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A global assessment of glyphosate and AMPA inputs into rivers: Over half of the pollutants are from corn and soybean production

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ABSTRACT

Glyphosate is widely used in agriculture for weed control; however, it may pollute water systems with its by-product, aminomethylphosphonic acid (AMPA). Therefore, a better understanding of the flows of glyphosate and AMPA from soils into rivers is required. We developed the spatially explicit MARINA–Pesticides model to estimate the annual inputs of glyphosate and AMPA into rivers, considering 10 crops in 10,226 sub-basins globally for 2020. Our model results show that, globally, 880 tonnes of glyphosate and 4,090 tonnes of AMPA entered rivers. This implies that 82 % of the river inputs were from AMPA, with glyphosate accounting for the remainder. Over half of AMPA and glyphosate in rivers globally originated from corn and soybean production; however, there were differences among sub-basins. Asian sub-basins accounted for over half of glyphosate in rivers globally, with the contribution from corn production being dominant. South American sub-basins accounted for approximately two-thirds of AMPA in rivers globally, originating largely from soybean production. Our findings constitute a reference for implementing and supporting effective control strategies to achieve Sustainable Development Goals 2 and 6 (food production and clean water, respectively) simultaneously in the future.

1. Introduction

Glyphosate has been one of the most widely used herbicides in food production globally since the 1970s (Benbrook, 2016); it is commonly used in crop production to control weeds and clean vegetation before sowing and pre-harvesting crops (Maggi et al., 2020; Okada et al., 2020). In 2014, approximately 0.7 Tg of glyphosate was used globally, of which 90 % was used in agriculture (Benbrook 2016). According to Maggi et al. (2019), annual glyphosate use in agricultural areas is expected to exceed 0.9 Tg globally by 2025, potentially leading to increased glyphosate and aminomethylphosphonic acid (AMPA) pollution in rivers.

A better understanding of how the interrelations between glyphosate and AMPA affect river pollution is required. AMPA is the main metabolite involved in glyphosate biodegradation in the environment (Grandcoin et al., 2017). Compared to glyphosate, AMPA is highly persistent in the environment (with a half-life of 39–958 days) and has lower water solubility (Ferreira et al., 2023; Okada et al., 2020). Furthermore, AMPA is detected in the environment more frequently than glyphosate, even though glyphosate and AMPA are generally considered concomitant (Okada et al., 2020). This implies that the control of glyphosate in agriculture may also affect its by-product, AMPA, which flows into rivers.

Pollution caused by glyphosate and AMPA is of great concern globally owing to the associated potential negative effects on the environment and society (Carles et al., 2019; Van Bruggen et al., 2018). Following agricultural land application, glyphosate and AMPA can infiltrate into rivers and groundwater through runoff, soil erosion, and leaching (Geng et al., 2021; Lutri et al., 2020; Maggi et al., 2020). Despite degradation processes in the environment, both glyphosate and AMPA are considered pollutants in various environmental

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compartments, including soil and water (Aparicio et al., 2013; Brovini et al., 2021). The presence of glyphosate and AMPA in rivers can induce eutrophication (e.g. certain cyanobacteria can degrade glyphosate and utilize it as a source of phosphorus), reduce biodiversity, and pose hazards to microorganisms and invertebrates (Annett et al., 2014; Brovini et al., 2021; Carles et al., 2019). The potential effects on human health remain under debate. The International Agency on Research on Cancer of the World Health Organization has classified glyphosate as 'probably carcinogenic to humans' based on assessments of its potential chronic effects on human health in 2015(IARC, 2015; Van Bruggen et al., 2018). The European Food Safety Authority (EFSA) and the European Chemicals Agency (ECHA) have concluded that glyphosate is 'unlikely to pose a carcinogenic hazard to humans' (Kudsk and Mathiassen, 2020). Furthermore, glyphosate and AMPA may disrupt the human endocrine system and affect the ovarian and uterine functions in females (Ingaramo et al., 2020). These potential impacts have generated debates regarding banning the use of glyphosate, resulting in policy differences among countries (De Araujo et al., 2023; EC, 2023; Krimsky, 2021). Since 2023, the use of glyphosate in Europe has been proceeding with approval for the next 10 years, albeit with restrictions, such as the prohibition of pre-harvest use and protection of non-target organisms (EC, 2023). Other countries, such as Sri Lanka and Vietnam, have announced bans on the import and/or use of glyphosate (Finger et al., 2023; González-Moscoso et al., 2023).

The spatial origins of global glyphosate and AMPA pollution are not well documented at the sub-basin scale. Previous studies have determined glyphosate and AMPA concentrations in rivers at specified periods and locations (Geng et al., 2021; Okada et al., 2020), thereby providing valuable insights for policymakers and other stakeholders regarding the circumstances locally. Even though such insights are not easily available for sub-basins globally, they are needed to support the international Sustainable Development Goals (SDGs) 2 and 6 (food production and clean water, respectively). River sub-basins play crucial roles in the interactions between terrestrial and aquatic ecosystems. Chemicals used in agricultural production may impact water quality in sub-basins (Maggi et al., 2023). Documenting the production of glyphosate and AMPA within river sub-basins—especially for large rivers such as the Mississippi, Ganges, Danube, and Yangtze Rivers—helps identify pollution hotspots and better understand the sources of the pollutants.

There is a lack of quantitative information on which crops contribute to water pollution, by which pollutants, and for which sub-basins globally. Such comprehensive analyses could facilitate agriculture-related policies and contribute toward achieving SDGs 2 and 6 simultaneously. In the current literature (Jayasiri et al., 2022; Liu et al., 2020; Washuck et al., 2022), such analyses are sparse and often focus on a limited number of crops or specific locations. However, our knowledge is limited to the contributions of different crops to river pollution by pesticides, such as glyphosate. Few models consider glyphosate and AMPA in rivers (Desmet et al., 2016; Maggi et al., 2020); however, they are often on a grid scale (Maggi et al. 2020) or specific to catchments and streams (Desmet et al., 2016). Geng et al. (2021) used a modelling approach to quantify the environmental risks of glyphosate and AMPA in rivers and groundwater in 10 Chinese provinces and for nine crops (corn, rice, wheat, apple, pear, soybean, sunflower, vegetables, and sugarcane). However, such studies involving more than 10,000 sub-basins do not exist. The model family of Models to Assess River Inputs of pollutaNts to seAs (MARINA) has been developed for 10,226 sub-basins in the world. These models are primarily used for assessing water pollution caused by nutrients (Li et al., 2022; Wang et al., 2024), pathogens (Li et al., 2022), chemicals (triclosan and diclofenac) (Zhang et al., 2024), and plastics (Strokal et al., 2023). Such models offer opportunities for sub-basin-scale analyses; however, they do not consider pesticides. There is a need to better quantify the flows of glyphosate and AMPA from crop production into rivers globally and regionally (e.g. at the sub-basin scale) to prioritise investigations on where (i.e. in which sub-basins), which crops, and which pollutants (glyphosate and/or AMPA) dominate.

In this study, we developed the spatially explicit MARINA—Pesticides model to estimate the annual inputs of glyphosate and AMPA into rivers, considering 10 crops in 10,226 sub-basins globally for 2020. The model considers various factors, including land use, glyphosate application in crop production, soil processes (e.g. degradation and adsorption), and transport into rivers (e.g. runoff). The model estimates the flows of glyphosate and AMPA from cropland to rivers through surface runoff from 10 crops. Our research provides an up-to-date quantitative overview of glyphosate and AMPA inputs to rivers worldwide, highlighting the contribution of 10 crops to water pollution and prioritising areas (i.e. sub-basins) with considerable glyphosate and/or AMPA pollution. These findings constitute a reference for the development of enhanced international water pollution control strategies and can guide policymakers and stakeholders regarding prioritising the design of crop production policies to simultaneously achieve SDGs 2 and 6 (food production and clean water, respectively) in the future.

2. Material and methods

2.1. MARINA–Pesticides model (Global-1.0)

The model family of MARINA focuses on nutrients, plastics, and chemicals (diclofenac and triclosan). These models operate on the same temporal and spatial levels of detail (annual scale and 10,226 sub-basins, respectively). Here, we developed and evaluated the MARINA–Pesticides model to quantify the annual inputs of glyphosate and AMPA (i.e. the main by-product of glyphosate) from crop production (Fig. 1) and applied this model to 10,226 sub-basins globally for 2020. Our MARINA–Pesticides model is inspired by the existing MARINA-Antibiotics (China-1.0) (Zhang et al., Under review) and various approaches for pesticides (Ippolito et al., 2015; Maggi et al., 2020).

In the MARINA–Pesticides model, we use a lumped approach to estimate the annual inputs of glyphosate and AMPA into rivers from 10 crops. Crops include corn, soybean, wheat, cotton, rice, alfalfa, vegetable and fruit, orchards and grapes, pasture and hay, and other crops, in accordance with Maggi et al. (2019). We consider the application rates of the active ingredient of glyphosate, degradation (persistence) in the soil, soil adsorption, chemical characteristics, and surface runoff to determine the export fractions of glyphosate and AMPA from crop production to rivers (Fig. 1; Eqs. (1-5)). All model inputs were processed using ArcGIS (see Tables S2–S3 for details). Below, we explain the calculation of the annual inputs of glyphosate and AMPA into rivers from crop production.

The annual inputs of glyphosate and AMPA into rivers from cropland are estimated as a function of the active ingredient of glyphosate applied to cropland, its amount in the soil after crop interception, soil adsorption and degradation, and surface runoff (Eqs. (1)-(5)).

Firstly, we estimate the inputs of glyphosate to cropland using the active ingredient of glyphosate applied to 10 crops and its interception by these crops (Eq. (1)). The application rates of the active ingredients of glyphosate per crop production for the 10,226 sub-basins are calculated following Maggi et al. (2019). We aggregate the application rates of glyphosate active ingredients at a grid scale of 0.5 to the sub-basin scale. Details of the data processing of the glyphosate application rates are shown in Table S3. For the glyphosate interception by crops, we use 50 %, in accordance with Ippolito et al. (2015).

Secondly, we estimate the degradation of glyphosate in the soils and the conversion of its by-product, AMPA (Eqs. (2-4)). The degradations of glyphosate and AMPA in the soil are influenced by physical (e.g. soil properties), chemical (e.g. soil pH, soil organic carbon content, and the half-lives of glyphosate and AMPA), and biological (e.g. microorganisms) processes (Tables S1–S3). In our model, we consider physical processes through soil texture, chemical processes through the *Kd* value (i.e. the linear adsorption constant), and biological processes through the responses of microorganisms to soil pH, soil organic carbon,

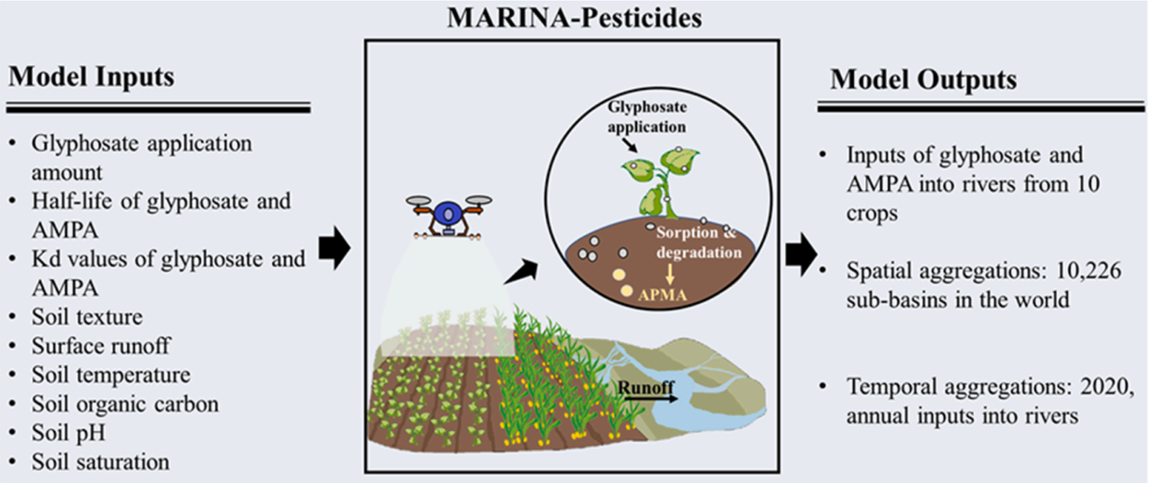

Fig. 1. Summarised overview of model inputs and outputs for the MARINA–Pesticides model. MARINA–Pesticides is short for Model to Assess River Inputs of pollutaNts to seA for Pesticides from crop production. The model is developed in this study and is a part of the MARINA model family. The model estimated inputs of glyphosate and aminomethylphosphonic acid (AMPA) into the rivers at the sub-basin scale for the year 2020. Sources: the MARINA–Pesticides model (see the model description in Section 2 and model inputs in Tables S1–S3).

soil temperature, and soil saturated water content. Details on these model inputs and calculations are provided in Tables S1–S3. We distinguish the dominant soil textures among the sub-basins based on data from NASA (2023). We take global data of *Kd* values for glyphosate and AMPA in the soil at a grid of 0.5 from Maggi et al. (2020). We then statistically average the *Kd* values over grids for each sub-basin. These processes are incorporated into our model to calculate the adsorption and degradation of glyphosate and AMPA in the soil (details are provided in Tables S1–S3).

According to previous studies (Grandcoin et al., 2017; Sun et al., 2019), 90 % of glyphosate can be converted to AMPA after 80 days in the soil. Based on this information, we set the threshold period for the conversion of glyphosate to AMPA to 80 days in the MARINA–Pesticides model. The amount of AMPA remaining after adsorption and degradation in the soil solution with a conversion time less than the threshold period (i.e. 80 days) is determined using Eq. (3). With a conversion time greater than 80 days, the amount of AMPA remaining after adsorption and degradation in the soil solution is calculated following Eq. (4).

Thirdly, we estimate the annual inputs of both glyphosate and its by-product, AMPA, into rivers (Eq. (5)) which are influenced by runoff and precipitation. This implies that the likelihood of glyphosate and AMPA entering rivers in sub-basins with higher export fractions is generally higher than that in sub-basins with lower export fractions. In our model, we evaluate surface runoff in upstream, midstream, and downstream sub-basins and do the same for precipitation. Details of the data processing and calculations for the model inputs are provided in Tables S1–S3. Below, we describe the main equations used to estimate glyphosate (Eqs. (1), (2), and (5)) and AMPA input to the rivers (Eqs. (3), (4), and (6)). More details are provided in Tables S1–S3.

Inputs of glyphosate to cropland at the sub-basin scale. The estimation occurs as follows:

$$WSdif_{gly.i.j} = D_{gly.i.j} \times \left(1 - \frac{I_j}{100}\right) \tag{1}$$

where $WSdif_{gly.i.j}$ is the annual amount of glyphosate (*gly*) in the soil after glyphosate application and interception by each crop (*i*) in sub-basin (*j*) (kg/year); $D_{gly.i.j}$ is the annual application amount of glyphosate (*gly*) to each crop (*i*) in a sub-basin (*j*) (kg/year); and I_j is the glyphosate interception rate by each crop (*i*) in a sub-basin (*j*) (%).

Degradation of glyphosate in the soil and the conversion of its by-product AMPA. The estimation is based on our modelling approach at the sub-basin scale:

$$Ssol_{gly.i.j} = WSdif_{gly.i.j} \times FS_{sol.gly.i.j} \times e^{-k_{gly.i.j} \times t_{i.j}} \tag{2}$$

where $Ssol_{gly.i.j}$ is the amount of glyphosate (*gly*) for each crop (*i*) that is retained in the soil solution (*Ssol*) after adsorption and degradation in a sub-basin (*j*) (kg glyphosate/year); $FS_{sol.gly.i.j}$ is the adsorption fraction (*FS*) of glyphosate (*gly*) in the soil solution (*sol*) from each crop (*i*) in a sub-basin (*j*) (value range: 0–1). This adsorption fraction of glyphosate is calculated based on the *Kd* value (i.e. the linear adsorption constant (L/kg)) for soil textures; $k_{gly.i.j}$ is the degradation rate of glyphosate (*gly*) in the soil following the application and glyphosate interception by each crop (*i*) in a sub-basin (*j*) (1/day); and $t_{i.j}$ is the degradation time duration (*t*) of glyphosate in the soil of a sub-basin (*j*) to each crop (*i*) (days).

$$Ssol_{AMPA.i.j} = \left(WSdif_{gly.i.j} - WSdif_{gly.i.j} \times FS_{sol.gly.i.j} \times e^{-k_{gly.i.j} \times t_{i.j}}\right) \times FS_{AMPA} \tag{3}$$

If the conversion time from glyphosate to its by-product AMPA is greater than the threshold period (80 days), then $Ssol_{AMPA.i.j}$ is estimated using Eq. (4) instead of Eq. (3).

$$\begin{aligned} Ssol_{AMPA.i.j} = {} & \left(WSdif_{gly.i.j} - WSdif_{gly.i.j} \times FS_{sol.gly.i.j} \times e^{-k_{gly.i.j} \times t_1}\right) \times FS_{AMPA} \\ & \times FS_{sol.AMPA.i.j} \times e^{-k_{AMPA.i.j} \times \left(t_{i.j} - t_1\right)} \end{aligned} \tag{4}$$

where $Ssol_{AMPA.i.j}$ is the amount of AMPA (*AMPA*) to each crop (*i*) that is retained in soil solution (*Ssol*) after adsorption and degradation in a sub-basin (*j*) (kg glyphosate/year); FS_{AMPA} is the fraction (*FS*) of degraded glyphosate that could be converted to AMPA (*AMPA*) without further degradation when the conversion time is less than the threshold period (value range: 0–1); $FS_{sol.AMPA.i.j}$ is the adsorption fraction (*FS*) of AMPA (*AMPA*) in soil solution (*sol*) from crop production (*i*) in a sub-basin (*j*) (value range: 0–1). The adsorption fraction of AMPA is calculated based on the *Kd* value (i.e. the linear adsorption constant (L/kg)) using soil textures; $k_{AMPA.i.j}$ is the degradation rate of AMPA (*AMPA*) in the soil following glyphosate application and interception by each crop (*i*) in sub-basin (*j*) (1/day); and t_1 is the threshold period (80 days) for glyphosate to its by-product AMPA in the soil (days).

Inputs of glyphosate and its by-product AMPA into rivers in sub-basins. The estimation occurs as follows:

$$RS_{gly.i.j} = Ssol_{gly.i.j} \times \ FEsr_j \tag{5}$$

$$RS_{AMPA.i.j} = Ssol_{AMPA.i.j} \times \ FEsr_j \tag{6}$$

where $RS_{gly.i.j}$ and $RS_{AMPA.i.j}$ are the total annual inputs of glyphosate (*gly*) and its by-product AMPA (*AMPA*) to rivers from each crop (*i*) in a sub-basin (*j*) (kg glyphosate/year and kg AMPA/year, respectively); $FEsr_j$ is the export fraction (*FE*) of glyphosate and AMPA transport from soil to rivers via runoff (*sr*) in a sub-basin (*j*) (value range: 0–1). This parameter is estimated as a function of surface runoff and precipitation. The Variable Infiltration Capacity (VIC) hydrological model provides data (natural river discharge and precipitation) (Stefan and Matthias, 2021). We estimate the export fraction in 2020 based on the 30–year (1990–2020) averaged runoff divided by the 30–year (1990–2020) averaged precipitation per sub-basin, following Li et al. (2023). For further details, we refer to Fig. S1 and Tables S2–S3.

2.2. Model evaluation approach

In our study, we follow the "building trust" approach, which has been widely used in existing large-scale water quality studies (e.g., (Li et al., 2023; Strokal et al., 2021)). This approach includes several options for building trust in the model. In our study, we focus on four main options and describe them in the following text, and the results are presented in Section 3.1.

The first option is to build trust in our model inputs. For this purpose, we compare our model inputs with those of other datasets. We do this for the following input parameters: soil temperature, soil saturation, soil organic carbon content, and soil pH. We plot these model inputs on the 1:1 line and assess the model's performance using two statistical indicators: Pearson's coefficient of determination (R_P^2; value range:0–1) and the Nash–Sutcliffe efficiency (NSE; value range: $-\infty$–1) (Moriasi et al., 2007). The values of R_P^2 and NSE are greater than 0.5, indicating an acceptable performance. In addition, we compare our model inputs with those of existing studies (Benbrook, 2016; Brookes, 2019; Clapp, 2021) based on collected global and regional data.

The second option is to build trust in our model's performance in estimating soil pollutants. For this purpose, we evaluate the performance of our model in estimating the pollutants in the soil by comparing our values with available measurements and other modelling results. Soil measurements of glyphosate and AMPA residues are obtained from previous studies (Alonso et al., 2018; Aparicio et al., 2013; Jing et al., 2021; Silva et al., 2018) (Table S4). In addition, we compare our modelling values for glyphosate and AMPA residues in the soil with the results of Maggi et al. (2023) (Table S4).

The third option is to build trust in our performance in estimating river pollution hotspots. For this purpose, we compare the spatial variability of river pollution hotspots with those of other studies (Brovini et al., 2021; Maggi et al., 2023; Maggi et al., 2019). We focus on glyphosate and AMPA river pollution hotspots that can be found in other available models and observations worldwide and in certain regions.

The fourth option is to reflect on the uncertainties in our model (including those associated with the inputs and the modelling approach). For this purpose, we follow Strokal et al. (2021) to test the sensitivity of the model outputs to changes in model inputs. We apply ±10 % perturbations to eight model inputs. The selected model inputs are: the export fraction of glyphosate and AMPA transport from the soil to rivers via runoff ($FEsr_j$; value range: 0–1, Eqs. (5) and(6)), the adsorption fraction of glyphosate in the soil solution ($FS_{sol.gly.i.j}$; value range: 0–1, Eqs. (2-4)), the adsorption fraction of AMPA in the soil solution ($FS_{sol.AMPA.i.j}$; value range: 0–1, Eq. (4)), the degradation time duration of glyphosate in the soil ($t_{i.j}$; days, Eqs. (2-4)), the degradation rate of glyphosate in the soil ($k_{gly.i.j}$; 1/day; Eqs. (2-4)), the degradation rate of AMPA in the soil ($k_{AMPA.i.j}$;1/day;Eq (4)), the annual application amount of glyphosate ($D_{gly.i.j}$; kg/year; Eq.(1)), and the rate of glyphosate interception by crops (I_j;%; Eq. (1)). This results in 16 additional model runs for 10,226 sub-basins globally. The sensitivity analysis is used to better understand how the uncertainties of these model inputs influence the model outputs. The results of the sensitivity analysis are shown in Figs. S5–S6 and discussed in Section 3.3.

2.3. Definition of pollution hotspots

We define "pollution hotspots" for our modeled annual inputs of glyphosate and its by-product AMPA to rivers in sub-basins following Li et al. (2022). We rank the sub-basins based on the inputs per km^2 of the sub-basin area in descending order: from Level I (lower inputs to rivers per km^2) to Level IV (higher inputs to rivers per km^2). For Level I, the inputs of glyphosate to rivers range from 0.000 to 0.008 g/km^2/year. For AMPA, this range is from 0.0 to 0.1 g/km^2/year. Ranges of Level II are as follows: 0.008–0.200 g/km^2/year for glyphosate and 0.1–2.0 g/km^2/year for AMPA. Ranges of Level III are as follows: 0.2–9.0 g/km^2/year for glyphosate and 2–53 g/km^2/year for AMPA. Ranges of Level IV sub-basins are considered pollution hotspots as follows: 9–1497 g/km^2/year for glyphosate and 53–7320 g/km^2/year for AMPA. For glyphosate and AMPA inputs to rivers, we further split Level IV into Levels IV-A and IV-B to better elucidate the spatial variabilities of glyphosate and AMPA river pollution hotspots, respectively. We also define sub-basins with priority glyphosate and/or AMPA pollution. For this purpose, sub-basins are further classified based on the inputs of glyphosate and/or AMPA into rivers that are under Level IV.

3. Results and discussion

3.1. River pollution with glyphosate and its by-product AMPA

3.1.1. River pollution globally and by continent

Globally, 880 tonnes of glyphosate and 4090 tonnes of AMPA entered rivers in 2020. At the continental scale, rivers in Asia and South America were generally more polluted than rivers in other continents.

Asia accounted for more than half of the total glyphosate inputs into rivers globally (Fig. 2), followed by South America and North America, which accounted for 25 % and 14 %, respectively (Fig. 2). Other continents contributed 0.4–5.0 % to the global pollution level. However, glyphosate river pollution varied across crops (Figs. 2 and 3). In Asia, corn production contributed more to glyphosate input into rivers than other crops (Fig. 2). A similar pattern was found for many rivers in South America. In other continents, the contribution of corn production ranged from 1 % (Australia) to 46 % (Africa). In contrast, soybean production was an important contributor to glyphosate pollution in rivers in South and North America but not in rivers in Asia (Fig. 2). For example, glyphosate pollution from soybean production in South and North American rivers accounted for more than 40 % of the global river pollution (Fig. 2). These results can be explained by the net effect of spatial variability in crop production and applications of glyphosate (Figs. S8–S9).

South America was responsible for approximately two-thirds of the AMPA input into rivers globally (Fig. 2) whereas the contributions of soybean production to AMPA river pollution in Asia, Europe, and Africa were much lower (Fig. 2). For the Asian and European continents, the contribution of corn production to the total AMPA river pollution was higher than those of other crops (Figs. 2-3). For rivers in Africa, the contribution of vegetable and fruit production was relatively higher than that for rivers in other continents (Fig. 3). Our results indicate that most crops contributed substantially to the annual AMPA inputs into rivers and not as much to the annual glyphosate into rivers. An exception was cotton production, for which we estimated a higher contribution to glyphosate than that to AMPA (Fig. 3).

3.1.2. River pollution at the sub-basin scale

We identified sub-basins with river pollution hotspots associated with glyphosate, AMPA, or both (Fig. 4). In Section 2.3, sub-basins with river pollution levels were defined from Level I (lower pollution) to

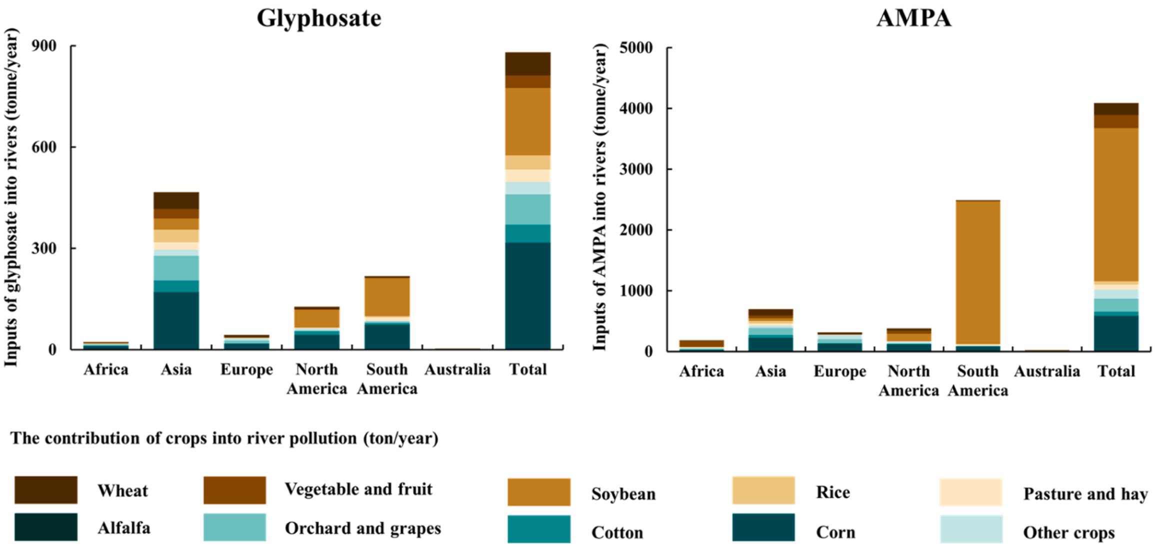

Fig. 2. Total annual inputs of glyphosate and aminomethylphosphonic acid (AMPA) into rivers by continents and crops in 2020 (tonne/year). "Other crops" include barley, flax, hops, oats, canola, tobacco, etc. following Maggi et al. (2019). Sources: the MARINA–Pesticides model (see Section 2 for the model description).

Level IV (most polluted sub-basins; pollution hotspots). Sub-basins with river inputs exceeding 9 g glyphosate/km^2/year and 53 g AMPA/km^2/year were considered pollution hotspots (Level IV).

3.1.3. River pollution hotspots associated with both glyphosate and AMPA

These hotspot sub-basins (Level IV) were largely located in Central Asia, southern South America, Europe, and North America (Figs. 4c). Over 50 % of the glyphosate and AMPA input into rivers in these sub-basins (Level IV) was attributed to corn and soybean production (Figs. 5 and S10). The hotspot sub-basins received approximately 100 g of glyphosate per km^2 of the sub-basin area and 550 g of AMPA per km^2 of the sub-basin area (Fig. 5). Higher pollution levels in these sub-basins could largely be associated with higher glyphosate application amounts on land compared to those in the other sub-basins (Fig. S9 and Supplementary Analysis). Consequently, more glyphosate and AMPA entered rivers. In addition, the hotspot sub-basins generally had moderate runoff (Figs. S11) and relatively slow degradation processes, which could also facilitate the mobility of these pollutants through the topsoil into rivers. Generally, glyphosate degradation is largely influenced by microbes. The intensity of their activity depends on several factors, such as soil pH, temperature, and organic carbon content. These hotspots associated with glyphosate and AMPA had soil pH at around 7.5 (alkaline), soil temperature at around 286 K, and soil organic carbon content at around 0.01 kg C/kg soil (Figs. S12–S13, and S15) The alkaline pH (pH >7) may inhibit microbial activities and decrease the adsorption of glyphosate and AMPA in the soil (Lupi et al., 2015). Lower soil temperature may inhibit microbial activities and slow the degradation of glyphosate and AMPA in the soil (Moller et al., 2024; Muskus et al., 2020; Muskus et al., 2019). This means that glyphosate and AMPA may have longer residence times in the soil than those in other sub-basins with higher soil temperatures (Bento et al., 2016; Muskus et al., 2020; Muskus et al., 2019). Lower soil organic carbon content may reduce the adsorption of glyphosate and AMPA to soil particles but may increase the availability of these substances in the soil solution and their accessibility to soil microbes for metabolism and degradation (Muskus et al., 2019; Van Bruggen et al., 2018).

3.1.4. River pollution hotspots associated with either glyphosate or AMPA

Most hotspot sub-basins (Level IV) were primarily located in Asia, North America, and Europe (Fig. 4). Their rivers were estimated to receive approximately 3–26 g of glyphosate per km^2 of the sub-basin area and 20–121 g of AMPA per km^2 of the sub-basin area (Fig. 5). For river pollution hotspots associated with AMPA, the contributions of corn production, orchard and grape production, and vegetable and fruit production were higher than those of other crops (Figs. 5 and S10). For river pollution hotspots associated with glyphosate, the contribution of corn and soybean production (60 %) was much more important than those of other crops (Figs. 5 and S10). These results could be explained by the fact that these crops were important in agriculture in these sub-basins, making them important contributors to river pollution (Fig. S9 and Supplementary Analysis). Other factors were associated with sub-basin and soil characteristics. For example, these hotspots were characterised by a generally higher runoff potential (i.e. a high runoff coefficient of approximately 0.5 on average; Figs. S11) and moderate degradation processes that could also facilitate the mobility of these pollutants through the topsoil to the rivers. Examples were soil pH (approximately 6.5 (slightly acidic)), soil organic carbon content (approximately 0.015 kg C/kg soil), and average soil temperature (approximately 288 K) (Figs. S12–S13, and S15–S16). A slightly acidic pH (i.e. 6–7) generally promotes the degradation of glyphosate, which results in increased AMPA from the degradation in the soil (Muskus et al., 2020; Muskus et al., 2019). In addition, a slightly acidic pH enhances microbial activities and reduces the adsorption of glyphosate and AMPA to soil particles (Padilla and Selim, 2020). Enhanced microbial activities can further degrade AMPA, primarily resulting in carbon dioxide and water; however, this process is also influenced by other factors (e.g. soil organic carbon and soil temperature), and as a result, more pollutants may enter rivers.

3.1.5. River pollution in other sub-basins

The inputs of glyphosate and AMPA into the rivers of Level I–III sub-basins were generally lower than those of the Level IV sub-basins (see above). Furthermore, the contribution of crops to river pollution with glyphosate and/or AMPA differed among the levels.

Level I sub-basins were mainly located in Africa, Australia, and Central Asia (Fig. 5). Their rivers received the lowest inputs of glyphosate and AMPA compared with those of the other sub-basins. For example, the rivers received approximately 0.002–0.070 g of glyphosate per km^2 of the sub-basin area and 0.03–1.00 g of AMPA per km^2 of the sub-basin area (Fig. S17). Corn, pasture, and hay production accounted for more than 50 % of glyphosate in the rivers (Fig. 5). Approximately 40 % of the total AMPA in the rivers was mainly from corn and other crops

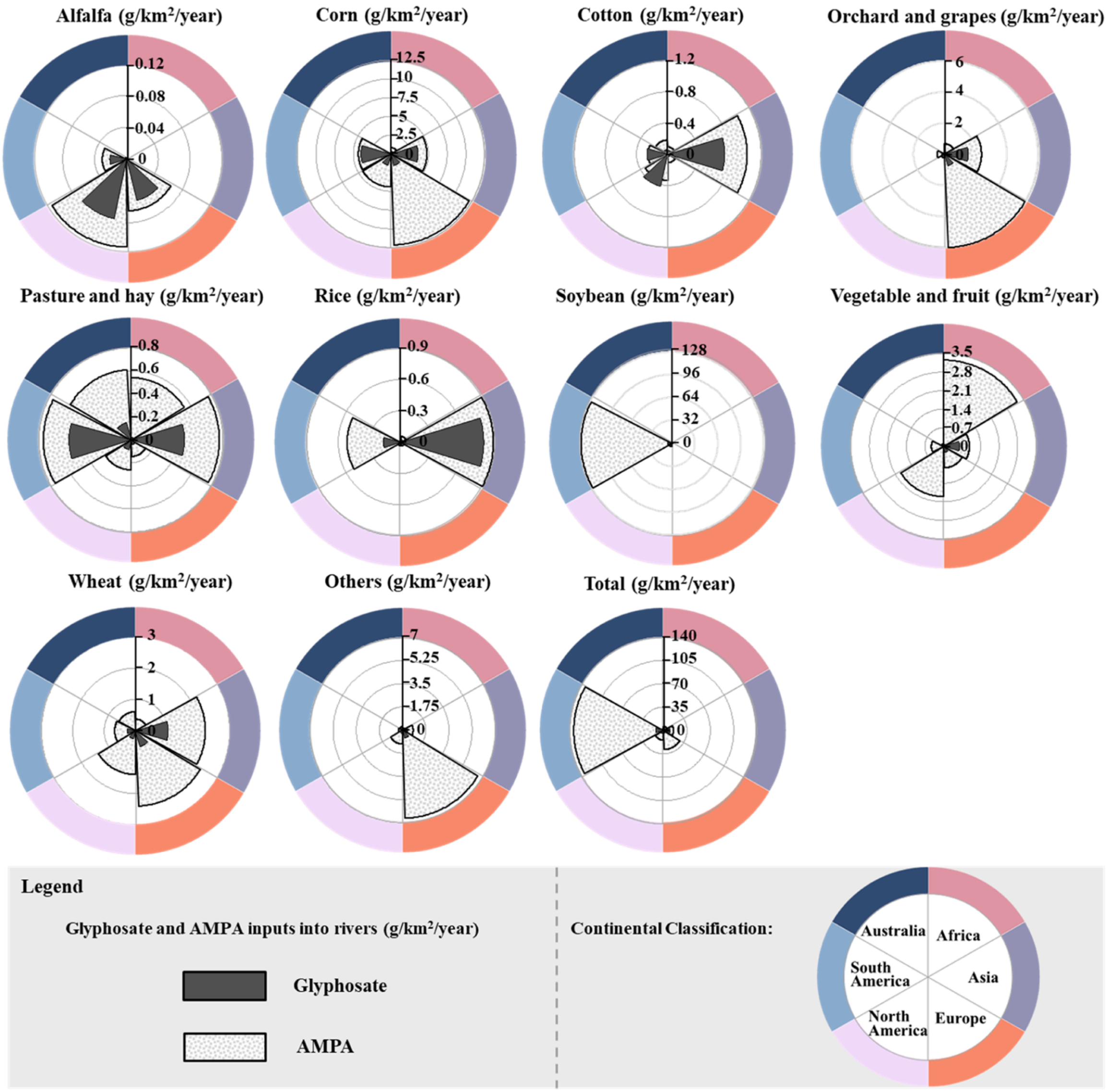

Fig. 3. Annual glyphosate and aminomethylphosphonic acid (AMPA) inputs into rivers by crops in 2020 (g/km^2/year). This figure shows modeled annual inputs with a focus on different crops for continents. "Other crops" include barley, flax, hops, oats, canola, tobacco, etc. following Maggi et al. (2019). Sources: the MARINA–Pesticides model (see Section 2 for the model description).

(e.g. barley, oats, and tobacco)(Figs. 5 and S17).

Level II sub-basins were largely located in Europe, Africa, and Australia (Fig. 5). Their rivers received approximately 0.06–0.40 g of glyphosate per km^2 of the sub-basin area and 0.6–2.0 g of AMPA per km^2 of the sub-basin area (Fig. S17). The contributions of corn, pasture, and hay production and vegetable and fruit production to glyphosate river pollution were higher than those of other crops (Fig. S17). For AMPA river pollution, the contribution of corn, wheat, pasture, and hay production was approximately 60 % (Fig. S17).

Level III sub-basins were primarily located in Central Asia, Europe, and North and South America (Fig. 5). Their rivers received approximately 0.002 g of glyphosate per km^2 of the sub-basin area and 0.009–0.012 g of AMPA per km^2 of the sub-basin area (Fig. S17). The production of corn, wheat, and soybeans was an important contributor to river pollution associated with either glyphosate or AMPA (Fig. S17).

The Level I–III sub-basins typically had lower glyphosate application rates (Fig. S9) and lower surface runoff (Figs. S11) but a faster degradation process than those in the other sub-basins. For example, on average, among the Level I–III sub-basins, pH was approximately 6.4 (slightly acidic), soil temperature was 290 K, and soil organic carbon content was approximately 0.025 kg C/kg soil (Figs. S12–S13 and S15). Previous studies have indicated that a slightly acidic pH generally promotes the degradation of glyphosate and AMPA in the soil (Bento et al., 2016; Muskus et al., 2020; Muskus et al., 2019). Higher soil organic carbon content and soil temperature can promote the degradation of glyphosate and AMPA in soil particles by enhancing the metabolic activity of soil microbial biomass, adsorption, and enzymatic processes (Muskus et al., 2020; Muskus et al., 2019). This combined effect resulted in faster degradation of glyphosate and AMPA in the soil, reducing their release into rivers.

3.2. Model evaluation

We evaluated our model results by considering four options (detailed descriptions in Section 2.2). For the first option, the model inputs were compared with independent datasets (Gruber et al., 2019; Martens et al., 2017; Meng et al., 2017; Meng and Wang, 2023; Nachtergaele et al., 2023; Shi et al., 2011). According to Moriasi et al. (2007), the comparisons of the model inputs with independent datasets indicated acceptable model performances ($R_P^2 > 0.8$ and NSE > 0.6; Figs. S2–S5;

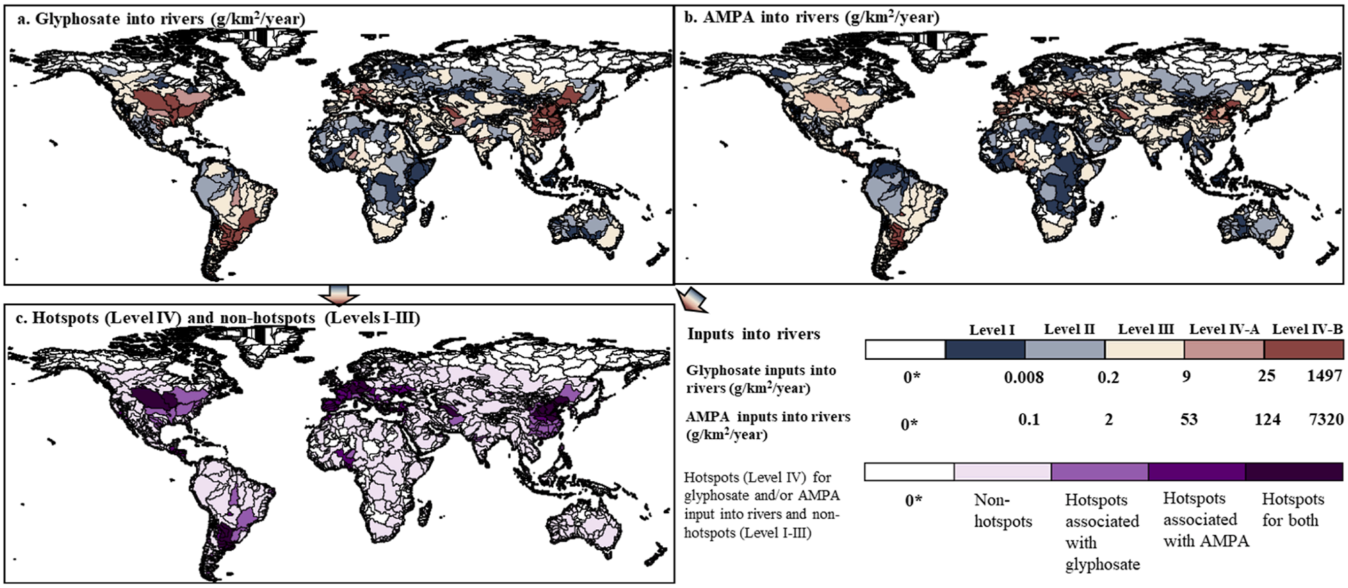

Fig. 4. River pollution with glyphosate and aminomethylphosphonic acid (AMPA) from crop production at the sub-basin scale in 2020. The maps show the total inputs of glyphosate (a) and AMPA (b) into rivers (g/km^2/year). Inputs are presented at the sub-basin scale and range from Level I to Level IV. Level IV sub-basins are considered pollution hotspots (see definition in Section 2.3). We further split Level IV into Levels IV-A and IV-B to better indicate the spatial variability of glyphosate and AMPA river pollution hotspots. "0*" indicates that no application of glyphosate or no data in these sub-basins. (c) Map of the hotspots of sub-basins associated with annual inputs of glyphosate and AMPA into rivers in 2020. Sources: the MARINA–Pesticides model (see Section 2 for the model description).

see Section 2.2 for detailed descriptions of the model evaluation). The comparisons of the model inputs with those of other studies showed the following. For application rates, our annual global glyphosate application in agricultural production was estimated at 777 million kg of active ingredient in 2020. Benbrook (2016) estimated 747 million kilograms of glyphosate as an active ingredient in agricultural production globally in 2014. Our model inputs were higher than those of Benbrook (2016) because of the different years. Furthermore, Brookes (2019) indicated that fruits, rice, vegetables, and corn were the dominant crops responsible for glyphosate use in China in 2015, which is consistent with our findings. Liang and Greene (2020) simulated the global runoff coefficient for 2016. They estimated that higher global runoff coefficient values in 2016 were distributed in the eastern part of Asia and North America, as well as in the northern part of Europe and South America. Our runoff coefficients matched these results.

For the second option, we compared our estimated glyphosate and AMPA levels in the soil using available observations and existing studies. For the South American sub-basins, our estimated concentration of glyphosate and AMPA in the soil (mg/kg soil) were within the ranges reported in other studies (see Table S4 for references). For example, our glyphosate concentrations in the soil in Colombia were estimated to be 0.0003–8.0000 mg/kg, which is within those reported by Maggi et al. (2020) (0–10 mg/kg) and Ferreira et al. (2023) (4 mg/kg) (Table S4). For the North American sub-basins, we estimated the glyphosate concentration in the soil to be 0.0006–36.0000 mg/kg, which was higher than 0.01–2.00 mg/kg reported by Ferreira et al. (2023), Tush et al. (2018), Okada et al. (2018) and Samson-Brais et al. (2022) (Table S4). Our estimates for most European sub-basins, except Italy, were within the ranges reported by Silva et al. (2018) and Karanasios et al. (2018) (0.02–41.00 mg/kg). Our glyphosate and AMPA concentration in the soil in Argentina was estimated at 0.02–29.00 and 0.0007–24.0000 mg/kg, respectively. Our estimates of glyphosate in the soil in Argentina were higher than measured values (0.002–8.000 mg/kg) (Alonso et al., 2018; Aparicio et al., 2023) and modelled results (0.003–1.000 mg/kg) (Maggi et al., 2020). Our estimated AMPA concentration in the soil in Argentina was within the range of measured values (0.002–39.000 mg/kg) (Aparicio et al., 2013; Bernasconi et al., 2021; Primost et al., 2017). These results were expected owing to variations in time and space. Importantly, the measurements were specific to particular times and locations and may not correspond to the spatial and temporal characteristics of our model. For example, Samson-Brais et al. (2022) measured glyphosate and AMPA in the soil during the 2015 cropping season in Canada. Okada et al. (2018) analysed the seasonal soil concentrations of glyphosate and AMPA between 2015 and 2016. Our study estimated the transport of glyphosate and AMPA from land to rivers in 2020. In addition, our hotspots for glyphosate and AMPA in the soil matched those estimated by other studies (Ferreira et al., 2023; Maggi et al., 2020).

For the third option, we focused on comparing the spatial variability of river pollution hotspots with other studies. For instance, Maggi et al. (2019) indicated that watersheds in Europe, North America, South America, and Asia have a relatively high runoff potential for both glyphosate and AMPA inputs into rivers, which is in line with our findings (Fig. 5). Other studies have indicated higher levels of glyphosate and AMPA in freshwater in Central North America and South America (Brovini et al. 2021), as well as in Central and Eastern China (Geng et al., 2021), which is consistent with our results.

For the fourth option, we performed a sensitivity analysis to reflect on uncertainties (see Section 2.2 for the setup and description). We applied ±10 % perturbations to eight model inputs reflecting the calculation of glyphosate and AMPA degradation, adsorption, and transportation in the soil and into rivers (see the list in Section 2.2). We compared the results of the original model run with those of 16 alternative model runs (from the sensitivity analysis; see Section 2.2). We presented our results by continent and focused on river pollution in sub-basins defined as hotspots (Level IV) and non-hotspots (Levels I–III; Figs. S6–S7). Overall, the model outputs were insensitive to the most perturbed model inputs. However, our comparisons indicated that model outputs were generally more sensitive to –10 % changes in degradation-related model inputs. This sensitivity differed across continents and pollution hotspots. For hotspot sub-basins associated with glyphosate and AMPA, the glyphosate inputs into rivers increased by 20 % as a result of a 10 % decrease in the duration and rate of glyphosate degradation in the sub-basins located in Africa, North America, and Europe. For hotspots associated with AMPA, similar results were obtained for the sub-basins in Asia, North America, and Europe. Hotspots

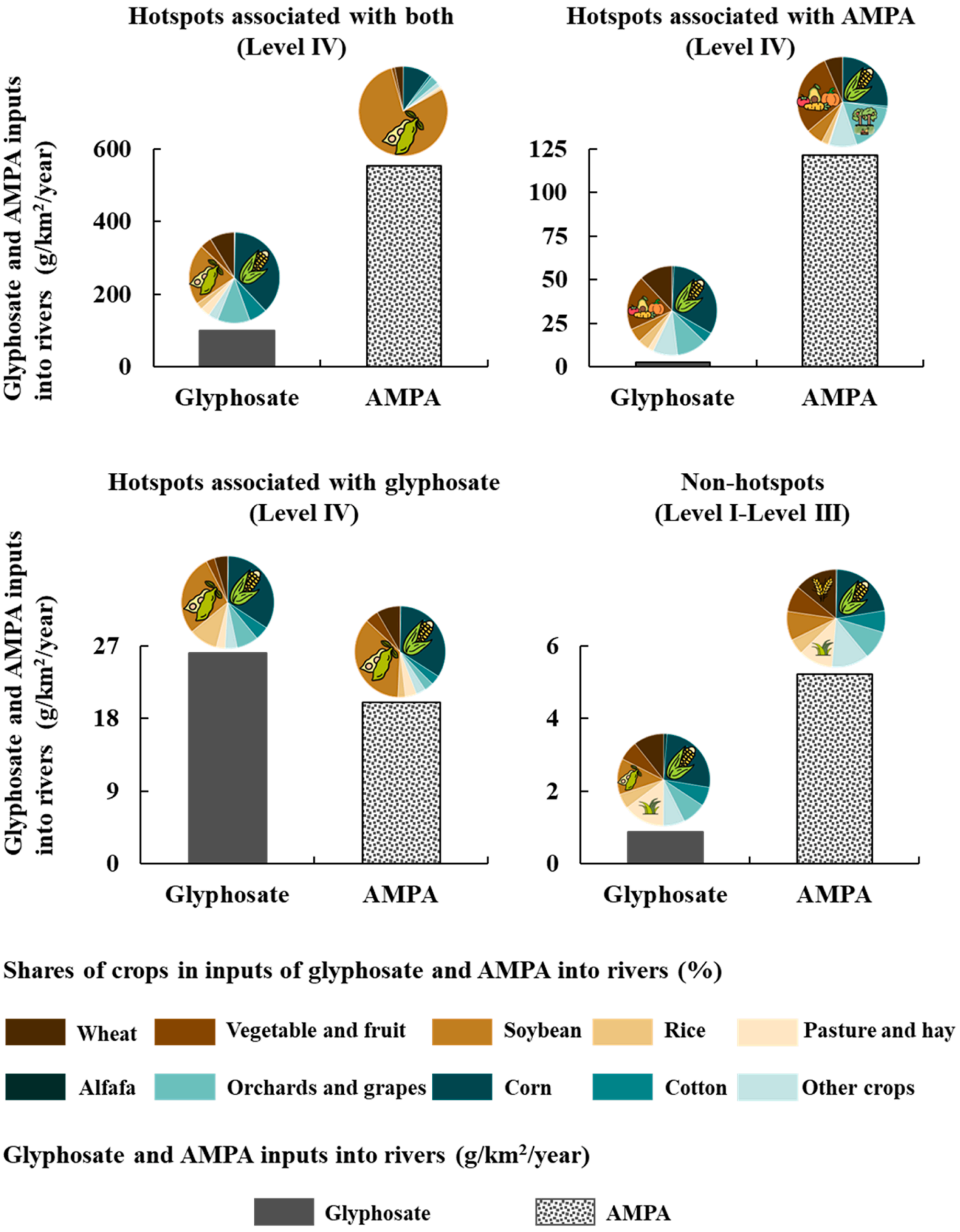

Fig. 5. River pollution with glyphosate and aminomethylphosphonic acid (AMPA) from crop production by pollution levels (Levels I–IV) in 2020. Bar charts show modelled inputs of glyphosate and AMPA into rivers in hotspots for both, hotspots associated with only glyphosate or AMPA, and non-hotspots sub-basins in 2020 (g/km^2/year). Pie charts show the shares of crops contributing to glyphosate and AMPA inputs into rivers (%). “Other crops” include barley, flax, hops, oats, canola, tobacco, etc. following Maggi et al. (2019). Inputs are presented at the sub-basin scale and range from Level I to Level IV. Level IV sub-basins are considered pollution hotspots (see definition in Section 2.3). Sources: the MARINA–Pesticides model (see Section 2 for the model description).

associated with glyphosate in Asia and Europe received approximately 20–40 % more glyphosate and AMPA into rivers as a result of a 10 % decrease in the duration and rate of glyphosate and AMPA degradation. For Levels I-III sub-basins, rivers received 20–30 % more glyphosate as a result of a 10 % decrease in the duration and rate of glyphosate degradation in the sub-basins located in Asia, Australia, and Europe (Fig. S6). These differences in the sensitivity results between hotspots and non-hotspots were largely associated with differences in the dominant crops, soil characteristics (e.g. soil temperature, pH, and soil organic carbon), hydrology (e.g. surface runoff), and planting seasons.

3.3. Uncertainties

Uncertainties were largely associated with the model inputs, processing methods, and uncertain parameters. Not all model inputs were at the sub-basin scale. Examples include the application rates of glyphosate per crop that were available at a grid of 0.5 scale (Maggi et al., 2020). We aggregated the gridded application rates to the sub-basin scale using the gridded harvested area at a grid of 0.5 scales (Table S3). We estimated the export fraction of glyphosate and AMPA leaving the soil and entering the rivers. However, the export fraction was generally uncertain. The calculations were based on surface runoff and precipitation per sub-basin, inspired by Li et al. (2023) and Zheng et al. (2021). Runoff and precipitation data were derived from the VIC hydrological model (Section 2.1) (Stefan and Matthias, 2021). The VIC is a large-scale hydrological model that has also uncertainties. The model was previously evaluated, exhibiting consistency with available observations (Van Vliet et al., 2016). We averaged the surface runoff and precipitation over five global climate models to avoid bias among different climate models. Additionally, the export fraction used in our study showed a result comparable to that of an existing study (Liang and Greene, 2020).

Our model used a lumped approach developed for large-scale analysis. Although our study calculated the fluxes of glyphosate and AMPA into rivers, we did not account for spatial variability within the sub-basins (e.g. distances between cropland and rivers). Thus, our approach may not be suitable for local analyses (e.g. specific fields or test plots). We realised that there were missing sources and transport processes, such as wind erosion, soil erosion, industry, non-agricultural usage, floods, and drought. Additionally, we only considered glyphosate and AMPA entering rivers via surface runoff, meaning that our estimates of glyphosate and AMPA pollution into rivers might have been underestimated. Nevertheless, we believe that these missing sources did not affect our main conclusions regarding river pollution from agricultural sources, because we accounted for the most relevant crop production sources of glyphosate and AMPA associated with agriculture on a global scale. Our modelling results were annual. Previous studies have indicated the seasonality of glyphosate pollution in surface waters (Carles et al., 2019; Feltracco et al., 2022). Future studies can build on our findings by accounting for missing sources and seasonality.

Our definition of hotspots differs from existing definitions focusing mainly on environmental, ecological, or human risks (Peake et al., 2015). Examples include the average daily doses of pesticides (Ferreira et al., 2023), maximum exposure thresholds to glyphosate in freshwater (CCME, 2012), and maximum permissible concentrations of pesticides in water, sediment, and soil (Traas and Smit, 2003). In addition, countries may set their thresholds. This adds to the complexity of analysing large-scale river pollution with pesticides. In our study, we defined pollution hotspots as follows: 9–1497 g/km^2/year for glyphosate and 53–7320 g/km^2/year for AMPA. We used these ranges because we intended to identify sub-basins with higher pollution levels of glyphosate and AMPA among the studied 10,226 sub-basins. We can identify hotspot sub-basins globally using the same criteria and perform comparisons among them. For example, the inputs of glyphosate and AMPA into rivers per km^2 in Levels IV–A and IV–B sub-basins were much higher than those in Levels I–III sub-basins. Thus, our definition of pollution hotspots should not be used for risk assessments but rather to gain a better understanding of the pollution levels among sub-basins globally.

To understand the impacts of uncertain inputs and parameters better, we performed several ways discussed in Section 3.2. One of them is a sensitivity analysis (Figs. S6–S7). The other ways are our comparisons in Section 3.2 with other studies increased the understanding of how our model inputs and outputs are similar or different from others. We realised that these options did not directly quantify the uncertainties but did build trust in our model. We called this the "building trust" approach which was widely applied to evaluate model performance at large scales (Li et al., 2023; Strokal et al., 2021; Zhang et al., 2024). The advantage of this approach was that we were able to build trust in the entire model chain, from the model inputs to the modelling approach and model outputs. We consider this to be a strong aspect of our modelling study.

Our model is the first to estimate the inputs of glyphosate and its by-product, AMPA, into rivers from crops at the sub-basin scale globally. Our model is integrated and more process-oriented than existing models (Desmet et al., 2016; Maggi et al., 2020). We accounted for 10 crops that are used globally. Our model allowed us to simultaneously estimate the inputs of glyphosate and its by-product, AMPA, into rivers from crop production. This has not been done previously for over 10,000 sub-basins globally. Our model considers the chemical, physical, and biological processes of glyphosate and AMPA transport in the soil and from land to rivers. Our approach provides opportunities to conduct future analyses on the impacts of climate change and technological implementation drivers.

3.4. Implications for sustainable crop production and clean waters

We provide a better understanding of how crop production can influence river pollution with glyphosate and its by-product AMPA. Our findings indicate that 4090 tonnes of AMPA entered rivers globally in 2020, which was four times the glyphosate input into rivers (Fig. 2). This implies the importance of considering by-products from chemical metabolic processes (e.g. the long-lasting effects of by-products) in water pollution control, supporting the simultaneous achievement of SDGs 2 and 6 (sustainable food production and clean water, respectively) (Fig. 6).

Identifying the contributions of specific crops is important to achieve sustainable crop production and clean water. Studies have shown the high contribution of corn and soybeans to water pollution (Battaglin et al., 2014; Benbrook, 2016). Our results estimate that over half of the glyphosate and AMPA loadings from these two crops entered rivers globally. Thus, improving corn and soybean production with less pesticide use may considerably reduce river pollution globally (Aparicio et al., 2023; González-Moscoso et al., 2023). This would support SDG 6 (positive impacts, Fig. 6), but may not be beneficial for SDG 2 because of challenges in food security (negative impacts, Fig. 6). Currently, there is a debate regarding whether to ban the agricultural use of glyphosate (De Araujo et al., 2023; EC, 2023; Finger et al., 2023; Krimsky, 2021). On the one hand, banning glyphosate use could reduce its presence and that of AMPA in crops and soils, thereby mitigating their negative impacts on river pollution and society (Fig. 6). On the other hand, banning glyphosate could also pose challenges to achieving SDG 2 (negative impacts, Fig. 6) (Matousek et al., 2022; Pieter de, 2023). For example, farmers would need to use other herbicides or mechanical weed management (e.g. ploughing) to maintain their crop yields. Mechanical weed management may increase the environmental problem of soil erosion, and reduce soil quality and crop yields (Matousek et al., 2022). These can be both challenges and opportunities, especially for sub-basins that rely heavily on the use of glyphosate for crop production and contribute considerably to river pollution (e.g. Asia and South America; Fig. 2).

Our study provides a better understanding of where (i.e. which sub-basins), to what extent (pollution levels), and from which crops rivers were contaminated by glyphosate and its by-product AMPA (Figs. 4a–c). This can help prioritise glyphosate and AMPA pollution reduction strategies. The contribution of crops to glyphosate and AMPA river pollution varied between hotspot (Level IV) and non-hotspot (Levels I–III) sub-basins. We showed that soybean and corn production was the most important contributor in hotspots (Level IV) (Fig. 5), particularly in the sub-basins in North and South America. Other studies have shown similar spatial variability of glyphosate from corn and soybean production in the United States (Battaglin et al., 2014; Benbrook, 2016). For Level I sub-basins, corn, pasture, and hay productions were considerable contributors to the inputs of glyphosate and AMPA into rivers (Fig. 5). Corn, vegetables and fruits, and soybean productions were considerable contributors to river pollution in Level II sub-basins. To the best of our knowledge, existing studies have been limited to the analysis of Level

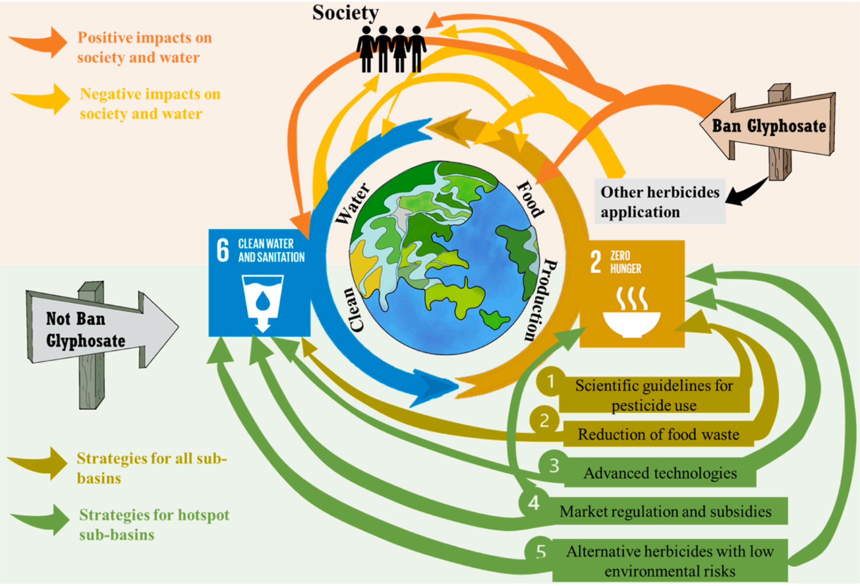

Fig. 6. Challenges and opportunities for achieving SDGs 2 and 6 under the implication of banning or not banning glyphosate use in agriculture. Options 3, 4, and 5 mitigate glyphosate and AMPA pollution in hotspot sub-basins. Options 1 and 2 mitigate glyphosate and AMPA pollution in all sub-basins. For the definition of hotspots (Level IV sub-basins) and non-hotspots (Level I–III sub-basins), see Section 2. The thickness of the arrow has the same meaning.

I–II sub-basins (Desmet et al., 2016; Maggi et al., 2020). Our results provide new insights and a basis for future studies on these regions. For Level III sub-basins, corn, wheat, and soybeans were important for the inputs of glyphosate and AMPA into rivers. The differences in the main crops among the sub-basins imply that crop–region–specific agricultural management is important for glyphosate and AMPA pollution reduction globally (Fig. 6).

Strategies for reducing river pollution may differ between non-hotspots (Levels I–III) and hotspots (Level IV). For Level I–III sub-basins, some basic strategies can be commonly applied, such as scientific guidelines for pesticide use and the reduction of food waste, which could serve as the first step for reducing river pollution with glyphosate and AMPA (Fig. 6). For Level I sub-basins, corn production and pasture and hay production are particularly in need of scientific guidance on agricultural practices as well as legal and subsidy support from the government. For Level II sub-basins, strategies could focus on better management of glyphosate usage in corn, vegetables and fruits, and soybean production and food waste. For Level III, strategies could include policies and scientific guidelines for glyphosate use in corn, soybean, and wheat production to effectively control the associated production, consumption, and application, as well as market regulations and subsidies (Fig. 6). Reducing food waste can also serve as a strategy for reducing pesticide pollution and helping achieve SDG 2 in non-hotspot sub-basins (Fig. 6). This is because reduced food waste decreases the pressure on food production, which reduces the application of pesticides, including glyphosate, in crop production.

More effort may be needed to control glyphosate and AMPA pollution in hotspots than in non-hotspots (Fig. 6). These strategies may depend on the dominant pollutants (glyphosate, AMPA, or both). For Level IV sub-basins (pollution hotspots), several strategies can be used to reduce river pollution associated with both glyphosate and AMPA. For example, promising strategies for hotspots associated with both glyphosate and AMPA pollution include advanced technologies, such as advanced oxidation processes (Mohd Ghazi et al., 2023), use of *Chryseobacterium* sp. for biological treatment in the soil (Zhang et al., 2022), market regulation and subsidies, and alternative herbicides with low environmental risks (e.g. use of plant extracts for the biological control of weeds) (Al-Samarai et al., 2018). For hotspots associated with glyphosate alone, strategies could focus on better management of glyphosate usage in agricultural production and food waste (Fig. 6). These strategies could include policies for scientific guidelines for glyphosate use to effectively control its production, consumption, and application in agricultural areas, as well as market regulations and subsidies (Fig. 6) (Chen et al., 2017; Möhring et al., 2020; Wuepper et al., 2023). For hotspots associated with AMPA only, strategies, such as advanced technologies and alternative herbicides with low environmental risks, could be important for mitigating river and soil pollution (Al-Samarai et al., 2018).

4. Conclusions

This study modelled in a spatially explicit manner the annual inputs of glyphosate and its by-product, AMPA, into rivers from crop production in 2020, while taking into account 10 crops globally. We developed the MARINA–Pesticides model and applied it to 10,226 sub-basins globally for glyphosate and AMPA. Our estimates indicated that approximately 880 tonnes of glyphosate and 4090 tonnes of AMPA entered global rivers in 2020. Asian sub-basins accounted for over 50 % of glyphosate entering rivers globally, with the contribution from corn production being dominant. South American sub-basins accounted for approximately two-thirds of AMPA in rivers globally, originating largely from soybean production. Our study provides a comprehensive overview of the inputs of glyphosate and AMPA into rivers globally. We identified specific sub-basins and crops for which control strategies could be prioritised to enhance the sustainability of crop production. These insights can inform the development of effective strategies for crop production, simultaneously contributing to the achievement of Sustainable Development Goals 2 and 6 (food production and clean water, respectively) in the future.

CRediT authorship contribution statement

Qi Zhang: Writing – review & editing, Writing – original draft, Visualization, Validation, Resources, Project administration, Methodology, Formal analysis, Data curation. **Yanan Li:** Writing – review & editing, Methodology, Conceptualization. **Carolien Kroeze:** Writing – review & editing, Supervision. **Wen Xu:** Writing – review & editing, Supervision. **Lingtong Gai:** Writing – review & editing. **Miltiadis Vitsas:** Writing – review & editing, Methodology. **Lin Ma:** Writing – review & editing, Supervision. **Fusuo Zhang:** Writing – review & editing, Supervision. **Maryna Strokal:** Writing – review & editing, Supervision, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

All sources to model inputs are provided in the Supporting Material. Model outputs are presented in the manuscript and the Supporting Material. Main model outputs supporting the display items in the manuscript will be made available through a DANS-EASY repository link.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.watres.2024.121986.

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