Front. Agr. Sci. Eng. 2024, 11(1): 134–139 https://doi.org/10.15302/J-FASE-2023511

NEWS & VIEWS

Multiple pollutants from crop and livestock production in the Yangtze River: status and challenges

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KEYWORDS

Agriculture Green Development, crop production, livestock production, multi-pollutant models, multiple pollutants, Yangtze River Basin

HIGHLIGHTS

- Cash crops and livestock production in Yangtze River Basin has grown rapidly.
- The agricultural inputs discharge multiple pollutants loads on water bodies in the YRB.
- Multiple pollutants impact on efficient utilization of nitrogen and phosphorus in agriculture.
- An explicitly multi-pollutant approach accounting for interactions is need.

Received October 8, 2022;
Accepted June 27, 2023.

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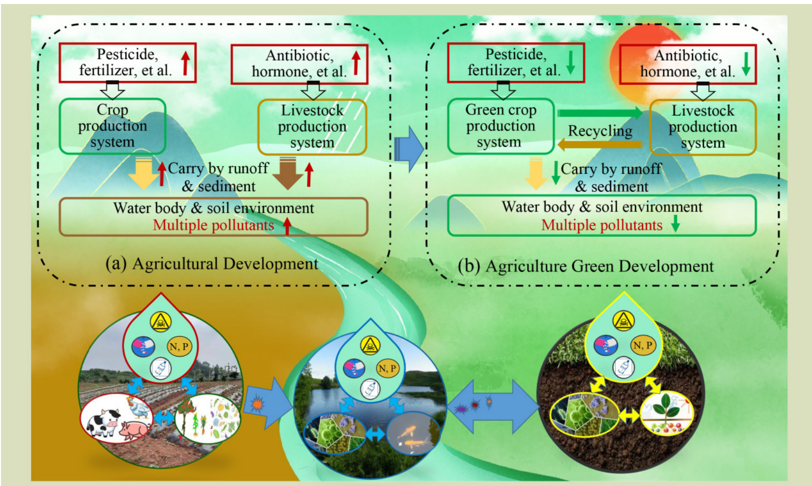
GRAPHICAL ABSTRACT



ABSTRACT

The rapid increase in the proportion of cash crops and livestock production in the Yangtze River Basin has led to commensurate increases in fertilizer and pesticide inputs. Excessive application of chemical fertilizer, organophosphorus pesticides and inappropriate disposal of agricultural waste induced water pollution and potentially threaten Agriculture Green Development (AGD). To ensure food security and the food supply capacity of the Yangtze River Basin, it is important to balance *green* and *development*, while ensuring the quality of water bodies. Multiple pollutants affect the transfer, adsorption, photolysis and degradation of each other throughout the soil-plant-water system. This paper considers the impact of multi-pollutants on the nitrogen and phosphorus cycles especially for crops, which are related to achieving food security and AGD. It presents prospective on theory, modeling and multi-pollutant control in the Yangtze River Basin for AGD that are of potential value for other developing regions.

1 Introduction

Water systems worldwide are increasingly affected by multiple pollutants (including plant nutrients, pesticides, antibiotics, animal hormones and microplastics) from crop and livestock production[1]. More concerningly, farmers, particularly in many developing countries, often overuse mineral fertilizers, pesticides, antibiotics and hormones to reduce the risk of agricultural failure and keep the economic returns[2]. For instance, the total fertilizer use per unit area in China has been about two and half times that of Europe and the USA. For instance, the investigated antibiotic loading per area, and plastic film, pesticide, mineral fertilizer input for cultivated land in the Yangtze River Basin (YRB) in 2020 were 60, 19, 16 and 476 kg·ha^{-1}, compared to the global average of 7, 3, 6 and 121 kg·ha^{-1}, respectively. Also, multiple pollutants introduced through manure and other biowaste application in the cropland may eventually make their way into the aquatic environment through surface runoff, leaching and soil erosion. Consequently, the continued intensification of crop and livestock production will dramatically impair and affect the environment, the well-being of humans, the regional economy[3] and biodiversity[4].

The YRB, which the most populous and prosperous basin in Asia, produces 40%, 64%, and 60% of China's rice, aquaculture and pigs, respectively, and represents 49% of the nation's arable land[5]. Livestock density per unit of arable land in the YRB is 20% higher than the national average. This highlights the need for greater production of forage and better management of larger amounts of animal waste, often concentrated in specific local areas of the YRB. Also, with an average annual precipitation exceeds 1000 mm, the annual sediment output is as high as 2200 Tg·yr^{-1}, which increases the risk of agricultural non-point source pollution from leaching and hydraulic erosion. The N and P inputs in the crop and livestock industries has increased sharply with nutrient use efficiency below the internal nutrient cycling rate[6]. It is reported that intensive crop production contributed more than half of dissolved inorganic N loads in the Yangtze and animal manure contributes 20%–30% to N pollution in the Yangtze River[7]. Agriculture Green Development (AGD) aims to transform unsustainable agricultural practices into high-efficiency sustainable production systems and turn water systems *blue* to provide clean water. It is a signifiant challenge to determine how to effectively balance the greening of agriculture and continued development to prioritize food security, maintain water quality and preserve the ecology of the YRB.

The quantity and range of pollution resulting from the intensification crop and livestock production are changing. These changes have impact on water pollution and potentially threaten AGD, a problem that has not received sufficiently broad attention. As mineral fertilizers are being replaced with organic fertilizer and agricultural waste is being utilized by returning straw to the field, there is a risk of antibiotics and insecticides further deteriorating the environment, as they are commonly used in crop and livestock production. The biogeochemical cycling of soil nitrogen and phosphorus is also affected by some pollutants (including antibiotics and pesticides), so deserves more attention. Given the importance of the YRB agricultural system for crop production, there is an urgent need to understand the pattern of multi-pollutants from land to rivers and the interaction mechanism between multi-pollutants.

2 Crop and livestock production in the YRB

To meet a constantly rising demand for a diverse range of food, cash crops (vegetables, fruits, oilseeds, and tea) and livestock production in the YRB in particular has grown rapidly[8]. Cash crops use 44% of the total cultivated area in the YRB (Fig. 1). Since 1989, vegetables and fruits have become the most rapidly expanded cash crops in the region, with these increasing by 321% and 378% and production areas reaching 7.4 and 3.1 Mha, respectively. During the same period, the production of meat, eggs, milk and freshwater aquatic products in the YRB has increased by 258%, 324%, 350% and 621%, with an output of 26, 9, 3 and 19 Tg, respectively.

The structure of the cropping system has evolved to simultaneously meet the increasing demand for both human food and animal feed. The increased area of fruit trees and vegetables compared to cereal crops has resulted in a greater amount and variety of agricultural inputs. Taking vegetables as

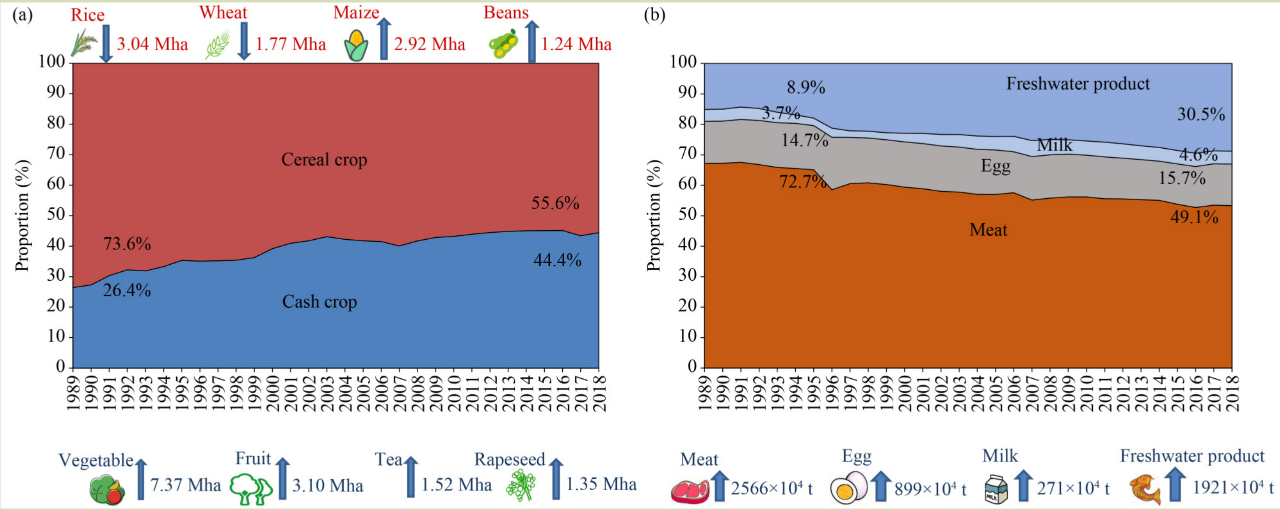


Fig. 1 Composition of crop (a) and livestock (b) production in the YRB from 1989 to 2018 (data sourced from National Bureau of Statistics of China).

an example, the amount of mineral fertilizer applied to vegetables is about three times higher than maize. Also, the significant and swift expansion of food products is accompanied by a vast amount of agricultural waste, including enormous amounts of manure. This results in two different outcomes. First, animal manure is effectively recycled for crop use, and these waste and pollution sources become the resources in crop production. However, the second outcome is the unwanted intensification of pollutants. The first is represents an opportunity to maximize the use of livestock waste as an organic fertilizer for crop production. To maintain the flavor and quality of cash crops organic fertilizer inputs are essential. However, the safe and sustainable use of organic fertilizers for crop production is yet to be fully implemented.

3 Status of multiple pollutants in the Yangtze River

The water quality of the Yangtze River is essential for ensuring the safety of drinking water for over 600 million people. Recent observations from 644 monitoring sites along the Yangtze River for ammonium nitrogen, total nitrogen (TN), and total phosphorus (TP) content showed an increasing trend from upstream to downstream[9]. The upstream values of ammonium nitrogen, TN and TP reported for 2021 were 0.09, 1.81 and 0.06 $mg \cdot L^{-1}$, respectively. However, these levels rose to 0.22, 2.17 and 0.09 $mg \cdot L^{-1}$ downstream[9]. Over the last decade, various departments and other organizations of the Chinese Government have been making concerted efforts to improve the water quality in the Yangtze River[10]. The average TP concentration in 2021 is lower than that reported for 2006–2012 (0.1–0.15 $mg \cdot L^{-1}$), so it now meets the National III Standards (TP < 0.1 $mg \cdot L^{-1}$)[11]. Nonetheless, the data given above highlights the continuing challenge posed by the elevated level of TN in the Yangtze River for water quality restoration, as the measured concentrations far exceeds the corresponding National III Standards for surface water (TN < 1.0 $mg \cdot L^{-1}$).

In addition to nutrient pollutants, the YRB faces severe water quality issues caused by the combined effects of other pollutants, including antibiotics and pesticides. Sulfonamides and tetracyclines are the most commonly detected antibiotics in the YRB and their environmental concentrations exceed the predicted no-effect concentration[12]. Antibiotic pollution in the middle and lower reaches of the YRB is particularly serious, with the highest concentrations found in the lower reaches (677 $ng \cdot L^{-1}$) which far exceeds both China's (401 $ng \cdot L^{-1}$) and the global average (425 $ng \cdot L^{-1}$). For pesticides, the YRB has been identified as one of the most heavily polluted regions for organophosphorus pesticides[13]. Also, the concentration of neonicotinoids in the YRB is significantly higher than those found in many other developing countries, and the potential ecological risk for aquatic invertebrates mostly exceeded the thresholds[14]. Also, the highest levels of organoamine pesticides were detected in the East China Sea during late spring, followed by the South China Sea and the Bohai Sea; the YRB was found to be a significant terrestrial source of pesticide pollution[13,15]. These distressing discoveries emphasize the need to raise awareness about the multiple pollutants in the

YRB and urge the public to take necessary measures to address these issues.

4 Challenges

Multiple pollutants act as barriers to AGD and hinder the provision of clean water (UN Sustainable Development Goal 6). Here, we have identified three knowledge gaps on pollution associated with crop and livestock production. Resolving these knowledge gaps will enhance our understanding of the occurrence, fate, effects and pathways of pollutants from crop and livestock production sites to the aquatic environment. Ultimately, addressing these gaps will assist in exploring effective solutions for controlling such pollutants.

Improved understanding of the interactions between multiple pollutants. Pollutants cross-react affecting their mobility, adsorption, photolysis and degradation throughout the soil-plant-water system. The biological, physical and chemical interactions of multiple pollutants like antibiotics, pesticides and nutrients (N and P) and their biogeochemical cycles limit global and national efforts to achieve AGD. For example, the cross-resistance of microorganisms to antibiotics and pesticides influences microbial growth, diversity, gene expression and enzyme activity[16], and affects N and P biogeochemical cycles in the pedosphere and hydrosphere. Agricultural systems are also accelerating aquatic sedimentation and the movement of pollutants to the aquatic environment[17]. It is essential to consider the transport mechanism of coexisting pollutants via hydrological processes, especially in mountain areas with cash crops. In addition to the toxicity of each pollutant, the complex interactions between multiple pollutants need to be more thoroughly understood to assess and manage the ecological risks of water and soil pollution effectively.

Modeling river export of multiple pollutants. The water quality modeling approach is a tool to better understand the hotspots and sources of water quality issues and to provide evidence for policymaking and policy implementation for the provision of clean water. However, most of the existing water quality models, such as Global NEWS-2[18] and IMAGE-GNM[19], are limited to simulating a single pollutant at multiple scales with a focus on nutrients. However, the MARINA model integrates modeling approaches for other pollutants (microplastics, triclosan and *Cryptosporidium*)[20]. The SWAT model simulates pesticide fate and transport at the watershed scale. At this stage, however, biological, physical and chemical interactions between multiple pollutants have not been explicitly modeled, as well as their combined impacts on the environment. We call for a multi-pollutant approach that not only integrates pollutants from crop and livestock production but also considers their interactions in the biogeochemical cycles.

Reducing the inputs to crop and livestock production. The implementation of science-based regulations aimed at reducing the use of fertilizers, pesticides and herbicides in the YRB is still inadequate. Achieving recycling the residues and manure in crop and livestock production is crucial to reduce N and P loading to the river from agricultural waste. Therefore, a well-planned integration of crop and livestock production, supported by scientific evidence, is essential for AGD in the YRB. We highlight synergetic solutions following top-down management that are needed to mitigate multiple pollutants in rivers arising from crop and livestock production. These are based on the water quality target management to determine the optimal technical options for crop and livestock production from an environmental impact perspective. Ecological thresholds are useful indicators for identifying pollution levels, and it serves as restoration goals for aquatic and terrestrial systems enabling the formulation of future management options. However, the ecological thresholds for multiple pollutants, other than nutrients, have yet to be set by consensus.

5 Outlook

Here, we propose three pathways to bridge the knowledge gap and support AGD in the YRB.

(1) Multiple pollutants affect N and P biogeochemical cycles

Reducing mineral fertilizer applications in line with efficient nutrient utilization is the key to achieving the goals of green and sustainable agriculture. Soil microorganisms drive key functions in agroecosystems, determining soil fertility, crop productivity and stress tolerance[21]. The existence of multiple pollutants can affect the microbial population, abundance and type, thus affecting the transformation of nitrogen. Organic fertilizer replacement brings the potential multiple pollutants, such as antibiotics and insecticides, directly threaten the microorganisms in water, soil, sediment and sewage sludge. There are effective strategies to evaluate complex environmental systems, prolong action time, strengthen multifactor and multilevel research assist molecular biology, via stable isotope probing, stable isotope-labeled tracing, and metagenomics, transcriptomics and similar technologies. Such evaluation can provide valuable insights into the impact of multiple pollutants on microorganisms-mediated nitrogen transformation processes, the negative impact of extra nutrient loss from microorganisms, and evaluate the sustainability in crop and livestock production in the YRB.

(2) Models for migration and transformation

Models can help in understanding pollutant movement in food-land-river systems, primarily caused by rainfall-runoff, erosion and soil infiltration. Simultaneously, pollutants in the soil environment and water bodies undergo complex transformations mediated by their microbiome. Multi-pollutant river models (MPRM) need to integrate information on sources of pollutants, such as plastic debris, nutrients, chemicals and pathogens, their effects and possible solutions[22]. Inspired directly by foundation hydrology models we identify three key capabilities that distinguish traditional water quality models from MPRM. First, adapting a foundation model (e.g., SWAT, SHE and DBSIM) to a new task will be describing the variable inputs, boundary conditions (environmental describing), the interaction process following the time steps to achieve by iterative numerical calculations or empirical models to the description of physical process, chemical process with microbial processes. Second, the MPRM can update the input parameters, edit, select or ignore the modules with the observation outputs results (either laboratory or published data) through inverse solutions or set for localization services. This flexible interactivity contrasts with the traditional models for the multi-pollutant conditions is necessary from the variable types and the complex interactions processes. Third, MPRM models will formally represent nutrient cycling processes knowledge, allowing them to reason through previously unseen tasks and use agricultural or environment-accurate language to explain their outputs. Overall, we reflect on future directions for multi-pollutant modeling and the linking model results to policymaking [22].

(3) Policy support for multi-pollutant control

Policymakers, scientists and other stakeholders have to work together with academics and technical experts for AGD in the YRB. Analyses of dietary trends and food supply should guide local agricultural development, which will determine future multi-pollutant scenarios. There are diverse crop and livestock production systems and geological conditions along the full length the YRB, which need the different appropriate environmental policy in the YRB. Also, a specific policy for recycling in crop and livestock production, and a plan for organic fertilizer alternatives are necessary for the range of fertilizer efficiency from different livestock manure (ruminant or monogastric sources), and the root absorption efficiency for different crops. Climate change effects, such as an extreme rainstorm, heat waves and drought events, require the policy design to ensure the crop and livestock production are more inclusive of extreme climate events in the YRB. The different scenario analyses for climate change and policy adjustments can be estimated by MPRM model, but it is noted that assessments of model uncertainty in multi-model intercomparisons, and perturbed physics and parameter studies cannot provide robust probabilities[23]. It is hoped that recognition of these potential risks will improve the overall level of accounting for consequences associated with multiple pollutants from crop and livestock production under policy scenarios in the YRB.

Acknowledgements

This research was financially supported by the National Natural Science Foundation of China (U20A2047 and 42107056), the Key Laboratory of Low-carbon Green Agriculture (Ministry of Agriculture and Rural Affairs), and the State Cultivation Base of Eco-agriculture for Southwest Mountainous Land (Southwest University).

Compliance with ethics guidelines

Lihua Ma, Shiyang Li, Linfa Fang, Xuanjing Chen, Ran Xiao, Xiaoxuan Su, Zhaolei Li, Zhaohai Bai, Lin Ma, Prakash Lakshmanan, and Xinping Chen declare that they have no conflicts of interest or financial conflicts to disclose. This article does not contain any studies with human or animal subjects performed by any of the authors.

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