Journal of Environmental Management 317 (2022) 115361

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Past and future pesticide losses to Chinese waters under socioeconomic development and climate change

Ang Li [a,b,**], Mengru Wang [b], Carolien Kroeze [b], Lin Ma [a], Maryna Strokal [b,*]

[a] Key Laboratory of Agricultural Water Resources, Center for Agricultural Resources Research, Institute of Genetic and Developmental Biology, The Chinese Academy of Sciences, 286 Huaizhong Road, Shijiazhuang, 050021, Hebei, China
[b] Water Systems and Global Change Group, Wageningen University & Research, P.O. Box 47, 6700 AA, Wageningen, the Netherlands

ARTICLE INFO

Keywords:
Pesticides
Water pollution
Socio-economic developments
Climate change
Trends
China

ABSTRACT

Increasing pesticide use pollutes Chinese surface waters. Pesticides often enter waters through surface runoff from agricultural fields. This occurs especially during heavy rainfall events. Socio-economic development and climate change may accelerate future loss of pesticides to surface waters due to increasing food production and rainfall events. The main objective of this study is to model past and future pesticide losses to Chinese waters under socio-economic development and climate change. To this end, we developed a pesticide model with local information to quantify the potential pesticide runoff from near-stream agriculture to surface waters after heavy rainfall. We project future trends in potential pesticide runoff. For this, we developed three scenarios: Sustainability, "Middle of the Road" and Economy-first. These scenarios are based on combined Shared Socio-economic Pathways and Representative Concentration Pathways. We identified hotspots with high potential pesticide runoff. The results show that the potential pesticide runoff increased by 45% from 2000 to 2010, nationally. Over 50% of the national pesticide runoff in 2000 was in five provinces. Over 60% of the Chinese population lived in pesticide polluted hotspots in 2000. For the future, trends differ among scenarios and years. The largest increase is projected for the Economy-first scenario, where the potential pesticide runoff is projected to increase by 85% between 2010 and 2099. Future pesticide pollution hotspots are projected to concentrate in the south and southeast of China. This is the net-effect of high pesticide application, intensive crop production and high precipitation due to climate change. In our scenarios, 58%–84% of the population is projected to live in pesticide polluted hotspots from 2050 onwards. These projections can support the development of regional management strategies to control pesticide pollution in waters in the future.

1. Introduction

In China, the use of pesticides increased since the 1970s to ensure food security, and to protect crops from pests, weeds and fungal disease. In 1995, the total pesticide use in China reached one million ton and has been increasing since then (NBSC and NBoSo, 2018). In 2006, 90 million tons of cereals and 78 million tons of vegetables were produced that required pesticides. However, pesticides can have environment impacts (Fang et al., 2017; Hernández et al., 2013; Morrissey et al., 2015; Zhang et al., 2019).

Pesticides and their related metabolites have been detected in soil and waters in China (Gao et al., 2009; Huang et al., 2018; Liu et al., 2016). Many pesticides are toxic and not easily degraded in the environment (Grung et al., 2015b; Huang et al., 2018; Yang et al., 2016). Despite regulations, pesticides are still detected in the environment. For example, dichlorodiphenyltrichloroethane (DDT) has been banned since 1983 (Tao et al., 2007). Nevertheless, DDT is still detectable in the North China Plain, Bohai Sea, the Yangtze River Delta, and the Pearl River Delta (Brauns et al., 2018; Grung et al., 2015a; Guo et al., 2009; Han and Currell, 2017; Hu et al., 2009; Nakata et al., 2005; Ta et al., 2006). Some studies reported past contamination of waters with pesticides at basin or national scales in China (Jin et al., 2019; Liu et al., 2015, 2016; Mai et al., 2002; Wauchope, 1978). For example, Ouyang et al. (2016) estimated that 4.39 × 10^3 tons of pesticide losses to the environment

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* Corresponding author.
** Corresponding author. Key Laboratory of Agricultural Water Resources, Center for Agricultural Resources Research, Institute of Genetic and Developmental Biology, The Chinese Academy of Sciences, 286 Huaizhong Road, Shijiazhuang, 050021, Hebei, China.
E-mail address: maryna.strokal@wur.nl (M. Strokal).

https://doi.org/10.1016/j.jenvman.2022.115361
Received 15 September 2021; Received in revised form 11 May 2022; Accepted 17 May 2022

nationally in 2011. These losses mainly occurred in the eastern and southern provinces, such as Shandong, Jiangxi, and Guangxi. Zheng et al. (2016) reported on 82 types of pesticides in water and sediments of the Jiulong River basin. The concentrations of 14 out of 82 types of pesticides exceeded 100 ng L^{-1}, with highest concentrations of procymidone (3904 ng L^{-1}). Many other studies report on pesticide contamination in China (Gao et al., 2009; Grung et al., 2015b; Wu and Chen, 2013; Zhou et al., 2006, 2008). Therefore, the Chinese government launched the National Agricultural Diffuse Pollution Action Plan in 2015 to prevent water pollution from pesticides (MOA, 2015).

In the future, pesticide losses to waters may increase (Delcour et al., 2015; Kattwinkel et al., 2011). The Chinese population and urbanization are projected to increase (Ding et al., 2018; Guo et al., 2019). Consequently, food demand will increase. However, the Chinese government prefers not to expand or reduce agricultural land (Zhao et al., 2011). Therefore, current Chinese agricultural practices are intensifying (Shen et al., 2013; Wang et al., 2018). This also holds for pesticide use (Zhang et al., 2015). This could increase pesticide pollution in Chinese waters. However, our knowledge about the effects of intensified agricultural practices on pesticide pollution in waters is limited. Additionally, climate conditions affect the number of pesticides lost to surface waters. Many pesticides are applied to cropland through drifting or spraying (Matthews, 2008). After application, pesticides enter the nearby waters through surface runoff generated after heavy rainfall events (Berkowitz et al., 2014; Ritter and Shirmohammadi, 2000; Wauchope, 1978). Climate change can influence future rainfall patterns affecting pesticide losses into surface waters (Lee et al., 2014; Wang and Chen, 2014; Zhou et al., 2014). However, studies focusing on the influence of climate change on pesticide losses into surface waters in China are lacking.

The main objective of this study is to model the past and future potential pesticide losses to Chinese waters under socioeconomic development (e.g., population growth, income) and climate change. We develop a pesticide model based on an existing global insecticide model developed by Ippolito et al. (2015) with local information to quantify the potential pesticide runoff in China in the past. We develop three scenarios reflecting future food production and climate change in China. These scenarios are based on combined Shared Socioeconomic Pathways (SSPs) describing future socioeconomic development and Representative Concentration Pathways (RCPs) describing future climate change (O'Neill et al., 2014; Van Vuuren et al., 2011). Finally, we analyse hotspots with high potential for pesticide runoff (see Section 2). Our study contributes to a better understanding of future spatial patterns in pesticide pollution in Chinese waters.

2. Material and methods

2.1. Model description and inputs

We develop a pesticide model based on the existing insecticide model by Ippolito et al. (2015) and used local information to run the model. The model is applied to the past and future. For future years, we develop scenarios and incorporate them into the pesticide model for China. The model quantifies the potential for pesticide runoff from the near-stream agriculture to surface waters in 2000, 2010, 2050, and 2099 at 0.5°. These calculated potential pesticide runoff can reflect the upper bound of pesticide losses to surface water in response to the maximum daily rainfall within the year. In addition to the maximum daily precipitation, our model considers other factors (see below, Fig. 1 and Table A.1). We model at the grid of 0.5° to show the spatial variability across China.

We modify the global insecticide model developed by Ippolito et al. (2015) for the Chinese situation. The main equations for quantifying the potential for pesticide runoff (gLOAD) and the generic indicator of the gLOAD (RP) are provided in Fig. 1. The RP is calculated as the logarithm of gLOAD (Eq.1 in Fig. 1). gLOAD is calculated as a function of nine major factors that affect pesticide losses to surface waters (Eq.2 in Fig. 1). These nine factors are the area of the near-stream agricultural land (A, km2), pesticide application rate (D, g km−2), soil carbon content (OC, %), soil texture (T, classified into fine and coarse soil), average

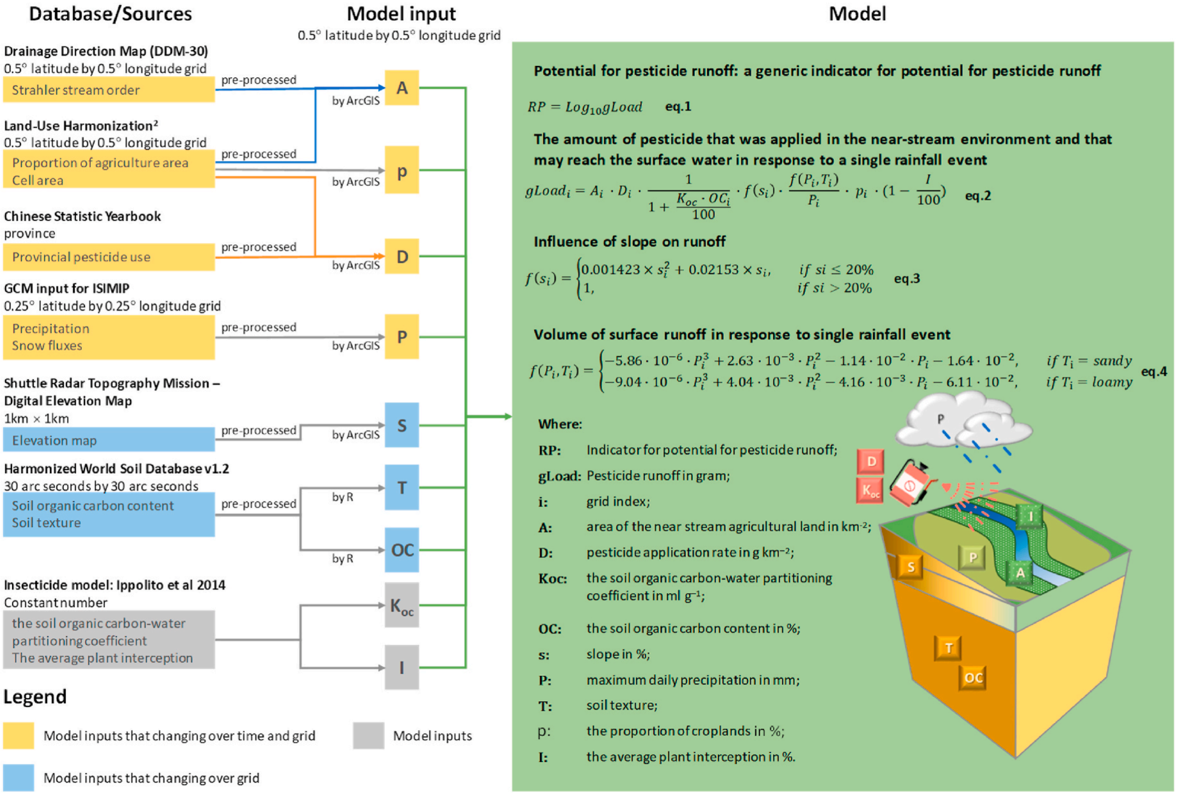


Fig. 1. Model inputs and model description for the pesticide model. See Table A.2 for input sources and pre-processing methods.

slope (s, %), the proportion of agricultural land (p, %), maximum daily precipitation (P, mm), soil organic carbon-water partitioning coefficient of the pesticide (Koc, ml g^{-1}), and plant interception (I, %). Model outputs are gLOAD and RP per grid of 0.5° for China.

The model inputs are pre-processed or derived from different existing databases (Fig. 1 and Table A.2). We modified the approach of Ippolito et al. (2015) to calculate the near-stream agricultural land for a 0.5° grid as follows. Based on the drainage direction map (DDM-30), grids are classified as those with a main channel or tributaries (Döll and Lehner, 2002). We assume that grids with the main channel have three-segmented streams. Grids with tributaries have two segmented streams. A segmented stream in the grid is assumed to be 1500 m in length. The near-stream area is defined as the area along the stream within 100 m. Agricultural land in the near-stream area is defined as near-stream agricultural land. If the near-stream area is less than the agricultural area, the near-stream agricultural land is set at 0.45 km^2 for a grid with the main channel and 0.30 km^2 for a grid with tributaries. If the near-stream area is larger than the agricultural land area, then the near-stream agricultural area equals the agricultural land in the grid.

The proportion of agricultural land in the grids of 0.5° (p, %) is derived from the Land-use Harmonization2 database (LUH2) (Hurtt et al., 2020). The agricultural land of the LUH2 database includes 175 different crops, which are aggregated and re-classified into five crop functional types based on their photosynthetic pathways (C3 or C4), lifespan (annuals or perennials), and whether they are nitrogen fixers. In this study, we focus on cropland as a whole. Therefore, the agricultural land is the sum of five types of cropland in LUH2. The pesticide application rate (D, g km^2) is estimated based on the pesticide use in provinces (g) and the agricultural land area in those provinces (km^2). The pesticide use for provinces for 2000 and 2010 is from the Chinese Statistical Yearbook (NBSC and NBoSo, 2001; NBSC and NBoSo, 2011). We allocated the provincial pesticide use to grids of 0.5° using the area-weighted method, which is based on the share of agricultural land area in each grid over the total agricultural land of the province (Fig. A1).

The organic carbon content (OC, %) and soil texture data (T) for grids of 0.5° are derived from the Harmonized World Soil Database (Fischer et al., 2000). The average slope of the 0.5° grid is calculated based on the Shuttle Radar Topography Mission- Digital Elevation Map using ArcGIS (RESDC, 2003). The model considers the influence of the slope on pesticide runoff. The influence of the slope on surface runoff is calculated using Eq. 3 in Fig. 1. We calculate the surface runoff generated after a single rainfall event using the maximum daily precipitation (P, mm). This is calculated as a function of the soil texture and the precipitation (see Eq. 4 in Fig. 1 and Ippolito et al. (2015)).

The maximum daily precipitation (P, mm) is retrieved from the Global Climate Model (GCM) inputs from the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP) project (Hempel et al., 2013). We calculate the pesticide runoff using precipitation from four different climate models, GFDL-ESM2M, HadGEM2-ES, IPSL-CM5A-LR, MIROC-ESM-CHEM, to account for uncertainties of the modeled precipitation. In other words, we ran our pesticide model individually for the four GCMs to calculate the pesticide runoff. Next, we took the averaged modeled gLOAD value over these four GCMs.

The plant interception (I, %) in the planting and growing period is assumed to be 50% based on the approach developed by Ippolito et al. (2015). The plant interception depends on the plant species, growing periods, and pesticide application time. However, this information is not available in China. Therefore, we used 50% for each grid as assumed by Ippolito et al. (2015). The soil organic carbon-water partitioning coefficient of the pesticides (Koc, ml g^{-1}) is a substance-specific value. However, this information is not readily available for specific pesticide substances for a 0.5° grid in China. We assume to be Koc of 100 following the approach by Ippolito et al. (2015).

We define hotspots for the potential pesticide runoff based on the RP results. We classify the RP values based on the approach developed by Ippolito et al. (2015). We then convert values of gLOAD to a logarithmic scale (RP). The RP results are classified as very low (below −3), low (−3 to −2), medium (−2 to −1), high (−1 to 1), very high I (above 1), very high II (2–3), and very high III (above 3). Grids of 0.5° are assigned to these classes. Grids classified as very high (I, II, and III) are considered pollution hotspots for high potential pesticide runoff to surface waters. We calculate the population in pesticide pollution hotspots. The Chinese population data is from Jones and O'Neill (2016).

2.2. Scenario description

We develop three scenarios for the future describing both socio-economic developments and climate changes based on the combined SSPs-RCPs: the Sustainability (SSP1-RCP2.6), "Middle of the Road" (SSP2-RCP4.5), and Economy-first (SSP5-RCP8.5) scenarios. SSPs are the latest global storylines that indicate future socioeconomic development in population, urbanization, agricultural activities, and gross domestic products (O'Neill et al., 2014). SSPs are often used alongside RCPs. RCPs describe different pathways for radiative forcing reaching 2.6–8.5 W m^{-2} by 2100, indicating future climate change (Van Vuuren et al., 2011).

The Sustainability scenario follows SSP1 and assumes rapid socio-economic development towards an environmentally friendly future with high productivity on the land. Based on this, global population growth will slow down and more people will be concentrated in urban areas. The Chinese population is projected to decrease to 1254 million in 2050. By 2099, the Chinese population is projected to further decrease to 664 million (Table A.1). Cropland is predicted to decrease between 2010 and 2050, and then increase to above 1400 thousand km^2 in 2099 (Table A.1). In the agriculture sector, it is assumed that the best pest-control technologies (e.g., improvement of the extension services, better-trained farmers) would be adopted to replace pesticides. Therefore, we assume that the pesticide application rate will be reduced by 10% in 2050 and 30% in 2099 compared to 2010 (Table A.1). In this scenario, the greenhouse gas emission will be largely controlled to achieve the maximum warming of 2 °C. Thus, the maximum daily precipitation is predicted to be relatively low (Table A.1).

The "Middle of the Road" scenario assumes that socio-economic development will follow the same historical trends as SSP2. The total population is projected to decrease slightly between 2010 and 2050 and largely decrease between 2050 and 2099. By 2050, the Chinese population is projected to reach 1293 million, which is the highest value of the three scenarios. The population is projected to decrease to 790 million in 2099 (Table A.1). Cropland area is projected to increase in 2050 and then decrease in 2099. In this scenario, the development and implementation of technologies are slow in the agricultural sector. Thus, we assume that the pesticide application rate would not change in the future and would remain at the 2010 level. This scenario assumes that efficient climate mitigation strategies against climate change will be implemented (Van Vuuren et al., 2011). Thus, the projected maximum daily precipitation is slightly increased in 2050 compared to 2010. Compared with the Sustainability scenario, some climate models, such as GFDL-ESM2M and IPSL-CM5A-LR, indicate that precipitation will increase in 2099 in this scenario (Table A.1) (Hempel et al., 2013).

The Economy-first scenario assumes that the world will develop rapidly with intensive use of resources as in SSP5. The total population in China is projected to decrease slightly between 2010 and 2050. After 2050, the total population is projected to decrease largely by 2099. This would result in 1259 million people in 2050 and 676 million people in 2099 (Table A.1). However, the food demand would double nationally between 2010 and 2099. This is associated with an increasing preference for a meat-rich diet, leading to intensive animal production and crop production to produce animal feeds in China. The doubled food demand would require high productivity in the agricultural sector with intensive use of resources. Therefore, it is assumed that the pesticide application rate would increase by 10% in 2050 and by 30% in 2099 compared with

2010 (Table A.1). Cropland area is also projected to increase to 1360 thousand km^2 in 2050 and 1362 thousand km^2 in 2099 due to increasing food demand (Table A.1). RCP8.5 is the scenario with the highest greenhouse gas emission. This will result in a large increase in the maximum daily rainfall in China in the future (Table A.1). For example, MIROC5 projects the median (min.−max.) of the maximum daily precipitation for China at 29 mm (2–155 mm) in 2050 and 40 mm (2–267 mm) in 2099.

3. Results and discussion

3.1. Pesticide pollution in the past

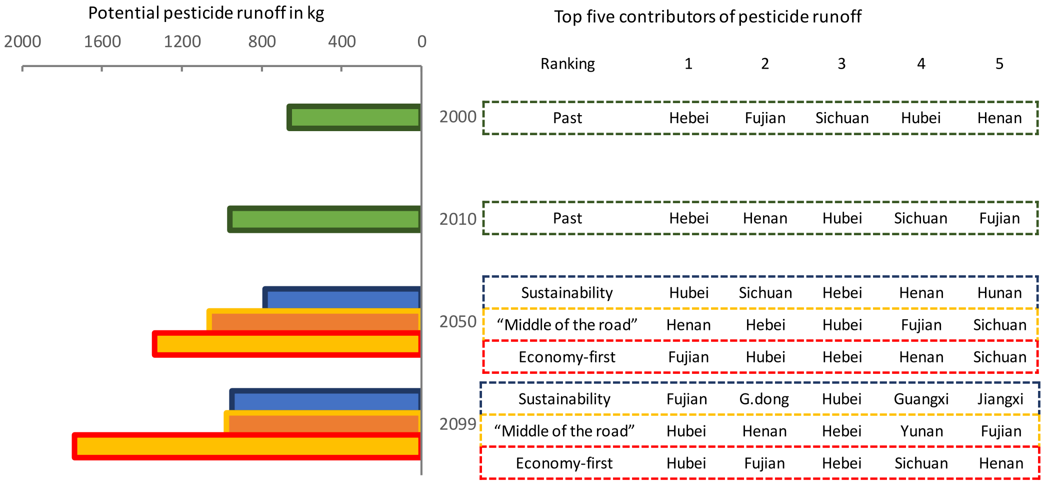
Pesticide runoff to surface waters from the near-stream agriculture increased considerably in the past. **In 2000**, the potential pesticide runoff in China was calculated as 660 kg. Over half of this was concentrated in five provinces: Hebei, Fujian, Sichuan, Hubei, and Henan (Fig. 2 and Fig. A2). We mapped the pesticide hotspots with classes as *very high I*, *II*, and *III* (see Section 2) in China for the past. Pesticide hotspots were in densely populated areas in the north, east, south, central, and southwest of China, which is in many areas except for the west and north-west (Fig. 3). Additionally, the hotspot areas were distributed in large parts of the Yangtze, North China, and the Chengdu Plains in 2000. The hotspot area covered 26% of China and 55% of the cropland area. Moreover, 62% of the Chinese population lived in pesticide hotspots in 2000 (Fig. A.6). This applies to the north, central, south, and east part of China (Fig. 4).

In 2010, the total pesticide runoff in China had increased to 960 kg (Fig. 2). The largest increases between 2000 and 2010 were calculated at grids of 0.5° in six agro-ecological zones including north, northeast, south, southeast, east, and central China (Fig. 3, indicated by orange and red). The hotspot area increased to 34% of China (Fig. 3). The hotspot area expanded in all agro-ecological zones except for the plateau. Some hotspot areas classified as *very high III* in 2000 increased to *very high II* and *I* in 2010 (Fig. 3). The cropland area in the hotspots increased to 69% (Fig. A.7), and the number of people living in hotspots increased to 72% in 2010 (Fig. 4 and A.7).

3.2. Future pesticide pollution

Under the Sustainability scenario, the total pesticide runoff in China is projected to decrease to 780 kg in 2050 and then increase to 950 kg in 2099 (Fig. 2). In 2050, over 50% of the national pesticide runoff is projected to be in the provinces of Hubei, Sichuan, Hebei, Henan, Hunan, and Fujian. This differs from the past and 2099. In 2000 and 2010, Hunan was not among the top five pollution contributors (Fig. 2 and A2). The top province was Hebei in 2000 and 2010. This is the province with intensive crop production. This province accommodates large cities such as Beijing. Thus, the demand for food is high leading to high crop and animal production in Hebei. The other top provinces were Fujian (located in the south part), Sichuan (located upstream of the Yangtze basin), Hubei (located in the middlestream of the Yangtze basin), and Henan (located in the middle part of China). However, the contribution of these four provinces to pollution changed between 2000 and 2010. In 2000, Fujian was the second top province contributing to pesticide pollution. In 2010, this was Henan (Fig. A2). These differences among the provinces are the net effect of factors such as crop production (driven by the population growth and socio-economic developments), and precipitation. In the future, this may differ. In 2099, over 50% of the national pesticide runoff is projected to occur in Fujian, Guangdong, Hubei, Guangxi, Jiangxi, and Yunnan provinces. Some southern provinces, such as Sichuan, Fujian, and Hubei, are projected to use few pesticides but still have high potential for pesticide runoff (Fig. A2). This is associated with the steepness of their terrain, heavy rainfall, and/or intensive crop production in these provinces.

From 2010 to 2050, many grids in all agro-ecological zones are projected to show a decreased potential pesticide runoff (blue and dark blue in Fig. 5) or to remain unchanged (yellow in Fig. 5). Grids showing an increased potential pesticide runoff are projected to be concentrated in two agro-ecological zones including southwest and central China, where the Chengdu Plain is located. In the north, which covers the North China Plain with intensive agriculture, increases in pesticide runoff are projected for fewer grids (Fig. 5 and A5). From 2050 to 2099, increases are projected for most grids in the south (Fig. 5). This could be associated with more crop production in those areas than in the past. Another driver is climate. In general, areas in the south are projected to be wetter leading to more runoff in 2100 than in the past and 2050. In contrast, decreases are projected for most grids in the north (Fig. 5). This could be



Ranking		1	2	3	4	5
2000	Past	Hebei	Fujian	Sichuan	Hubei	Henan
2010	Past	Hebei	Henan	Hubei	Sichuan	Fujian
2050	Sustainability	Hubei	Sichuan	Hebei	Henan	Hunan
	"Middle of the road"	Henan	Hebei	Hubei	Fujian	Sichuan
	Economy-first	Fujian	Hubei	Hebei	Henan	Sichuan
2099	Sustainability	Fujian	G.dong	Hubei	Guangxi	Jiangxi
	"Middle of the road"	Hubei	Henan	Hebei	Yunan	Fujian
	Economy-first	Hubei	Fujian	Hebei	Sichuan	Henan

Fig. 2. Potential pesticide runoff that is generated after heavy rainfall events in China and the top five polluting provinces in 2000 and 2010 (historical data), 2050, and 2099 under the Sustainability (SSP1-RCP2.6), "Middle of the Road" (SSP2-RCP4.5) and Economy-first scenarios. SSPs are short for Shared Socioeconomic Pathways. The ranking starts from the most polluting provinces (left) and ends with the 5th polluting province. Most polluting provinces are the provinces that contribute the most to the national potential pesticide runoff. RCPs are short for Representative Concentration Pathways. Source: See Section 2 in the main text for the model and scenario description.

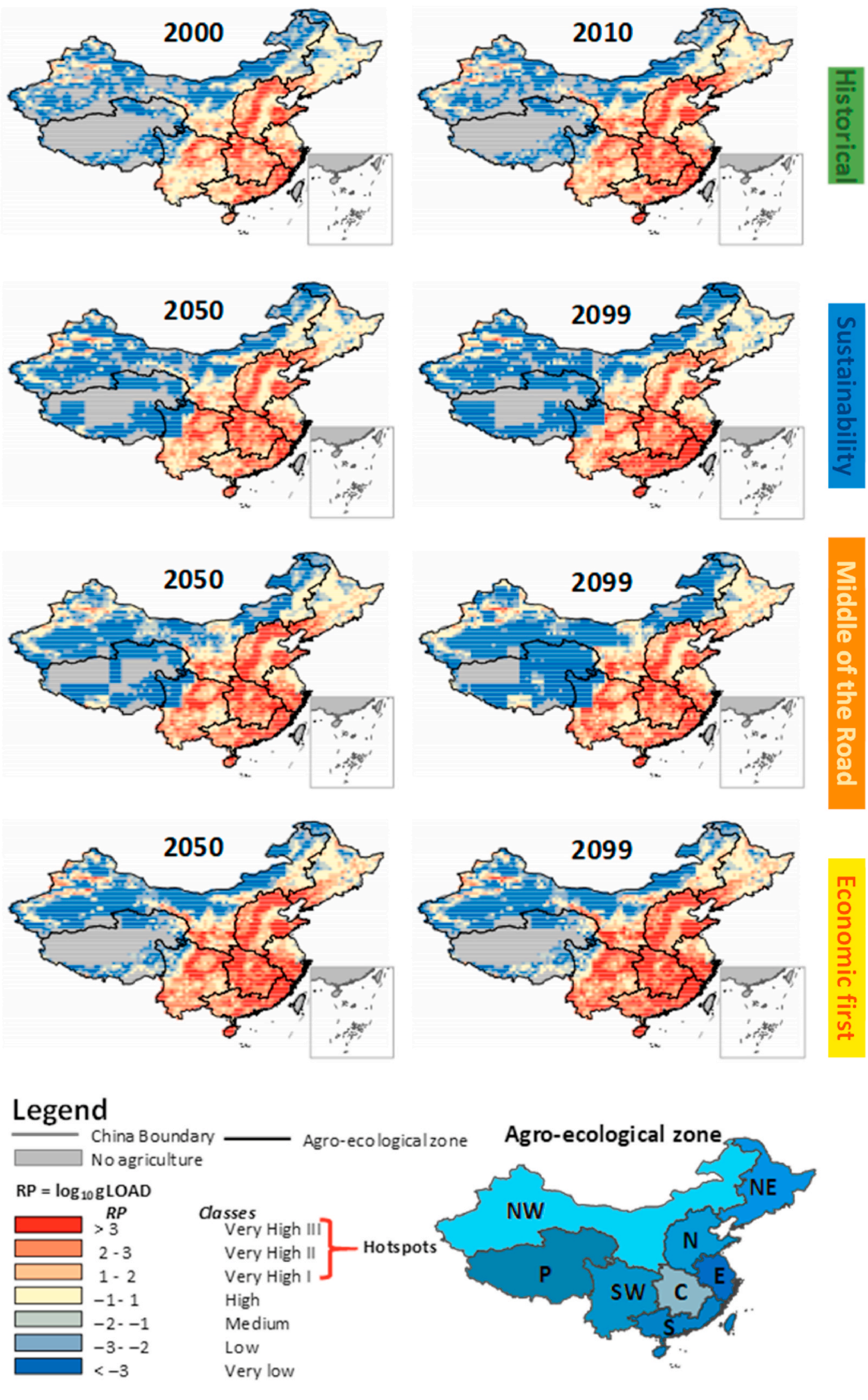


Fig. 3. Pesticides polluting hotspots map in China in 2000 and 2010 (historical data), and 2050 and 2090 under the Sustainability (SSP1-RCP2.6), Middle of the road (SSP2-RCP4.5) and Economy-first (SSP5-RCP8.5) scenarios. Hotspots are defined based on the generic indicator of potential pesticide runoff (RP). We convert values of gLOAD into a logarithmic scale (RP). Results of RP are classified as *very low* (below −3), *low* (−3 to −2), *medium* (−2 to −1), *high* (−1 to 1), *very high I* (above 1), *very high II* (2–3), and *very high III* (above 3). Grids of 0.5° are assigned to those classes. Grids classifies as *very high I, II,* and *III* are considered the pollution hotspots for high potential pesticide runoff to surface waters. SSPs are short for Shared Socioeconomic Pathways. RCPs are short for Representative Concentration Pathways. Source: see Section 2 in the main text for the model and scenario description.

associated with the net effect of less pesticide application and climate change (e.g., these areas are projected to be drier than in the past).

The hotspot areas may shrink to 32% and 30% in 2050 and 2099 compared to the past. The projected spatial distribution of the hotspots in 2050 is similar to that in 2000. Hotspot areas with potential for high pesticide runoff (very high I and II classes in Fig. 3) are projected to expand in three agro-ecological zones including the south, southwest, and east, and to shrink in two agro-ecological zones including the north and northwest in 2050 compared to 2010 (Fig. 3 and Fig. A.6). The cropland area in hotspot areas is projected to decrease to 65% by 2050

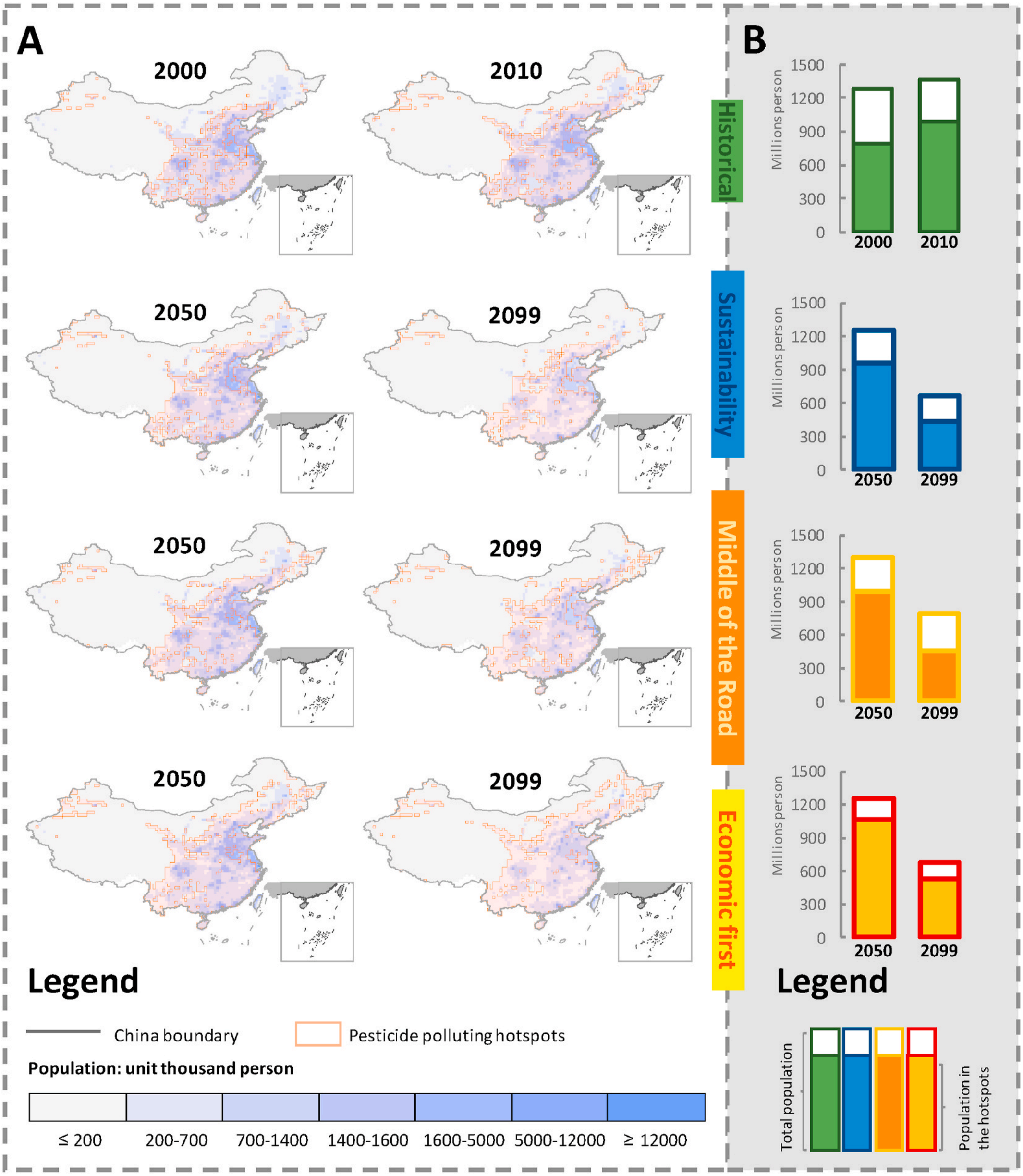


Fig. 4. Population living in pesticides polluting hotspots in China in 2000 and 2010 (historical data), and 2050 and 2090 under the Sustainability (SSP1-RCP2.6), "Middle of the Road" (SSP2-RCP4.5) and Economy-first scenarios. Hotspots are defined based on the generic indicator of potential pesticide runoff (RP). We convert values of gLOAD into a logarithmic scale (RP). Results of RP are classified as *very low* (below −3), *low* (−3 to −2), *medium* (−2 to −1), *high* (−1 to 1), *very high I* (above 1), *very high II* (2–3), and *very high III* (above 3). Grids of 0.5° are assigned to those classes. Grids classifies as *very high I, II,* and *III* are considered the pollution hotspots for high potential pesticide runoff to surface waters. The total population in hotspots is the sum of the population in the hotspot grid of 0.5°. The Chinese population is the sum of the population in grids of 0.5° in China. SSPs are short for Shared Socioeconomic Pathways. RCPs are short for Representative Concentration Pathways. Source: the data on population was from Jones and O'Neill (2016). See Section 2 in the main text for the model and scenario description.

and 67% by 2099. The Chinese population is projected to decrease slightly to 1.25 billion in 2050 and further decrease to 0.66 billion in 2099 (Fig. 3). The population in the hotspot areas is projected to increase to 76% by 2050 and then decrease to 65% by 2099 (Fig. A.7). The hotspot area in the Sustainability scenario is smaller than in the other scenarios. Yet, over half of the Chinese population is projected to live in grids with high potential for pesticide pollution in the future.

Under the "Middle of the Road" scenario (SSP2 RCP4.5), the pesticide runoff is projected to increase to 1060 kg in 2050 and then decrease to 980 kg in 2099 (Fig. 2). In 2050, the top five contributing provinces are the same as in 2010: Hubei, Sichuan, Hebei, Henan, and Hunan. Over half of the pesticide runoff is projected to occur in Guangdong and the top five contributing provinces (Fig. 2 and Fig. A.3).

A large spatial variation is projected in future pesticide runoff trends from 2010 to 2050 (Fig. 5 and Fig. A.5). In the south and southeast, we project many grids of 0.5° to show an increased pesticide runoff between 2010 and 2050. Increases are also projected for some grids in north, central, and east China. This could be explained by increases in crop production and the use of pesticides. In the other agro-ecological zones, the pesticide runoff is projected to decrease from 2010 to 2050 (Fig. 5 and Fig. A.5). From 2050 onwards, the spatial differences in the potential pesticide runoff are smaller. We calculate that the potential pesticide runoff would stabilize in the future in most areas of China by 2099. This implies that the socio-economic development (e.g., crop production) and the use of pesticides will not change largely between 2050 and 2099. Decreases are projected for some grids of 0.5° in the

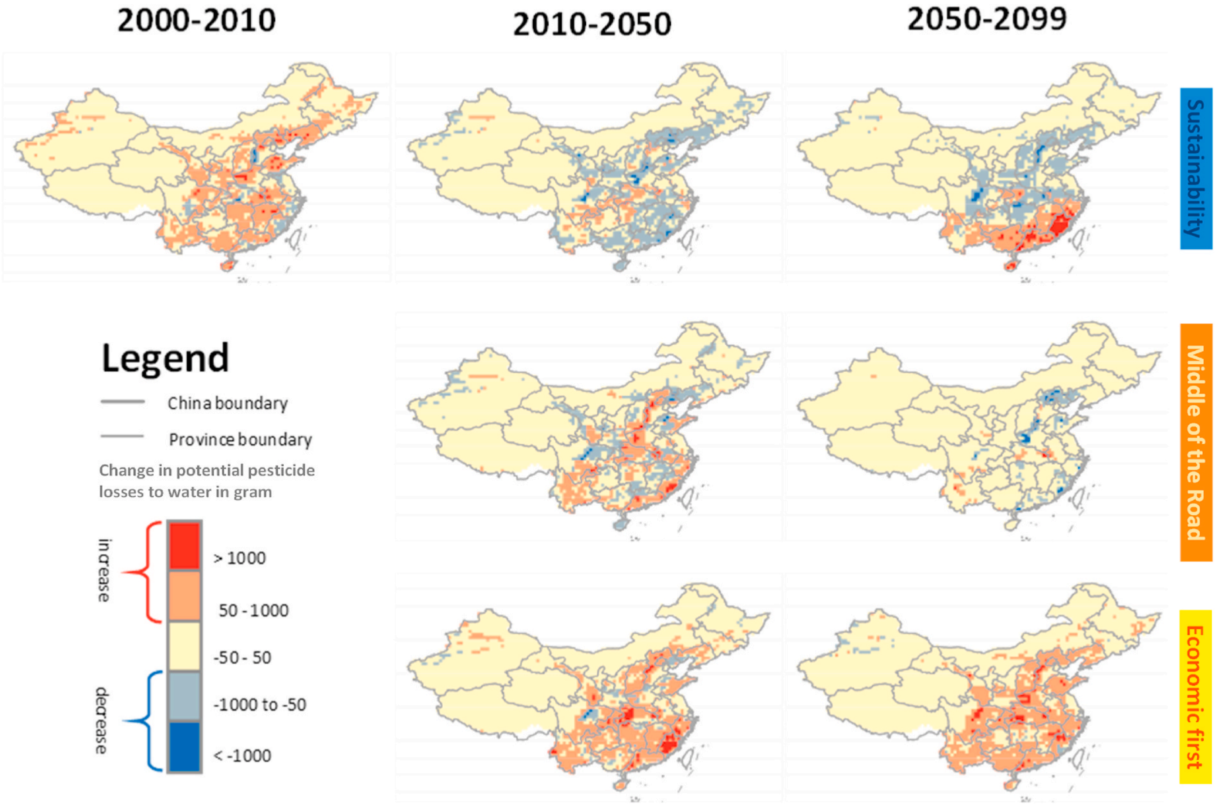


Fig. 5. Changes in potential pesticide runoff (gLOAD) to surface water that is generated after maximum daily rainfall event during the periods of 2000–2010 (historical data), and 2010–2050 and 2050–2090 under the Sustainability (SSP1-RCP2.6), “Middle of the Road” (SSP2-RCP4.5) and Economy-first (SSP5-RCP8.5) scenarios. SSPs are short for Shared Socioeconomic Pathways. RCPs are short for Representative Concentration Pathways. Source: see Section 2 in the main text for the model and scenario description.

north, central, southeast, and southwest of China from 2010 to 2050 as a result of crop production, pesticide use, and maximum daily rainfall events (Fig. 5 and Fig. A.5). In central, south, and southwest China, the grids showing a decreased pesticide runoff outnumbered those showing an increased pesticide runoff (Fig. 5 and Fig. A.5).

The pesticide pollution hotspots are projected to cover 33% of China in 2050 and 2099 (Figs. 3 and 4, and Fig. A.7). In 2099, we projected a larger hotspot for China in the “Middle of the Road” scenario than in the Sustainability scenario (Figs. 3 and 4). However, we projected a smaller hotspot in the northeast of China under the “Middle of the Road” scenario than under the Sustainability scenarios in 2099 (Figs. 3 and 4). In the “Middle of the Road” scenario, we projected that 77% of the Chinese population would live in the pesticide hotspots in 2050 (Fig. 3 and Fig. A.7). For 2099, this percentage drops to 58% which is the lowest of the three scenarios. The percentage of the population in the hotspots in the “Middle of the Road” scenario is lower than that in the Sustainability scenario (Fig. 3 and Fig. A.6). This is because grids with high populations in the northeast of China are not classified as hotspots in the “Middle of the Road” scenario (Fig. 4). The cropland area in the pesticide hotspots is higher than in the Sustainability scenario and stabilized at 71% from 2050 (Fig. A.7).

The Economy-first scenario (SSP5 RCP8.5) can be considered the scenario with the highest environmental impact. Pesticide runoff is projected to reach 1340 kg in 2050 and 1740 kg in 2099. These values are much higher than the other scenarios. The top five contributing provinces of 2010 and Guangdong and Hunan together are projected to contribute over 50% of the national pesticide runoff in China in 2050 and 2099 (Fig. 2 and Fig. A.4).

Future trends in the potential pesticide runoff differ considerably among agro-ecological zones and in the other two scenarios. From 2010–to 2050, 50 to 1000 g increase in potential pesticide runoff are projected for most grids of 0.5° in four agro-ecological zones including north, east, central, and southwest China (Fig. 5). Grids with a 50 to 1000 g decrease in potential pesticide runoff during this period are scattered in all parts of China, except for the plateau (Fig. 5). From 2050 onwards, the pesticide runoff is projected to increase further (Figs. 2 and 5, and Fig. A.5).

The hotspot area is projected to be the largest among the three scenarios. The hotspot areas are projected to cover 38% of China by 2050 and 40% by 2099 (Figs. 3 and 4, and Fig. A.7). The cropland area in the pesticide hotspots is projected to cover 75% by 2050 and 79% by 2099 (Fig. A.7). More people are projected to live in the hotspot areas in 2050 (84%) and 2099 (78%) in the Economy-first scenario (Fig. 4 and Fig. A.7). These percentages are higher in this scenario compared to the other two scenarios.

Our future trends in pesticide runoff are the net effect of several factors (Fig. 1). Climate change can influence the flow of pesticides from land to water. This can happen when rainfall events are high. For example, in the Economy-first scenario (SSP5 RCP8.5), climate change impacts are generally larger than in the Sustainability (SSP1-RCP2.6). This is because RCP8.5 projects larger impacts of climate change than RCP2.6. In RCP8.5, it is expected to have more heavy rain events than in RCP2.6. Thus, one of the reasons for future pesticide pollution in SSP5 RCP8.5 could be climate change. Other important reasons are land degradation, application of pesticides on cropland, crop production, and area characteristics (see Fig. 1). For example, some areas in China such as the North China Plain have intensive crop production. This may increase in the future. In the Sustainability scenario (SSP1-RCP2.6), it is assumed to reduce the use of pesticides. However, this is not the case for the Economy-first scenario (SSP5 RCP8.5). In areas with a steep slope (e.g., some areas in the south part of China), the flow of pesticides could be higher because of the slope which leads to more runoff and thus more pesticide export. In our future analyses, the pollution levels are, thus, a result of rainfall events (influenced by climate change), soil characteristics, pesticide applications, and crop production (influenced by population growth and socio-economic developments).

3.3. Model evaluation

Our pesticide model for China is based on the existing approach developed and evaluated by Ippolito et al. (2015). They evaluate the model performance by conducting sensitivity and uncertainty analyses. Their results show that the model outputs are sensitive to changes in the slope and precipitation. They also show that the insecticide application rates, interception, and precipitation are model inputs contributing largely to uncertainties in the model outputs. To reduce the uncertainty associated with the pesticide application rate, we use the pesticide application rate specific to the Chinese provinces (see Section 2.1). To reduce the uncertainty associated with precipitation, we calculate gLOAD using precipitation from the four GCMs and then average the gLOAD results over the four GCMs (see Section 2.1). Thus, we avoid the influence of outliers in precipitation on our results.

Model validation is challenging. Our pesticide model calculates the potential pesticide runoff rather than concentrations. This value reflects the pesticide losses when the maximum daily rainfall event occurs immediately after applying the pesticides. Measurements for such potential pesticide runoffs do not exist for China. We compare our results with those of existing studies. We also compare the spatial patterns in pollution hotspots with existing studies for the past years for the whole of China. Our model results are in line with those for the pollution hotspots from several existing studies (Grung et al., 2015a; Han and Currell, 2017; Ouyang et al., 2016; Sun et al., 2019). Ouyang et al. (2016) quantified the pesticide losses to waters by provinces from 1990 to 2011. The top ten contributing provinces were Shandong, Guangdong, Anhui, Jiangxi, Henan, Hubei, Jiangsu, Hunan, Sichuan, and Heilongjiang. Grung et al. (2015a); Han and Currell (2017) found that concentrations of pesticides are high in the North China Plain, Yangtze River Delta, and Pearl River Delta. Our results also indicate that provinces in these regions are hotspots except for Anhui, Jiangsu, and Heilongjiang. Sun et al. (2019) calculate a small increase in hotspots from 2004 to 2013. We also calculate an increase that is somewhat higher between 2000 and 2010 than the estimate of Sun et al. (2019). A possible reason for the differences between our study and others could be associated with differences in spatial and temporal aggregation levels. We also compare the trends in pesticide use with available studies from the past. Our study shows that pesticide use in China increased nationally by 37% from 2000 to 2010. This increase is close to the estimate of Ouyang et al. (2016). Generally, our results are in line with those of existing studies. Therefore, we believe that our pesticide model identifies plausible pollution hotspots. We consider that our model reflects China's pesticide use situation because we use Chinese information on pesticides. Thus, we argue that the model can be used to analyse future pesticide pollution hotspots in China in our study. We discuss uncertainties in Section 3.4.

3.4. Uncertainties and strengths of this study

Uncertainties are associated with model inputs, approaches, sources, and scenario assumptions. We derived model inputs from existing studies. Some model inputs were processed to match the spatial level of detail in our study. Examples are the near-stream agriculture (corridor area) and the pesticide application rates (see Section 2). Processing model inputs may generate uncertainties in model results. Some model inputs are fixed such as the Koc value, while some model inputs are area specific. Examples are pesticide use, precipitation, and slope. We used the best available datasets to us reflect the situation in China (see Section 2).

Another source of uncertainties is in the modeling approach. We used the approach of Ippolito et al. (2015). This approach was applied globally and regionally. However, it has limitations. An example is that the model treats pesticides as a group and does not distinguish between types and varieties of pesticides. The approach also considers the application of pesticides to all crops and does not separate crop types explicitly. This approach was applied to Europe (Kattwinkel et al., 2011; Schriever and Liess, 2007). Schriever and Liess (2007) validated the model for Finland, France, and Germany. They modeled the RP for streams. They compared polluted streams (with high potential pesticide runoff) with streams where they observed negatively affected invertebrate communities in Finland, France, and Germany. Schriever and Liess (2007) concluded that the modeling approach provides appropriate estimates of potential pesticide runoff. Additionally, Ippolito et al. (2015) evaluated the model performance and concluded that the modeled RP is a valuable tool to identify potential hotspots of insecticide runoff. All this builds trust in using this modeling approach for analyzing the potential pesticide runoff, acknowledging that future research is needed to integrate D (use of pesticide) and Koc by pesticide group (herbicides, fungicides, and insecticides) and to relate potential pesticide runoff to concentrations in surface waters.

The model accounts for agricultural sources. However, it does not account for pesticide losses from urban areas and sewage. It assumes that all pesticides are applied to agricultural land. However, studies indicated that pesticide losses from urban areas and sewage account for small proportions of the total losses of pesticides to waters. Generally, the largest pathway of pesticide losses is surface runoff. Furthermore, agriculture is a large user of pesticides nationally in China. During heavy rainfall events, it is likely that more pesticides enter nearby waters. Our approach accounts for the most important source (agriculture) and pathway (runoff). Our study focuses on the impact of agriculture on water pollution. We compared our results with Ouyang et al. (2016) and Sun et al. (2019). To our knowledge, these are the only existing studies estimating pesticide losses from agriculture to waters at a national level using an empirical model. The comparisons show that our results are in line with the pollution hotspots from the two existing studies (Ouyang et al., 2016; Sun et al., 2019). Therefore, we believe that the major conclusions of this study are not affected by these uncertainties. Future studies can improve the model by distinguishing between different pesticide varieties. Local studies are required to validate the model for local assessments and to add missing sources such as sewage.

Our future projections are based on SSPs for socioeconomic developments and RCPs for climate and hydrology. Our scenarios need projections for cropland, precipitation, and pesticide use in agriculture for 2050 and 2099. We took the projections from existing studies for population, cropland, and precipitation. We made our projections for the pesticide use on cropland following the storylines of SSPs (Table A.1). The future is uncertain. Thus, the projections for these variables are also uncertain. Nevertheless, we believe that the projections are useful for exploring future trends in the potential pesticide runoff.

The model offers a first insight into the spatial variability in pesticide pollution in China. It can be used to analyse pesticide pollution in data-poor regions. We perform scenario analyses to better understand the trends of potential pesticide runoff under global change including socio-economic developments and climate change. This is the first study analysing the effects of global change on pesticide pollution for the whole of China at the 0.5° grid scale. We projected future pollution hotspots for potential pesticide runoff in three scenarios. Our study identifies hotspots in the north, east, central, and southwest China. This indicates that effective policies to reduce pesticide losses should focus more on these regions. This study provides scientific insights into future changes in pesticide pollution in Chinese waters. These insights can help policymakers to identify pollution areas requiring their attention and develop region-specific policies for those areas to reduce future pesticide pollution under socio-economic developments and climate change.

4. Conclusion

This study aims to analyse past and future potential pesticide losses to Chinese waters under socio-economic developments and climate change. To calculate the potential pesticide runoff, we developed a pesticide model based on the existing insecticide model. We used available data from Chinese Statistical Yearbooks as input to the model. To model the impact of socio-economic developments and climate change on the potential pesticide runoff, we selected and interpreted three combinations of the SSPs and RCPs. These combinations are SSP1-RCP2.6 (Sustainability), SSP2-RCP4.5 ("Middle of the Road"), and SSP5-RCP8.5 (Economy-first).

The potential pesticide runoff increased nationally by 45% from 2000 to 2010. Five out of 31 provinces (Hebei, Hubei, Sichuan, Fujian, and Henan) contributed over 50% to the national pesticide runoff in China in 2000 and 2010. In some southern provinces, such as Sichuan, Fujian, and Hubei, pesticide use was less; however, the potential pesticide runoff was relatively high in 2000 and 2010. This is due to steep terrains, heavy rainfall, and/or intensive crop production in these provinces. The pollution hotspots of potential pesticide runoff were concentrated in the agro-ecological zones including the south, southeast, and east, and they cover most parts of the Yangtze, North China, and Chengdu Plains in the past. Over 60% of the Chinese population lived in pesticide hotspots in 2000. This value increased to 72% in 2010.

In the future, 58%–84% of the Chinese population are projected to live in pesticide pollution hotspots. Future trends in the potential pesticide runoff vary among scenarios. In the Economy-first scenario (SSP5-RCP8.5), the potential pesticide runoff increases relatively rapidly in the future. The top five provinces with the highest potential pesticide runoff in 2010 are projected to remain unchanged in the future. In these five provinces, the potential pesticide runoff is projected to increase by 85% from 2010 to 2099. Pesticide pollution hotspots are projected to expand particularly in the densely populated areas of the southeast China. The hotspots are calculated to accommodate 84% of the total population in 2050. However, we also show that pollution levels can be lower than in 2010 in the future. In the Sustainability scenario (SSP1-RCP2.6), the potential pesticide runoff can be largely controlled. This is due to the reduction in the pesticide application rate and agricultural land, and lower maximum daily rainfall over the year. We projected very different the top five provinces with the highest potential pesticide runoff in 2050 and 2099. In 2050, the top five are Hubei, Sichuan, Hebei, Henan and Hunan. In 2099, the top five provinces change to Fujian, Guangdong, Hubei, Guangxi, and Jiangxi. In the Sustainability scenario, hotspots for pesticide runoff are concentrated in the southeast China where the population is projected to be high in 2099. The population living in the hotspots is projected to increase to 76% by 2050 and then decrease to 65% by 2099. In the "Middle of the Road" scenario, we show that pollution levels may increase by 2050 but then decrease to the level of 2010 by 2099. This is due to the reduction in agricultural land from 2050 to 2099 in the "Middle of the Road" scenario. In this scenario, the projected top-five provinces with the highest potential pesticide runoff are Henan, Hebei, Hubei, Fujian, and Sichuan in 2050. In 2099, Yunnan is projected to replace Sichuan in the list of the top five polluting provinces. The distribution of hotspots in 2050 is similar to that in 2099. However, the population in the hotspots is projected to change between 2010 and the future years. The population living in the hotspots is projected to increase to 77% by 2050 and then decrease to 58% by 2099.

Our study shows that pesticide pollution may increase in the future and that without additional measures, many people in China may be exposed to polluted waters in the future. Our study indicates areas with high potential pesticide runoff. This information can facilitate the formulation of effective, province-specific agricultural policies to reduce pesticide pollution in China in the future.

Author statement

Ang Li: Conceptualization, Roles/Writing - original draft, Validation, Visualization, Writing - review & editing. **Carolien Kroeze:** Conceptualization, Methodology, Funding acquisition, Supervision, Writing - review & editing. **Mengru Wang:** Conceptualization, Methodology, Writing - review & editing. **Lin Ma:** Conceptualization, Funding acquisition, Supervision Writing - review & editing. **Maryna Strokal:** Conceptualization, Methodology, Supervision, Writing - review & editing.

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.

Acknowledgments

This work was supported by the National Key Research & Development Program of China MOST project [grant numbers 2016YFE0103100]; KNAW project "Sustainable Resource Management for Adequate and Safe Food Provision (SURE+)" [grant numbers PSA-SA-E-01]; President's International Fellowship Initiative of the Chinese Academy of Sciences [2019DC0006] and the Dutch Talent Program (Veni) [grant numbers 0.16.Veni.198.001].

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2022.115361.

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