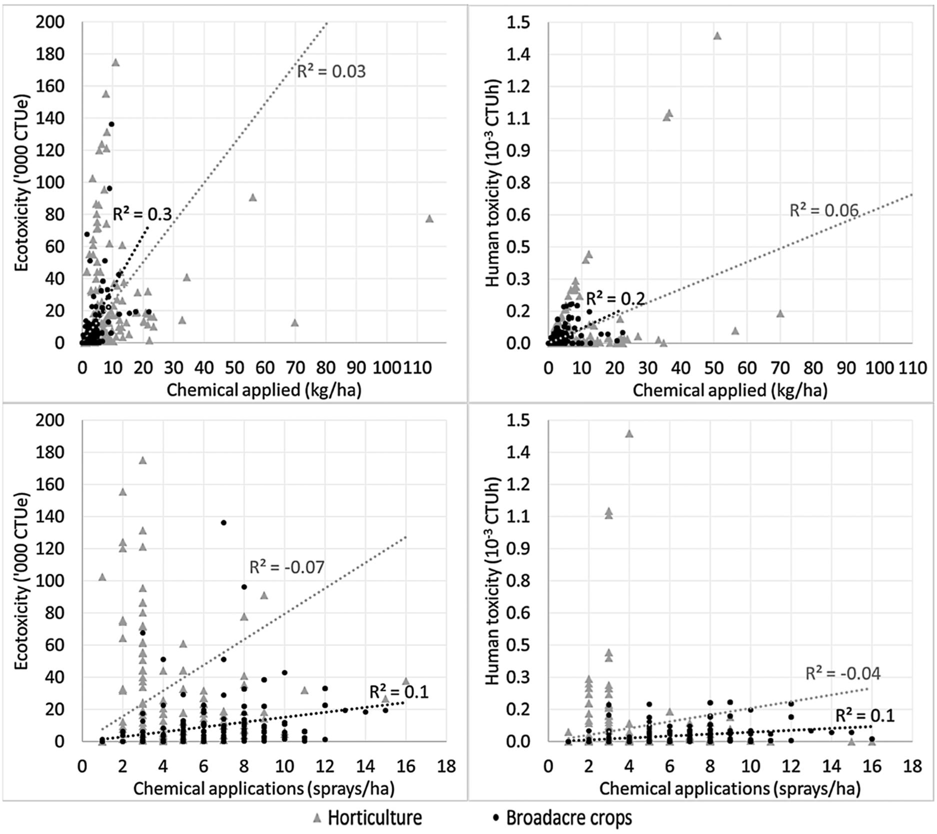

Figure 5. Scatterplot of toxicity hazard values vs pesticide use metrics.

The results presented here will help broaden the discussion around pathways toward sustainability in the land-use sector. There is a broad consensus on the environmental benefits of lower-meat diets,[58] but chemical use or toxicity has been mostly absent from the discourse. This analysis shows that livestock toxicity hazard is relatively lower on a per hectare, per tonne produced, and per $ revenue basis (it is worth noting here that pesticide use to treat livestock parasites was out of scope because of the complexity in determining the persistence of chemicals as they travel the digestive tract of different animals). A similar trend for water-scarcity footprint was identified in a recent study.[59] Future research should explore whether widespread adoption of lower-meat diets could increase the overall toxicity hazard by leading to increases in cropping and horticulture area or increases in crop and horticulture production intensity.

National and International Significance. Reductions in chemical toxicity could bring significant benefits for Australian agricultural exports as a whole: because of the export-focused nature of Australian agriculture, Australia has a strict policy stance on quarantine and food safety. This policy stance results in a costly pesticide registration process that deters the registration or widespread use of some pesticides available elsewhere.[60] There is evidence that this has helped export-oriented producers gain and retain market access when opportunities have arisen.[60] Still, on the other hand, local growers may also be disadvantaged by a review process that slows down the availability of chemicals that international competitors have access to. It is, therefore, in the best economic and environmental interest of the nation to invest in research that enables more agile evaluations of the pros and cons of pesticide registration/deregistration. The methodology presented here could allow national regulators to assess the total and distributional effects of licensing new chemicals or canceling existing licenses and, as a result, complement their chemical review process. As of January 2020, 18 chemicals are being reviewed by the Australian Pesticides and Veterinary Medicines Authority (APVMA), citing concerns over worker safety, public health, or environmental safety.[61] Eleven of these are part of this study: simazine, cyanazine, dicofol, acephate, methomyl, trichlorfon, picloram, permethrin, chlorothalonil, triazole fungicides, and hexazinone.

Internationally, there are several initiatives aiming to reduce pesticide use, such as the EU's Farm to Fork Action Plan[62] or the Chinese "Double Reduction Action" plan, both of which aim to halve pesticide use within the next 10−20 years while not impacting productivity. Australia does not have a similar policy at the time of writing. Still, past research indicates that improving sustainability in the land use system goes hand in hand with achieving productivity growth above the historical trend of 1% p.a.[44,63] Our results indicate that at high levels of aggregation, there is no linear relationship between pesticide use or frequency of spraying and toxicity hazard. This is because the toxicity hazard of an active ingredient depends on its physicochemical characteristics [such as environmental persistence, soil sorption or half-life (λ)], not on how many grams need to be applied to control a pest. Further, the actual toxicity risk is site-specific, as it depends on local soil and environmental factors including soil organic carbon, bulk density, water table depth, and recharge rate. Therefore, nationwide reductions of pesticide use, unless they happen across the board, will have an unknown effect on overall chemical hazard or risk. Decision-makers must ask themselves what it is they really want to reduce. Here, we propose toxicity hazard (the potential of a chemical to do harm) as one measure which is closer to real-world impact than pesticide use and could be considered where risk is too difficult to quantify (although ideally, it is the risk—i.e., the combination of hazard and exposure—which needs minimizing). Reductions in toxicity hazard or risk will be easier to balance with sustained or increased productivity growth by focusing on the most hazardous chemicals first and relying on the best scientific evidence available to guide our decisions.[64] Reductions in risk can be achieved by addressing hazards or via additional pesticide application measures, which can be tailored to specific regions. Geographical characteristics such as rainfall, travel time between fields and water bodies, and local soil archetypes will also influence chemical risk.

Technology Change and Toxicity. Future widespread adoption of new pest-control technologies or pest management techniques could influence the toxicity risk posed by agriculture. Research on the nano-encapsulation of chemical active ingredients aims to improve their pest control efficiency, protect them from premature biodegradation so they can remain effective for longer, and reduce leaching and volatilization.[65] However, slowing the degradation of the active ingredient can significantly alter the spatial and temporal nature of exposure to nontarget organisms,[66] and so more research is needed to develop safe nano-enabled pesticides.[67] Integrated pest management and area-wide management are promising techniques to achieve low-toxicity landscapes, but they currently suffer from socio-economic adoption barriers due to their requirement for continued monitoring and coordinated action. With the right incentives, decision-support tools, and guidelines in place, along with increasing evidence of long-term economic and environmental benefits, they could become more widely adopted by producers.[68] Automation in agriculture is another field that could offer low-toxicity pest-control options such as robotic weeders[69] and air-blasting drones for use in tree canopies.[70]

Uncertainty and Future Work. There are two primary sources of uncertainty in the results. First, the pesticide use data are obtained from gross margin handbooks that are produced by combining district agronomist expert knowledge with informal surveys of local producers. Typical values for a location and point in time are supplied without uncertainty estimates. By using a sample of 457 handbooks (all the available ones at the time of writing), we aim to represent the real variability in pesticide use within commodity groups (Figures 2 and 3, built using the values mapped in Figure 4). Previous comparisons with other pesticide use datasets[30] are encouraging. The other main source of uncertainty is the toxicity hazard estimates from USETox.[31,47] Although the CFs are built using continent-specific parametrization complemented with aquatic archetypes,[47] in the future, modeling the specific soil, landscape, and environmental conditions[71] at high resolution will be needed to better assist the industry in reducing its footprint efficiently. Similarly, this study's focus on aquatic ecotoxicity was dictated by the data available in USETox, but in the future, we must also build our understanding on chemical impacts on terrestrial biodiversity at the national scale. Because the effects of chemicals on different taxa vary significantly,[71,74] this will alter our current understanding of national-scale toxicity hazard and risk.

The distribution of human and aquatic ecotoxicity of pastures is adjusted based on the distribution of livestock stocking rates for sown pastures, natural pastures, and open grazing land uses. As a result, pixels with low livestock densities were given very low values for human and ecological toxicity. As we lacked a systematic way to determine a cut-off stocking rate or rainfall level below which there would be zero herbicide use, there could be an overestimation of total national toxicity from pastures, particularly natural pastures and open grazing.

The toxicity map assumes continuous cropping systems with an intensity of one crop per year (i.e., no crop rotations). This is consistent with the Global Yield Gap Atlas protocol which is based on a one crop per year assumption too. In parts of Australia it is possible for producers to increase this intensity by rotating winter cereals such as wheat and barley with short fallows and summer and winter legumes (such as mung beans, fava beans, or chickpeas) and summer and winter oilseeds (such as safflower and canola).[72] Since recent research indicates there can be strong productivity increases arising from the selection of ideal crop rotations,[73] future research should focus on the trade-offs between productivity and toxicity that arise from the choice of rotation.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.est.0c05717.

Area and revenue statistics for dryland and irrigated agriculture in Australia, for the year 2010, by agricultural land use; example Gross Margin Handbook; substituted endosulfan rates of application for industry-recommended application rates of trichlorfon, by commodity; proportion of unspecified chemicals to specified chemicals by land use; correspondence of pasture types from ref[46] to Australian Land Use Map pasture land uses; mapping of individual commodities to land uses; sum of aquatic ecotoxicity and human toxicity (cancer and noncancer effects) hazard per major Australian basin, national-scale land use (based on Land Use of Australia 2010−11, Version 5);[24] and ASGS[34] and AERs[51] used for spatial gap filling via a rule-based approach[23] (PDF)

Revised data (XLSX)

Data tables: pesticide rates and CTU values; farmgate prices 2000−2020; unspecified chem tox components; unspecified chem tox results; and the national toxicity map at 1.1 km^2 resolution (ZIP)

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Author Contributions

J.N., B.A.B., and B.R. conceived the work; J.N. designed and implemented the method, analyzed and interpreted the results, and wrote the manuscript; M.H. codesigned and implemented parts of the analysis and contributed substantially to the writing; all authors contributed to the writing of the manuscript and critically revised it.

Notes

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