

## PESTICIDE TOXICITY

# Increasing applied pesticide toxicity trends counteract the global reduction target to safeguard biodiversity

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The 15th United Nations Biodiversity Conference (COP15) obligates all countries to reduce pesticide risks by 50% by 2030. In this study, we derived the trends of total applied toxicity (TAT) globally between 2013 and 2019, weighting applied masses by ecotoxicity, of 625 pesticides for eight species groups to assess pathways toward this reduction goal. We found that the TAT of most species groups has increased; that only  $20 \pm 14$  pesticides per group define >90% of the TAT nationally; that fruits, vegetables, maize, soybean, rice, and other cereals contribute 76 to 83% of the global TAT; and that China, Brazil, the United States, and India contribute 53 to 68% of the global TAT. Our target achievement categorization shows that substantial actions, combining shifts to less-toxic pesticides, increased adoption of organic agriculture, and also provision of national pesticide use data, will be required globally to approach the United Nations' target.

Global biodiversity is threatened by many anthropogenic activities (1–6), including the use of toxic chemicals, such as agricultural pesticides (7–9). The effects of pesticide use, however, remain difficult to quantify on large scales (10). In 2022, the United Nations Global Biodiversity Framework (UN GBF) set a global target to reduce pesticide risks by 50% by 2030 relative to the 2010–2020 baseline (11). However, no indicator for setting the baseline and gauging the success of reaching the reduction goal was specified at that time (12, 13). In February 2025, the UN Biodiversity Conference (COP16.2) then adopted the aggregated total applied toxicity (ATAT) as an option (14, 15), building on the total applied toxicity (TAT) framework (16).

Two types of data input variables are required to estimate national TATs and their temporal dynamics: (i) the annual amount of pesticide active ingredients (hereafter “pesticides”) used in agriculture per country (16, 17) and (ii) the toxicity of these pesticides for different nontarget species groups (18), here defined as groups sharing functional characteristics (e.g., pollinators) and serving as proxies for potential ecological effects. In this context, pesticide toxicity—varying across several orders of magnitude even among chemically similar pesticides (16)—is key for calculating the TAT of the pesticide mix used in agriculture, its changes over time, or differences between countries (10, 16, 19, 20). Although previous studies have presented global pesticide use or risk estimates (8, 9, 21–25), they were either restricted to specific pesticide types or to specific species groups, did not provide data over time, or selected pesticides solely on the basis of the amount used; thus they did not cover the full range of toxicities potentially affecting biodiversity (10, 16).

In this study, we used the TAT approach for pesticides (16) on a global scale, combining weight-based measures of pesticide use and distributions of regulatory threshold levels (RTLs) (26). RTLs denote

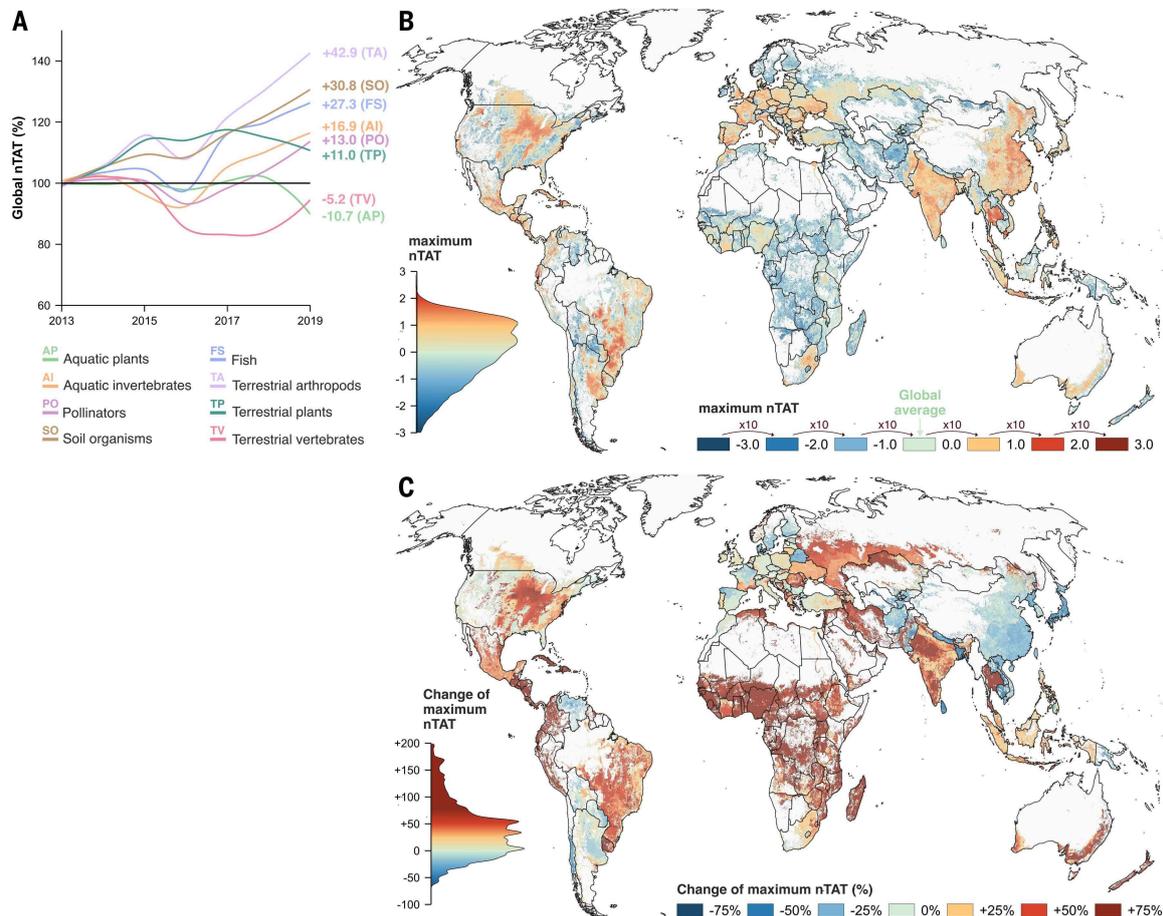
concentrations above which environmental risks are expected (16). Whereas previous studies relied on RTLs derived by individual regulatory authorities (8, 17, 19, 20), we used the global average RTL per species group and pesticide—derived from seven regulatory authorities (Australia, Canada, China, European Union, New Zealand, the US, and Japan; 15,041 RTLs total) (27)—to ensure global representativeness. Species groups (aquatic plants, aquatic invertebrates, fish, terrestrial arthropods, pollinators, soil organisms, terrestrial vertebrates, terrestrial plants) are used by regulators to characterize chemical risks for similar species and are based on taxonomic groups or functional characteristics. The annually applied pesticide amounts were weighted (i.e., divided) by RTLs to derive the TAT per substance ( $n = 511$ ), species group ( $n = 8$ ), crop group ( $n = 11$ ), country ( $n = 201$ ), and year (2013 to 2019) (26). Toxicity-weighted pesticide use, as represented by the TAT, has been repeatedly linked to both exposure and risks relevant to biodiversity in aquatic and terrestrial ecosystems (17, 26, 28, 29). The TAT was projected to 5 arc min (plane angle) using a comprehensive global crop raster (SPAM2010) (30) and subsequently spatially normalized (nTAT), which enabled new analyses (e.g., across species groups or between regions) on the macro scale (26). We then combined the highest nTAT values across species groups into a single nTAT metric (maximum nTAT) to ensure a broad coverage of species' biodiversity (11) and to avoid masking (e.g., through averaging) shifts in potential threats between groups or differences in trend strength (16, 26). We present aggregated nTAT trends for, for example, species and substance groups, crops, and countries. Furthermore, we calculated target achievement categories for 65 countries (representing ~80% of the global crop acreage) that synthesize national efforts needed to approach the UN GBF biodiversity target (11) of a 50% pesticide risk reduction (26), supporting urgent policy action.

## Global, continental, and species group-specific TATs

The global nTAT of pesticides is increasing for many species groups [Figs. 1 and 2; see supplementary materials for sensitivity analyses (26)]. Between 2013 and 2019, the global nTAT increased for six out of eight species groups, including all invertebrate species groups and terrestrial plants (Figs. 1A and 2, A and B). Terrestrial arthropods exhibited the strongest increase (6.4% per year; Fig. 1A and table S1), followed by soil organisms (4.6% per year, for both species groups consistent across all continents; Fig. 2A) and fish (4.4% per year, except in Asia, where it was 0.41% per year; Fig. 2B). The importance of all of these species groups is recognized in the biodiversity debate (2), in agroecology (31), and from an economic perspective (32). The global nTAT showed positive trends for aquatic invertebrates (2.9% per year), pollinators (2.3% per year; for both species groups across all continents except Asia, where it was –2.5 and –2.6% per year, respectively; Fig. 2A) and terrestrial plants (1.9% per year; table S1). In contrast, the global nTAT decreased only for aquatic plants and terrestrial vertebrates (–1.7 and –0.5% per year, respectively; Fig. 1A), although these trends varied considerably between continents (Fig. 2A). Previously reported national trends for the US (16) and Germany (19) are reflected in the global trends reported here. The increasing global TAT trends pose a challenge to achieving the UN pesticide risk reduction target and demonstrate the presence of threats to biodiversity globally.

Maximum nTAT across all species groups is elevated in regions with intensive agriculture, including North and South America, western Europe, and South and East Asia (Fig. 1B; see figs. S2 to S9 for species-specific TAT). Although agricultural intensification drives these patterns (fig. S10), we observed a decoupling between agricultural acreages and resulting TAT across species groups. By using the maximum nTAT values, our assessment ensured simultaneous improvements for all species groups (for differences and variability patterns, see figs. S11 and S12), aligning with UN biodiversity conservation goals and reflecting pesticides' potential impact on biodiversity. A decrease in maximum nTAT indicates concurrent declines across all species groups,

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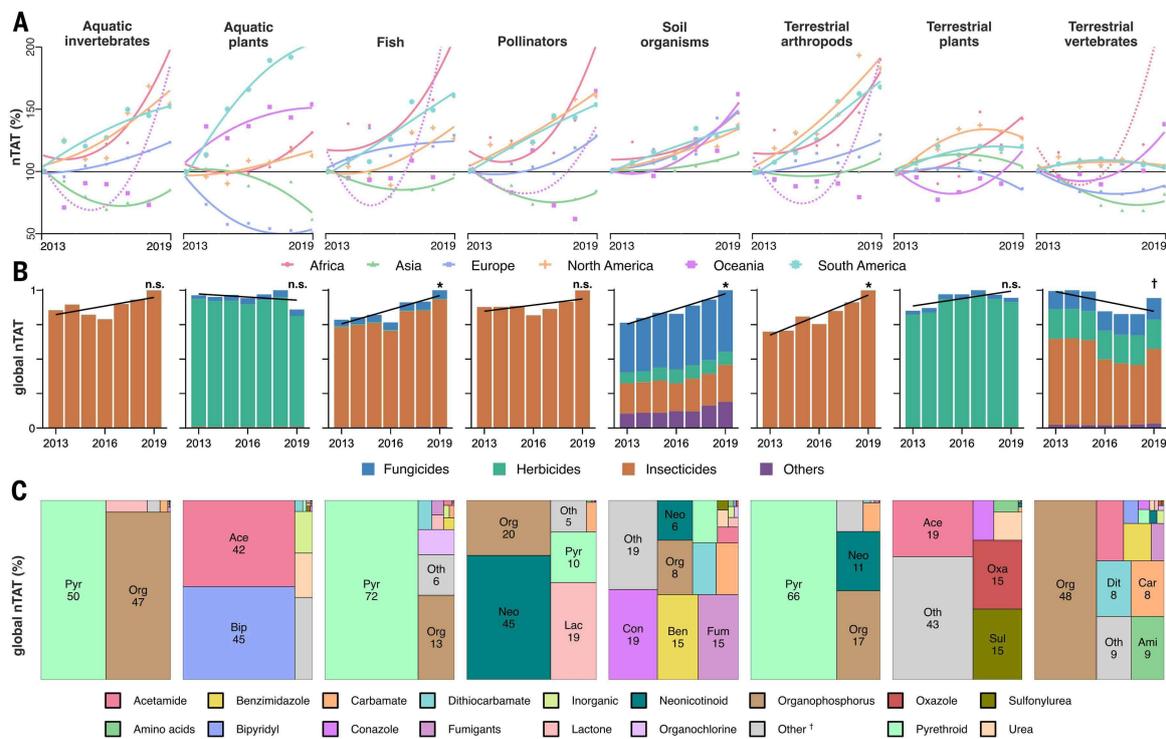


**Fig. 1. Global trends of the total applied toxicity of pesticides used in agriculture.** (A) Global nTAT trends for each of the eight species groups. (B) Global map and grid cell density plot of the maximum nTAT (2018–2019,  $\log_{10}$ , zero-centered) across the eight species groups. Maximum nTATs are based on highest nTAT values across all eight species groups; for sum-aggregated results, see fig. S1, and for species-specific maps, see figs. S2 to S9. (C) Global map and grid cell density plot of the change of maximum nTAT from 2013–2014 (100%) to 2018–2019 in percent.

providing the most protective measure of changing pesticide threats on the basis of the current regulatory knowledge. Regions such as sub-Saharan Africa, Central Asia, parts of the Indian subcontinent, and southern Australia exhibit particularly high maximum nTAT increases (Fig. 1C). Notably, the relatively low maximum nTAT in many of these regions (Fig. 1B) presents opportunities for early intervention, as the onset of intensifying agricultural practices can be managed through targeted strategies to mitigate adverse pesticide effects. In contrast, maximum nTAT decreases occur in parts of South America, western Europe, and East Asia (Fig. 1C), highlighting that dynamic TAT shifts can occur within short time frames (2013–2019), as documented in the US (16). The data presented here can assist in establishing the 2010–2020 baseline proposed by the UN GBF (11). Overall, the maximum nTAT increased during this baseline period (Fig. 1A and fig. S13), accompanied by a spatial intensification, with 54 to 80.0% of spatial units (grid cells,  $n = 832,827$ ) exhibiting increases (fig. S14).

Insecticides dominated TATs in many animal species groups, herbicides dominated in plants, and fungicides dominated in soil organisms (Fig. 2, B and C, and table S2). Specifically, a few classes of insecticides, including pyrethroids and organophosphates, contributed to the TATs of aquatic invertebrates, fish, and terrestrial arthropods by >80%. In contrast, neonicotinoids, organophosphates, and lactones (including some neonicotinoid follow-ups) accounted for >80% of pollinator TAT. Organophosphates, alongside other insecticide classes (e.g., carbamates), contributed most to the terrestrial vertebrate TAT (Fig. 2C; for details,

see table S3). The hazard of pyrethroids for invertebrates and fish, as well as neonicotinoids for pollinators, has been previously reported (16, 19, 33) and attributed to their high toxicity in these species groups (10, 28). However, assessing aquatic pyrethroid risks remains challenging owing to analytical limitations (10). Acetamide and bipyridyl herbicides contributed >80% to aquatic plant TATs, whereas a broader herbicide mix (including acetamide, sulfonylurea, and others) defined terrestrial plant TATs (Fig. 2C). High-volume herbicides, such as acetochlor (~54,000 metric tons per year), paraquat (~44,000 tons per year), and glyphosate (~518,000 tons per year), belong to these classes and have been linked to environmental and human health risks (34). Widely applied conazole and benzimidazole fungicides, along with neonicotinoid insecticides commonly used in seed coating (35), contributed mainly to the TAT of soil organisms, highlighting the need for attention given their regular presence in topsoils (36). Pesticide toxicity varies by more than seven orders of magnitude, even within the same pesticide class or species group (16, 19). Consequently, a small number of highly toxic pesticides (average  $20.3 \pm 14.3$  out of 511 pesticides) often dominate national TATs, contributing >90%. This underscores the need for robust toxicity estimates, such as those derived from global RTLs, to evaluate agricultural pesticide threats. Mass-based assessments alone can be misleading, as they ignore the disproportionate relationship between applied tonnages and ecotoxicological threats (figs. S15 and S16) (16). Reducing use of the few current-use pesticides driving high TAT fractions provides efficient leverage points for national risk reduction toward the UN biodiversity target.



**Fig. 2. Continental nTAT trends and pesticides contributing to the nTAT for each species group.** (A) nTAT trends per continent (2013–2019) for the eight species groups visually indicated by LOESS (locally estimated scatterplot smoothing) regressions (span = 3). Overly leveraged trends (26) are de-emphasized with dotted lines. For national trend aggregates, see fig. S13. (B) Pesticide types contributing to the global nTAT trends for the eight species groups. Trends are normalized (0–1) (16). Trend significance:  $P < 0.05$  (\*),  $0.05 < P < 0.1$  (†),  $P > 0.1$  (n.s., not significant). (C) Treemap charts displaying the contribution of important pesticide classes to the global nTAT for the eight species groups. †Note that glyphosate has been included in “Other.”

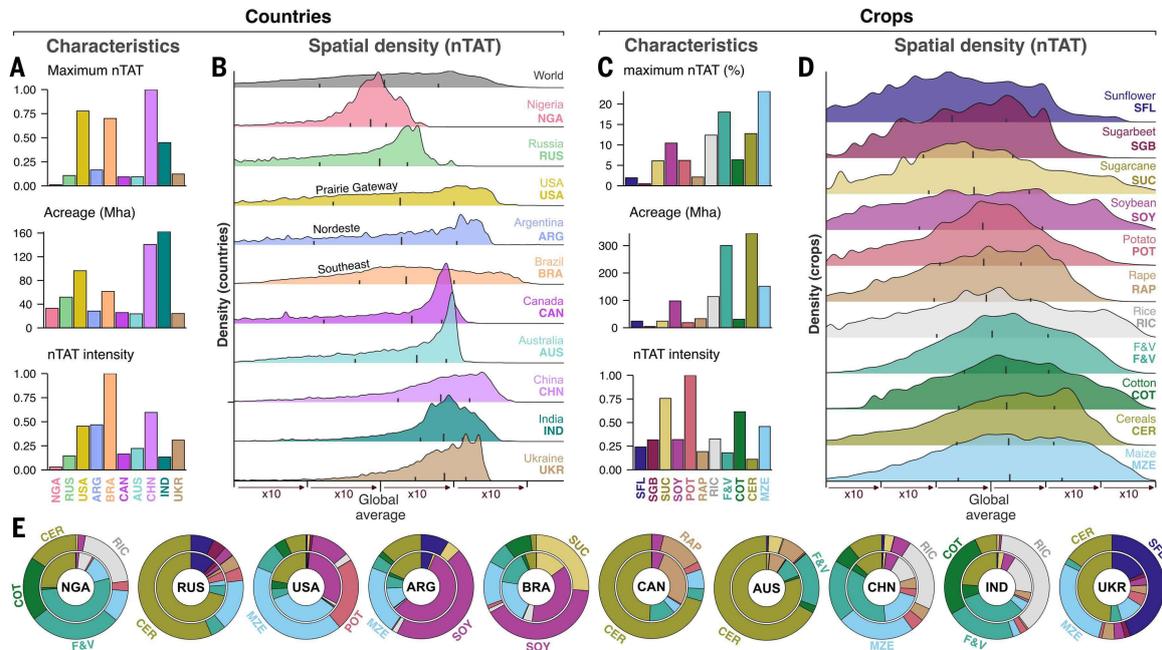
### Country- and crop-specific TATs

The maximum nTAT intensity (nTAT per area) is highest in Brazil, China, Argentina, the US, and Ukraine (Fig. 3A). Notably, India, despite having the largest crop acreage, exhibits a relatively low nTAT intensity owing to its moderate nTAT distributed across a relatively vast agricultural area. In contrast, spatial nTAT density (per grid cell; 5 arc min,  $\sim 85 \text{ km}^2$  at the equator) varies widely in countries with high agricultural diversity, such as the US (eastern Great Plains and Prairie Gateway), Argentina (Nordeste), and southeastern Brazil (Fig. 3B). The nTAT intensity quantifies the concentration of TAT per area in general (e.g., per country or crop), whereas the spatial nTAT density reveals finer-scale landscape patterns (i.e., grid cells) in the context of nTAT. Both metrics are likely to be critical for anticipating future pesticide-related ecological effects. In Nigeria, the only African country among the top 10 by crop area, the currently applied pesticide mix produces relatively low nTAT (Fig. 3, A and B). However, this may change, even in the entire African continent, as industrialized agriculture—which is often reliant on more-toxic pesticides to combat pest resistance (16, 37, 38)—continues to develop. Notably, some countries with high TAT intensities, such as Brazil, Argentina, and the US, have high adoption rates of genetically modified (GM) crops (39), underscoring that GM technologies do not necessarily reduce TATs and may even increase them, as observed in the US (16).

The nTAT intensity is highest for potatoes (primarily owing to mancozeb and paraquat; Fig. 3C; fig. S19 for continental overviews), sugarcane ( $\lambda$ -cyhalothrin and diuron), cotton (acetochlor and imidacloprid), soybean, and maize (glyphosate and chlorpyrifos). In contrast, the nTAT intensity is relatively low for cereals (here excluding maize and rice), fruit, and vegetables, despite the latter receiving numerous insecticide applications (fig. S20). The spatial nTAT density (Fig. 3D) is highest for

maize, cereals, and cotton, indicating more homogeneous and intensified cropping patterns that create regional ecotoxicological areas of concern. Conversely, crops with high nTAT intensities but low spatial densities (e.g., potatoes) reflect localized hotspots. Understanding crop-specific nTAT intensities and spatial density patterns is crucial for anticipating TAT changes, as future crop distributions will be shaped by factors such as shifting crop profitability and environmental conditions (40). Crops such as rape, maize, and cotton receive high herbicide applications (fig. S20), driving TAT in aquatic and terrestrial plants. However, high-toxicity insecticides, despite being applied at low rates in these crops, remain key contributors to rising invertebrate TATs (Figs. 3D and 1B). Crops in general—particularly major crops, covering large areas, or specialty crops, requiring highly toxic pesticides—are key determinants in future strategies for safeguarding biodiversity (figs. S15 and S16).

Crop contributions to national nTAT are disproportionately high relative to their cultivated area (Fig. 3E), particularly for soybean (Brazil), cotton (Brazil, China, India, Nigeria), rice (China, India, Nigeria), sunflowers (Ukraine), fruits and vegetables (US, Australia), and maize and potatoes (Argentina, China, Ukraine, Russia, US). Many of these crops also exhibit high nTAT intensities (Fig. 3C), underlining that substantial TAT contributions can arise from relatively small acreages. Cereals are an exception in several countries, including India, Nigeria, Ukraine, and the US, where their nTAT contribution is low relative to their acreage, much like fruits and vegetables in Brazil and Canada (Fig. 3E). The diverse pesticide mix in cereals (fig. S20) could offer opportunities to substitute compounds with higher specificity (i.e., lower toxicity to nontarget organisms), reducing TATs without compromising crop protection. For example, improved eco-efficiency in US cereal systems has been reported (20). More broadly, the variability

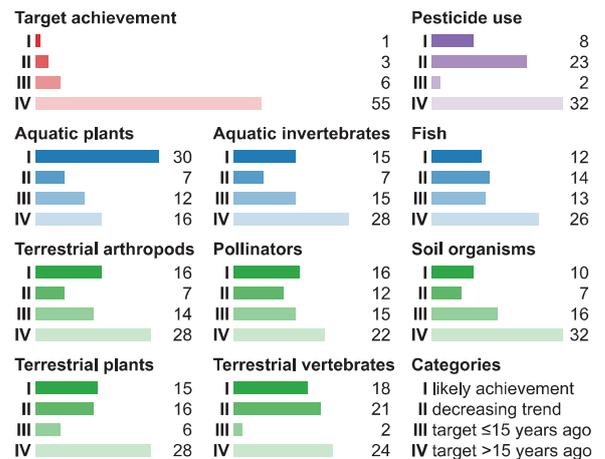


**Fig. 3. Country- and crop-specific characteristics of the maximum nTAT (2013–2019).** (A) Maximum nTAT (0–1 scaled), total agricultural area (megahectares), and resulting nTAT intensities (0–1 scaled) for the top 10 countries in terms of global agricultural area. (B) Spatial density distributions of maximum nTAT ( $\log_{10}$ , zero-centered; compare with Fig. 1) per grid cells for the top 10 countries versus the world, with quartiles shown as dashes. (C) Maximum nTAT (percent), total agricultural area (megahectares), and resulting nTAT intensities for the 11 main crops. National crop- and substance-specific statistics are shown in figs. S17 and S18. (D) Spatial density distributions of maximum nTAT ( $\log_{10}$ , zero-centered) per grid cells for the 11 main crops, with quartiles shown as dashes. (E) Radial histograms of the crop-specific contributions to national nTAT (outer ring) and the relative acreage per crop (inner ring) for the top 10 countries.

in country-crop combinations reflects diverse cropping systems and agronomic conditions, enabling multiple pathways to reduce national and global TATs.

**Pathways to approach the UN pesticide target**

Without intervention, only one (Chile) of the 65 countries with explicit national data—representing 79.4% of global crop acreage (26)—will achieve the UN GBF target of reducing pesticide risk by 50% by 2030 (II), as required to safeguard biodiversity (Fig. 4, target achievement category I). Target achievement categories synthesize national trends in nTAT, rating both direction and strength of change. China, Japan, and Venezuela are on track toward the target, showing declining trends for all indicators, although acceleration is needed (Fig. 4, category II). Thailand, Denmark, Ecuador, and Guatemala are currently moving away from the target (category III; see fig. S21 for categorization of countries), with at least one indicator doubling within the past 15 years. To meet the GBF target, they need to reverse rapidly increasing trends, which will presumably require immediate actions. All other countries require reverting pesticide risks to levels from >15 years ago (Fig. 4, category IV). Reverting such long-lasting and consolidated trends requires the most substantive efforts, including a systematic transformation of agriculture. However, trends toward the target (category I or II) are present in 26 to 57% of countries when assessed by species group individually (Fig. 4), enabling partial target achievement in shorter time frames. Risk categories for individual species groups can guide targeted toxicity reductions nationally, for example, neonicotinoids for pollinators (33) or pyrethroids for aquatic invertebrates (19). More intensive measures are needed for countries with increasing nTAT trends, forcing them to revert to nTAT levels that were present presumably years (Fig. 4, category III) or decades ago (Fig. 4, category IV). In these cases, enduring and substantive transformation efforts (e.g., integrated biological solutions, precision technologies, informed farmer



**Fig. 4. Categories showing the national efforts needed to achieve the UN biodiversity target of a 50% reduction by 2030 in pesticide risks and the respective number of countries.** Target achievement is the highest (considered to cover biodiversity in the broadest possible sense) category of a country in any of the TAT trends for the eight species groups. The category of the pesticide use reduction trend (purple) is based on FAO data (61). The categories of pesticide risk reduction trends in eight species groups are based on the nTAT (aquatic species, blue; terrestrial species, green). Categorizations are provided for 65 countries, representing 79.4% of global crop acreage, for which national pesticide use and TAT data were available (26) (see fig. S21 for national results). Category I denotes a likely 50% reduction by 2030; category II, a 50% reduction after 2030; category III, a required reversion to an empirical (pesticide use) or extrapolated (pesticide use or TAT) state of  $\leq 15$  years ago; and category IV, a required reversion to an empirical (pesticide use) or extrapolated (pesticide use or TAT) state of >15 years ago.

practices, supportive policies) are necessary. Countries with fast agricultural development should adopt these measures proactively before the increasing trends become entrenched. For pesticide use (Fig. 4), category distributions are similar to those of nTAT, although long-term data indicate that the 50% reduction requires reverting to levels from previous decades. Clustering countries by their nTAT trends (fig. S22), chemicals used (fig. S23), or crops (fig. S24; see fig. S25 for a metacluster of all three characteristics) supports national efforts toward the UN reduction target. For example, Costa Rica and Guatemala, both tropical rainforest biodiversity hotspots (1, 9), show annual TAT increases ranging from 5 to 64% across species groups (fig. S22). Other countries share a decreasing nTAT trend (fig. S22), including Japan (−8.4%), China (−4.2%), Chile (−8.2%), and Denmark (−2.9%), suggesting that measures such as China's zero-growth pesticide use policy (25, 41), the EU's neonicotinoid phaseout (19), fiscal policies [e.g., in Denmark (42)], or changes in crop compositions (43) can advance progress. Nevertheless, diverse and intensive measures will be required globally to achieve the UN target.

Reducing the toxicity of applied pesticide mixtures is key to achieving the UN reduction goal (Fig. 4, category I or II). Given that TATs are increasing in many countries (category III or IV), substantive measures are needed to restrict or substantially reduce use of highly toxic pesticides, which are often the dominant contributors to TATs (fig. S19). However, such measures must account for potential substitution effects: Reducing certain toxic pesticides may increase use of other toxic compounds as replacements (18), as assumed for pyrethroids replacing neonicotinoids (44), potentially shifting risks from one species group to another (16). A more effective approach is substituting pesticides with nonchemical alternatives. For example, it is assumed that nonchemical alternatives could replace neonicotinoids in 78% of case studies in France (44), suggesting that strict use reductions do not inherently produce compensatory effects. Furthermore, fast regime shifts in pesticide use are possible and have been observed in the US for aquatic plants, aquatic invertebrates, pollinators, or terrestrial arthropods within periods as short as 3 years (16). The development of novel pesticides, such as RNA interference-based and biological agents, could drive such shifts, but rigorous testing and assessment are required to ensure that toxicity-based indicators can capture their global ecosystem impacts.

Achieving a pesticide use reduction (i.e., mass reduction; Fig. 4) will likely require multiple measures, including spatially redistributed cropland (43, 45), feed-to-food shifts (46), food-waste reduction, dietary changes (47), and agricultural conversion to organic (48) or pesticide-free agriculture (49). However, increased adoption of organic or pesticide-free agriculture can lead to further changes in the agronomic system, with estimated reductions in crop yield ranging from 19 to 25%, depending on factors such as crop and bioclimatic conditions (50–52). While organic farming permits certain nonsynthetic pesticides, which can incur environmental costs (51), it offers several potential benefits, including higher biodiversity (48), improved soil and water quality (31), ecosystem multifunctionality (53), or enhanced profitability (54), although benefits are context dependent (51). Other measures, such as spatial structuring (45), agricultural diversification (50, 55, 56), and less intensive soil management (57), are beneficial for biodiversity or soil functionality without compromising yields and may even reduce reliance on chemical crop protection (55). Direct payment programs, such as those in Switzerland (58), or green insurance systems, also mitigate financial risks for farmers reducing pesticide use, as demonstrated by a 45% fungicide reduction in French viticulture (59).

### Challenges and perspectives

Globally, TATs are increasing (2013–2019) across many countries, crops, and species groups. Trends likely continued after 2019, as TATs have been shown to be stable over time (16, 19, 20, 60) provided no

abrupt changes in the agricultural or regulatory context occur (16, 19). Moreover, pesticide use shows continuing global trends since 2019 for all pesticide types (61). The reasons for the TAT increases observed here are manifold, including cropland expansion (61), intensification (43), and pest resistance (37) in both conventional and GM crops (16), all of which are expected to lead to further TAT increases in the future. Although various strategies and promising case studies exist, such as organic farming (48), pesticide-free farming (49), or crop diversification (55), their global adoption remains limited (62). The agriculture-policy-consumer system must accelerate the necessary transformation of global agriculture (47, 63, 64) to reduce the reliance on synthetic chemicals. Generally, the transition away from synthetic crop protection is still nascent and demands sustained political will, comparable to climate change mitigation efforts.

Substantial action is needed to reverse the rising dependency on synthetic pesticides (61, 65), driving increasing TATs across many species groups (16). With the UN GBF aiming to halve pesticide risks by 2030 (11), immediate actions are needed. The TAT approach, as proposed by the UN in the form of ATAT (14, 15) to measure target achievement, relies solely on two basic data inputs: pesticide use and toxicity metrics. However, pesticide use data, which detail the amount of pesticide active ingredients per crop and country annually, are often limited or incomplete. Many countries lack reliable data, and existing estimates [e.g., by the Food and Agriculture Organization of the United Nations (FAO) (61)] typically report mass per pesticide class or type, rendering them unsuitable for toxicity-based assessments. In the medium term, market research data (as used here) can fill this gap. Given the high toxicity of some pesticides, which are intentionally released into the environment (10), nations must collect and report detailed pesticide use data at the level of active pesticide ingredients over time. Pesticide toxicity data, which are essential for TAT estimations (16, 19), are now available (27) and can be used by agencies for future risk evaluations.

Our analysis, despite its high-quality curated data, carries some uncertainties. The method for distributing national pesticide use data per crop to grid cells was validated through uncertainty analyses (26). However, data-poor regions, such as central Africa, Southeast Asia, and the Middle East, may lack equivalent accuracy (26). In low- to middle-income countries with limited data availability, accessible indicators like the TAT may provide low-barrier tools to track progress toward UN reduction goals. Nevertheless, the link between pesticide use and biodiversity impacts is complex and influenced by various processes, and the TAT only indicates the role pesticide use plays in ecosystem degradation (16). Areas of high TAT values, as reported in the present study, coincide with RTL exceedances of 11,300 insecticide measurements in global surface waters, that is, risk quotients >1, and potential biodiversity effects thereof (8). A meta-analysis using 5830 concentrations of 32 insecticides measured in 644 US surface waters found toxicity-normalized insecticide use to be the most important driver for exposure and risks (17). Another meta-analysis of almost 1000 observations from North American and European field studies showed that nontarget arthropods are adversely affected by neonicotinoids and pyrethroids as the two groups of insecticides driving the TAT for this species group (66). Although evidence increasingly supports the connection between toxicity-weighted pesticide use and biodiversity effects (26), direct interpretation of TAT changes as biodiversity shifts remains speculative, often because of missing data. Given typical ecotoxicological dose-response relationships (67), biodiversity risks may respond nonlinearly. The categories presented here (Fig. 4) are intended to provide a framework until quantitative links between pesticide use and biodiversity effects are further established (2). Alternative pesticide indicators predict environmental pesticide concentrations and compare them to toxicity thresholds (9, 68, 69). Although these approaches integrate both key risk assessment elements, predicting exposure data requires numerous additional input variables, which are likely not yet readily available globally. Moreover, exposure predictions

on larger geographical scales either entirely lack validation with field measurements or studies have highlighted considerable shortcomings in these predictions (70, 71).

Validating pesticide risk indicators against biodiversity data is crucial, regardless of the approach used to assess pesticide risks or UN GBF target achievement. To enable validation, it is essential to prioritize the collection and sharing of key data, including active ingredient-specific pesticide use, exposure measurements, biodiversity metrics, and other relevant parameters, as a continued objective in each country. This will support data-driven decision-making, ensuring that efforts to address the pressing issue of the global biodiversity decline (2) are evidence-based and effective. Furthermore, these efforts will help to define the ill-defined planetary boundary (72) related to pesticides, which are among the most toxic chemicals actively released into the environment globally (10).

## REFERENCES AND NOTES

- M. J. W. Boyle *et al.*, *Nat. Rev. Biodivers.* **1**, 315–331 (2025).
- R. Cooke *et al.*, *Science* **388**, eadq2110 (2025).
- C. B. Edwards *et al.*, *Science* **387**, 1090–1094 (2025).
- P. Haase *et al.*, *Nature* **620**, 582–588 (2023).
- C. A. Hallmann *et al.*, *Nature* **639**, E7–E11 (2025).
- S. L. Rumschlag *et al.*, *Sci. Adv.* **9**, eadf4896 (2023).
- M. A. Beketov, B. J. Kefford, R. B. Schäfer, M. Liess, *Proc. Natl. Acad. Sci. U.S.A.* **110**, 11039–11043 (2013).
- S. Stehle, R. Schulz, *Proc. Natl. Acad. Sci. U.S.A.* **112**, 5750–5755 (2015).
- F. H. M. Tang, M. Lenzen, A. McBratney, F. Maggi, *Nat. Geosci.* **14**, 206–210 (2021).
- S. Bub, L. L. Petschick, S. Stehle, J. Wolfram, R. Schulz, *Science* **388**, 1301–1305 (2025).
- COP15, “Decision adopted by the conference of the parties to the convention on biological diversity: 15/4. Kunming-Montreal global biodiversity framework,” Convention on Biological Diversity, Montreal, Canada, 7 to 19 December 2022; <https://www.cbd.int/doc/decisions/cop-15/cop-15-dec-04-en.pdf>.
- N. Möhring *et al.*, *Nat. Ecol. Evol.* **7**, 1556–1559 (2023).
- M. Robuchon *et al.*, *Assessing Progress in Monitoring and Implementing the EU Biodiversity Strategy for 2030*, Joint Research Centre Science for Policy Report No. JRC136024 (Publications Office of the European Union, 2025); <https://data.europa.eu/doi/10.2760/8970981>.
- COP16, “Decision adopted by the Conference of the Parties to the Convention on Biological Diversity on 27 February 2025: 16/31. Monitoring framework for the Kunming-Montreal Global Biodiversity Framework,” Convention on Biological Diversity, Montreal, Canada, 25 to 27 February 2025; <https://www.cbd.int/doc/decisions/cop-16/cop-16-dec-31-en.pdf>.
- UN Environment Programme World Conservation Monitoring Centre, Metadata factsheet 7-2 Aggregated Total Applied Toxicity (ATAT); <https://gbf-indicators.org/metadata/headline/7-2>.
- R. Schulz, S. Bub, L. L. Petschick, S. Stehle, J. Wolfram, *Science* **372**, 81–84 (2021).
- J. Wolfram, S. Stehle, S. Bub, L. L. Petschick, R. Schulz, *Environ. Sci. Technol.* **53**, 12071–12080 (2019).
- L. Gensch, K. Jantke, L. Rasche, U. A. Schneider, *Environ. Pollut.* **348**, 123836 (2024).
- S. Bub, J. Wolfram, L. L. Petschick, S. Stehle, R. Schulz, *Environ. Sci. Technol.* **57**, 852–861 (2023).
- M. Love *et al.*, *Front. Insect Sci.* **5**, 1582496 (2025).
- W. Fang, Y. Peng, D. Muir, J. Lin, X. Zhang, *Environ. Int.* **131**, 104994 (2019).
- J. Hedlund, S. B. Longo, R. York, *Rural Sociol.* **85**, 519–544 (2019).
- H. Li, F. Cheng, Y. Wei, M. J. Lydy, J. You, *J. Hazard. Mater.* **324**, 258–271 (2017).
- C. A. Morrissey *et al.*, *Environ. Int.* **74**, 291–303 (2015).
- A. Shattuck, M. Werner, F. Mempel, Z. Dunivin, R. Galt, *Glob. Environ. Change* **81**, 102693 (2023).
- Materials and methods are available in the supplementary materials.
- J. Wolfram *et al.*, Additional data for Wolfram *et al.*: Increasing applied pesticide toxicity trends counteract the global reduction target to safeguard biodiversity, Zenodo (2025); <https://doi.org/10.5281/zenodo.17236389>.
- S. Fong, S. Louie, I. Werner, J. Davis, R. E. Connon, *San Franc. Estuary Watershed Sci.* **14**, 5 (2016).
- R. E. Mallinger, P. Werts, C. Gratton, *J. Insect Conserv.* **19**, 999–1010 (2015).
- Q. Yu *et al.*, *Earth Syst. Sci. Data* **12**, 3545–3572 (2020).
- P. Mäder *et al.*, *Science* **296**, 1694–1697 (2002).
- E. Fluet-Chouinard, S. Funge-Smith, P. B. McIntyre, *Proc. Natl. Acad. Sci. U.S.A.* **115**, 7623–7628 (2018).
- M. R. Douglas, D. B. Sponsler, E. V. Lonsdorf, C. M. Grozinger, *Sci. Rep.* **10**, 797 (2020).
- B. A. Vervaet *et al.*, *Kidney Int.* **97**, 350–369 (2020).
- M. R. Douglas, J. F. Tooker, *Environ. Sci. Technol.* **49**, 5088–5097 (2015).
- M. Hvězdová *et al.*, *Sci. Total Environ.* **613–614**, 361–370 (2018).
- F. Gould, Z. S. Brown, J. Kuzma, *Science* **360**, 728–732 (2018).
- M. A. Peterson, A. Collavo, R. Ovejero, V. Shivrain, M. J. Walsh, *Pest Manag. Sci.* **74**, 2246–2259 (2018).
- C. James, “Global status of commercialized biotech/GM crops: 2014,” ISAAA Brief No. 49 (International Service for the Acquisition of Agri-biotech Applications, 2014); <https://www.isaaa.org/resources/publications/briefs/49/executivesummary/>.
- A. Raza *et al.*, *Plants* **8**, 34 (2019).
- J. Shuqin, Z. Fang, *J. Resour. Ecol.* **9**, 50–58 (2018).
- H. Ø. Nielsen, M. T. H. Konrad, A. B. Pedersen, S. Gyldenkerne, *Land Use Policy* **126**, 106549 (2023).
- A. E. Larsen, F. Noack, *Proc. Natl. Acad. Sci. U.S.A.* **114**, 5473–5478 (2017).
- H. Jactel *et al.*, *Environ. Int.* **129**, 423–429 (2019).
- A. E. Larsen, F. Noack, L. C. Powers, *Science* **383**, eadf2572 (2024).
- A. Mottet *et al.*, *Glob. Food Secur.* **14**, 1–8 (2017).
- D. Gerten *et al.*, *Nat. Sustain.* **3**, 200–208 (2020).
- J. Bengtsson, J. Ahnström, A. C. Weibull, *J. Appl. Ecol.* **42**, 261–269 (2005).
- R. Finger, N. Möhring, *Nat. Plants* **10**, 360–366 (2024).
- L. C. Ponisio *et al.*, *Proc. Biol. Sci.* **282**, 20141396 (2015).
- V. Seufert, N. Ramankutty, *Sci. Adv.* **3**, e1602638 (2017).
- V. Seufert, N. Ramankutty, J. A. Foley, *Nature* **485**, 229–232 (2012).
- R. A. Wittwer *et al.*, *Sci. Adv.* **7**, eabg6995 (2021).
- D. W. Crowder, J. P. Reganold, *Proc. Natl. Acad. Sci. U.S.A.* **112**, 7611–7616 (2015).
- G. Tamburini *et al.*, *Sci. Adv.* **6**, eaba1715 (2020).
- A. Vialatte *et al.*, *One Earth* **8**, 101309 (2025).
- S. Q. van Rijssel *et al.*, *Science* **388**, 410–415 (2025).
- S. Dueri, G. Mack, *Sci. Total Environ.* **928**, 172436 (2024).
- M. Lefebvre *et al.*, *Eur. Rev. Agric. Econ.* **51**, 1201–1272 (2024).
- T. Perrot, J. Wolfram, R. Schulz, C. Fontaine, *J. Hazard. Mater.* **497**, 139695 (2025).
- Food and Agriculture Organization of the United Nations, FAOSTAT; [www.fao.org/faostat](http://www.fao.org/faostat).
- N. Möhring, A. Müller, S. Schaub, *Eur. Rev. Agric. Econ.* **51**, 1012–1044 (2024).
- B. Hofmann *et al.*, *Ambio* **52**, 425–439 (2023).
- J. Poore, T. Nemecek, *Science* **360**, 987–992 (2018).
- E. S. Bernhardt, E. J. Rosi, M. O. Gessner, *Front. Ecol. Environ.* **15**, 84–90 (2017).
- M. R. Douglas, J. F. Tooker, *PeerJ* **4**, e2776 (2016).
- C. H. Walker, R. M. Sibly, S. P. Hopkin, D. B. Peakall, *Principles of Ecotoxicology* (CRC Taylor & Francis, ed. 3, 2006).
- P. Kudsk, L. N. Jørgensen, J. E. Ørum, *Land Use Policy* **70**, 384–393 (2018).
- J. Strassmeyer, D. Daehmlow, A. R. Dominic, S. Lorenz, B. Golla, *Crop Prot.* **97**, 28–44 (2017).
- A. Knäbel, K. Meyer, J. Rapp, R. Schulz, *Environ. Sci. Technol.* **48**, 455–463 (2014).
- A. Knäbel, S. Stehle, R. B. Schäfer, R. Schulz, *Environ. Sci. Technol.* **46**, 8397–8404 (2012).
- K. Richardson *et al.*, *Sci. Adv.* **9**, eadh2458 (2023).

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## SUPPLEMENTARY MATERIALS

[science.org/doi/10.1126/science.aea8602](https://science.org/doi/10.1126/science.aea8602)  
Materials and Methods; Figs. S1 to S31; Tables S1 to S6; References (73–116);  
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## Increasing applied pesticide toxicity trends counteract the global reduction target to safeguard biodiversity

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### Editor's summary

During the 15th United Nations Biodiversity Conference, countries committed to reducing pesticide risk by 50% by 2030. To determine whether the world is on track to do so, Wolfram *et al.* looked at trends in usage and total applied toxicity (TAT) across more than 600 pesticides and eight species groups globally. They found that TAT has increased for most of these groups, but also that the majority of this impact comes from the 20 or so pesticides most commonly used in agriculture and from the largest crop-producing countries. Increased adoption of organic agriculture and shifts to less toxic pesticides are required to meet global commitments. —Sacha Vignieri

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