

# Agricultural non-point source pollution and agricultural green development: status, challenges and prospects

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## KEYWORDS

Agricultural green development, agricultural non-point source pollution, AI in agriculture, pollutant tracing, sustainable development

## HIGHLIGHTS

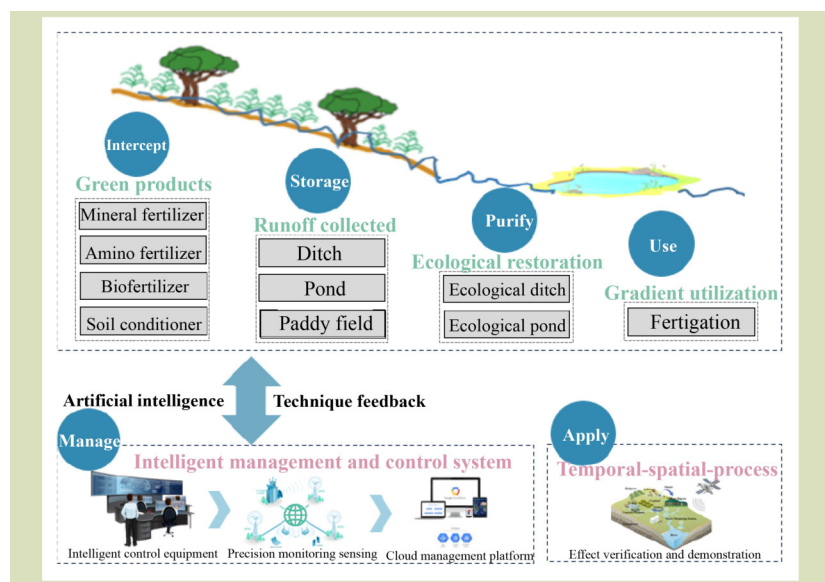
- Offers the theoretical and policy guidance for sustainable agricultural development.
- A comprehensive analysis of spatiotemporal dynamics and causes of ANPSP is presented.
- Integrated technologies and AI-based strategies are proposed for ANPSP control.

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## GRAPHICAL ABSTRACT



## ABSTRACT

Agricultural green development (AGD) is an essential process for achieving sustainable agricultural development. Among the challenges encountered in transitioning to green agriculture, agricultural non-point source pollution (ANPSP) is a primary concern. The environmentally friendly practices

advocated by AGD promote the reduction of ANPSP by controlling the emission and spread of pollutants. This paper provides a comprehensive overview of the current status of ANPSP, examining its causes from the perspectives of spatiotemporal dynamics, pollutant tracking and control mechanisms. Additionally, it offers targeted recommendations for the prevention and control of ANPSP, focusing on pollutant tracing, integrated technologies, the application of artificial intelligence and national policies. By systematically reviewing key advances in ANPSP research and governance, this paper provides both theoretical insights and practical suggestions for the development of efficient and sustainable prevention and control systems for ANPSP.

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## 1 Introduction

Agriculture is essential for global food production. However, current agricultural practices, characterized by inefficient use of resources and excessive pollutant emission, have attracted increasing concern in recent years due to their adverse impacts on the environment and sustainability<sup>[1,2]</sup>. Although high resource consumption and high environmental costs may increase yields in the short-term, activities such as land plowing, intensive application of mineral fertilizers and pesticides, irrigation, drainage and other forms of land degradation can negatively affect environmental health<sup>[3]</sup>. Currently, the main challenge for many countries is the development of an efficient agricultural system that not only ensures sufficient food production but also promotes the sustainable use of natural resources, thereby reducing the negative environmental impacts of farming<sup>[4]</sup>. Agricultural green development (AGD) incorporates agriculture production with environmental protection to create an agricultural system that is environmentally friendly, economically viable, and socially inclusive. The importance of AGD lies in its ability to reduce environmental pollution and prevent resource depletion, providing critical support for global food security. Therefore, the transformation from existing agriculture development to AGD has become an urgent priority.

Currently, controlling the environmental pollution caused by agricultural production and restoring the health of ecosystems are essential for the successful advancement of AGD. The effectiveness of ANPSP (agricultural non-point source pollution) governance can directly serve as the one of the key indicators to for measuring AGD progress. However, the

transformation of the agricultural system toward AGD has been hindered by numerous challenges, including inefficient irrigation practices, soil degradation, inefficient use of resources and environmental contamination. According to the Food and Agriculture Organization (FAO), reactive N released from agricultural activities is about 120 Tg·yr<sup>-1</sup>, with more than 60% not absorbed by crops and instead entering the environment. Additionally, about 8–10 Tg·yr<sup>-1</sup> P is used in agricultural system globally, with over 50% of it entering rivers and lakes through surface runoff or soil erosion. From 1961 to 2022 crop N leaching in China increased nearly 10-fold whereas the global crop N leaching increased by only about 2.5 times. Therefore, effective ANPSP management is crucial for improving agricultural resource use efficiency (e.g., through precision fertilization, water-saving irrigation, etc.), enhancing the sustainability of the ecological environment and promoting the application of green technologies, ultimately supporting the development of AGD. This paper provides a comprehensive analysis of the current status, challenges and potential mitigation measures for ANPSP, with the aim of establishing a solid environmental foundation and developing high-quality green agriculture through controlling ANPSP.

## 2 Agricultural green development concepts and trends

Sustainable development generally refers to meeting the needs of the present without compromising the ability of future generations to meet their own needs. This concept emphasizes a balance among economic growth, social equity and environmental protection, aiming to achieve long-term

prosperity for both humanity and the environment. Sustainable development addresses human aspirations for a better life while observing the limitations imposed by nature<sup>[5]</sup>. In 2015, the United Nations General Assembly approved the 17 Sustainable Development Goals (SDGs) with the aim to foster the organizational operationalization and integration of a sustainable future for all, balancing social, economic and environmental development<sup>[6]</sup>. AGD is a transformative approach that aligns agricultural production with environmental protection, which not only protects natural resources but also enhances food security, improves farmer livelihoods and increases consumer health<sup>[7,8]</sup>. Therefore, AGD can be seen as a concrete application of sustainable development in the agricultural context, helping to maintain ecological balance.

To achieve AGD, the following proposals are recommended: (1) fully consider the current state of resources; (2) use fertilizers, pesticides and other agricultural products in a scientific and rational way; (3) promote the reuse of agricultural waste; (4) reduce environmental pollution and damage; and (5) improve the quality and safety of agricultural products<sup>[9]</sup>. These AGD concepts align with the goals of SDG1 (No Poverty), SDG2 (Zero Hunger), SDG6 (Clean Water and Sanitation), SDG8 (Decent Work and Economic Growth) and SDG 15 (Life on Land)<sup>[10]</sup>. Therefore, the relationship between sustainable development and AGD can be viewed as goal-driven. AGD serves as a core means of achieving the SDGs, while the concept of sustainable development provides both a theoretical framework and practical direction for the green transformation of agriculture.

AGD has become an inevitable trend in modern agriculture worldwide, helping to mitigate soil and water pollution by reducing the use of mineral fertilizer and pesticides. With the intensification of global challenges including climate change, resource scarcity and population growth, AGD provides a viable approach to reshape agricultural systems, making them more resilient, efficient and environmentally friendly. As a major agricultural country, China has actively promoted AGD practices since 2015. The *China Agricultural Green Development Report 2023* shows that the national AGD index increased from 75.2 to 77.9, reflecting steady progress from 2015 to 2022<sup>[11]</sup>. From 2009 to 2018, while maintaining crop yields, China achieved a cumulative reduction of 14.6 Mt in mineral nitrogen fertilizer application, 0.54 Mt in pesticides and 55.6 Mt in greenhouse gas emissions<sup>[12,13]</sup>. AGD is not

only a technological innovation but also a systemic transformation, involving changes in production methods, policy support and public awareness. It is a long-term and challenging task that, while protecting the environment, injects sustainable momentum into the economy and society.

## 3 ANPSP hinders the advancement of agricultural green development

### 3.1 Current status of ANPSP

ANPSP is one of the main causes of global water body and ecosystem degradation. Due to its dispersive and unpredictable nature, ANPSP has become one of the major global threats to water resources and ecosystem health. Some 30%–50% of the Earth's surface has been contaminated by ANPSP, primarily from N and P fertilizers, pesticide runoff, atmospheric N deposition and intensive livestock production<sup>[14]</sup>. Available data indicates that 80% of water bodies and 50% of the global land areas are affected by ANPSP, with around 75% of these areas being affected by N and P pollution<sup>[15]</sup>. N and P from agricultural sources account for 81% and 93% of China's water pollution, respectively<sup>[16]</sup>. Excessive atmospheric N deposition affects aquatic ecosystems worldwide, which also increases the agricultural N pollutant emission in certain watersheds<sup>[17]</sup>. Since the implementation of the Action for Green Development of Agriculture policy in China, the utilization rate of mineral fertilizers increased to 41%, pesticide use rose to 42%, crop straw was maintained at 86% and the resource utilization rate of livestock manure reached 78% between 2015 and 2022. During the same period, cropland N leaching decreased by 15%<sup>[11]</sup>. In Jiangsu Province, the coverage rate of soil testing and formulated fertilizer technology exceeded 95% in 2021, leading to a reduction in agricultural N and P loss by 13%–20% compared to 2015. This also resulted in an average 5%–10% decrease in the concentration of total nitrogen (TN) and total phosphorus (TP) in Taihu Lake basin<sup>[18]</sup>. Except for the typical Yangtze River basin, the plateau basin region is also threatened by serious ANPSP, total loads of chemical oxygen demand (COD), TN and TP from ANPSP in the Erhai Lake basin were 11.2, 2.75 and 0.26 kt in 2018, respectively<sup>[19,20]</sup>.

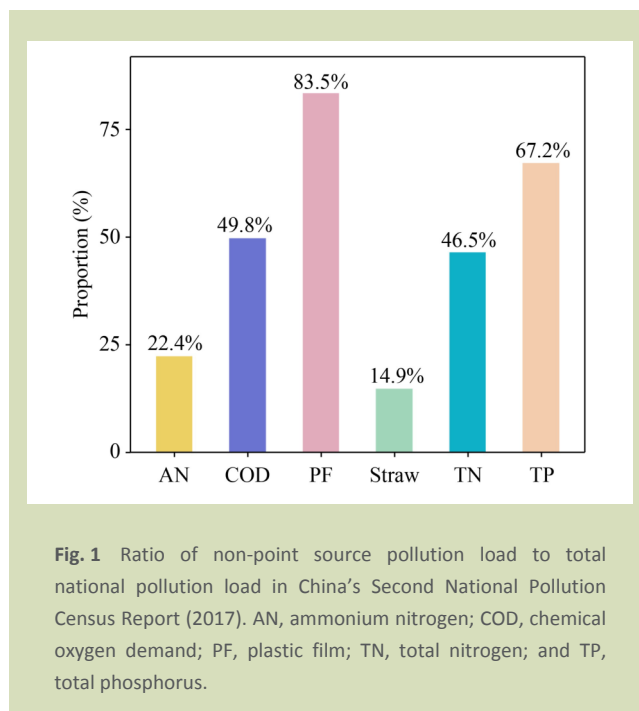
Agricultural pesticide application has led to contamination of soil, surface water, groundwater and crops. Over 4 Mt of pesticides are currently used globally each year, with high concentrations exceeding safe threshold limits detected in

water bodies worldwide<sup>[21]</sup>. Pesticide pollution has different sources, which enter the water cycle mainly through discharges from urban waste water treatment plants, storm overflows or urban runoff. Analysis of agricultural soils sampled under the European Union Land Use and Coverage Area Frame Survey revealed that over 80% of agricultural soils contains pesticide residues, with 58% percent showing a mixture of residues, and only 17% of soils being free of pesticides<sup>[22]</sup>.

Currently, there are 50 Mha of grain-producing land in China, which make up nearly one-fifth of China's agricultural land. This large amount of cultivated land generates a significant amount of agricultural waste. The annual waste from livestock manure, crop straw and other agricultural by-products amounts to about 4 Gt in China<sup>[23]</sup>. According to data from China's Second National Pollution Census Report (2017), the annual COD loading was 21.4 Mt, annual ammonium nitrogen (AN) loading was 0.96 Mt, annual TN loading was 3.04 Mt and annual TP loading was 0.32 Mt. Agricultural sources contributed significantly to national water pollution discharges, including 10.67 Mt of COD, 0.21 Mt of AN, 1.41 Mt of TN and 0.21 Mt of TP. Also, the annual total production of straw amounted to 805 Mt, with 120 Mt left abandoned. The annual total usage of plastic film (PF) reached 1.41 Mt, and the cumulative residual PF in farmland was 1.18 Mt. With the exception of AN and straw, the discharge of other agricultural pollutants accounts for a relatively high proportion, particularly PF contaminant, reaching 83.5% (Fig. 1). These findings highlight the critical need to increase the utilization rate of agricultural waste and strengthen the management of ANPSP. As ANPSP limits AGD in multiple areas, including food security, resource use and ecological protection, addressing ANPSP is an urgent imperative to ensure the realization of sustainable development.

### 3.2 The risks posed by ANPSP

The excessive application of fertilizers exacerbates ANPSP and leads to severe ecological and environmental degradation. Long-term fertilizer use has been shown to decrease soil organic matter by nearly 30% in the north-east black soil region in China<sup>[24]</sup>. Inappropriate nutrient ratio (N:P:K) in mixed synthetic fertilizers causes both biological and physicochemical damage to soils, leading to acidification, soil hardening and reduction in microbial biodiversity<sup>[25]</sup>. ANPSP has emerged as the most critical threat to global water quality, driving widespread degradation through nutrient overloads,



toxic chemical contamination and ecosystem destabilization<sup>[26]</sup>. It contributes over 50% of N inputs to freshwater systems in intensive cropping regions, directly correlating with 78% of eutrophication cases according to data from the Global Lake Ecological Observatory Network<sup>[27]</sup>. The UN Global Water Security 2023 Assessment identifies ANPSP as the dominant driver (63% of cases) of water quality crises in developing economies, where uncontrolled agrochemical runoff and manure mismanagement render surface waters unfit for human use, imposing 27 billion USD annually in treatment costs<sup>[28]</sup>.

Despite the recent annual decline in mineral fertilizer and pesticide application in China, the issue of ANPSP remains severe. In the Yangtze River basin, mineral fertilizer application loading reached 16.9 Mt, with an application intensity of 283 kg·ha<sup>-1</sup>, which is 1.26 times higher than the internationally recognized safe threshold level of 225 kg·ha<sup>-1</sup><sup>[29]</sup>. Persistent high use of fertilizers in intensive agricultural regions has led to significant N and P losses, further exacerbating eutrophication in ponds and lakes adjacent to paddies. Only 5 out of 18 nationally monitored water quality stations in the Poyang Lake basin met the TP concentration standard. Notably, nine stations exhibited an upward trend in TP concentrations, with the maximum increase reaching 39.6% in 2023<sup>[30]</sup>. ANPSP also directly impacts the quality of farmland soil and water, posing a

threat to both the quality and safety of agricultural products. Controlling ANPSP is akin to detoxifying the soil, only by prioritizing this detoxification will green agriculture become firmly established and succeed.

### 3.3 Challenges in controlling ANPSP

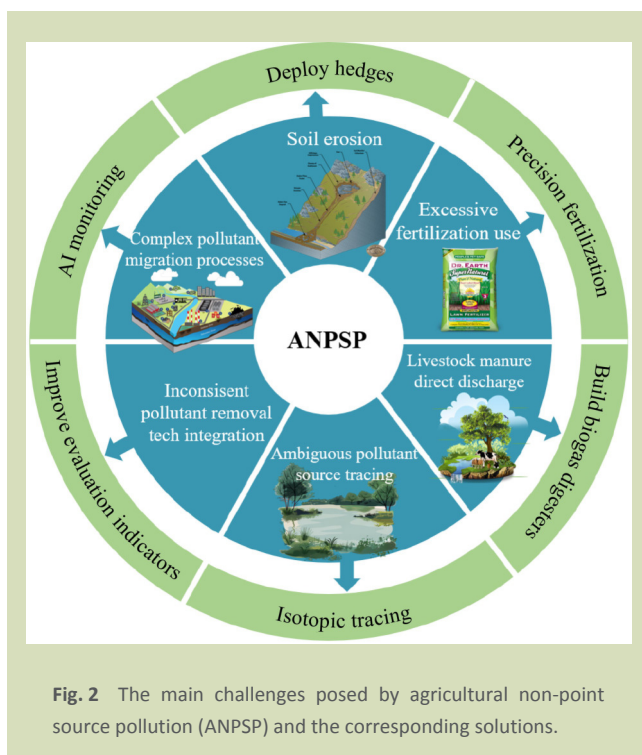
#### 3.3.1 Ambiguous pollutant tracing

The formation of ANPSP is a complex process, involving a multitude of factors. Figure 2 summarizes the major risks currently associated with ANPSP and the corresponding solutions. ANPSP is primarily caused by the use of fertilizers (especially N and P), pesticides, livestock manure and other organic-inorganic nutrients and contaminants that leak into waterbodies via field surface runoff or agricultural wastewater discharge. It is estimated that about 50% of excess fertilizer, i.e., applications exceeding the actual demand of the crop, are leached into water bodies<sup>[31]</sup>. In addition to the massive loss of nutrients and pollutants, the unclear traceability of pollution sources poses a significant challenge in the current management of ANPSP. This difficulty arises from the dispersed sources of pollution, complex migration paths, and strong spatiotemporal heterogeneity. Therefore, accurate traceability of pollutants is essential for efficient prevention

and control. This will involve clarifying the multi-path, multi-process and multiscale transport mechanisms of pollutants.

Existing tracing methods include isotopic labeling, hydrological models, high-resolution remote sensing and fluorescence fingerprinting, among others. However, these methods are often limited by factors such as the availability of local data or the complexity of model formulation. Isotopic tracing methods are widely used but can be limited by fractionation interferences, overlapping isotopic signatures of contaminants and low spatiotemporal resolution. For example, the  $\delta^{15}\text{N}-\text{NO}_3^-$  and  $\delta^{18}\text{O}-\text{NO}_3^-$  detected in a Mediterranean river basin in Greece ranged from 4.4 to 20.3 ppt and  $-0.5$  to 14.4 ppt, respectively, making it difficult to clearly identify the sources of the contaminants<sup>[32]</sup>. Hydrological models (e.g., AGNPS, SWAT and AnnAGNPS) coupled with GIS are also effective methods for tracking pollutant transport<sup>[33,34]</sup>. These models can identify and simulate hydrologically sensitive areas and regions with high pollution production and discharge. For example, in a study of the Choctawhatchee Watershed (spanning southern Alabama and north-west Florida, USA), SWAT modeling integrated with multivariate statistical analysis identified critical source areas that represented 28% of the total watershed area and contributed 47% of TN and 50% of TP<sup>[35]</sup>. However, while these models can be useful in tracing the sources of ANPSP, training the models requires substantial data and programming expertise. In addition, ongoing research and model development are necessary given that no universal model can be applied across regions with diverse climatic, geographic and anthropogenic conditions<sup>[36]</sup>. For example, models such as SWAT, which can simulate field-scale or small watershed-scale systems, are unsuitable for large-scale contaminant simulations<sup>[37]</sup>.

Compared with hydrological models, high-resolution remote sensing offers broad spatial coverage for real-time monitoring of various pollutants and enables accurate localization of high-intensity pollution hotspots. Therefore, developing high-resolution remote sensing coupled with machine learning is necessary to assess agricultural pollution<sup>[38]</sup>. While high-resolution remote sensing enables rapid screening of large-scale contaminants, quantifying the contribution of specific contaminants remains a challenge. Fluorescence fingerprinting is a promising new approach for identifying pollution sources<sup>[39]</sup>. However, this technology still faces challenges, such as highly overlapping source fingerprints, fingerprint distortion caused by environmental interference, inadequate multivariate mixing analysis capability and high analysis costs<sup>[40]</sup>.



Regardless of the tracing method used, upgrades are necessary for effective ANPSP management due to challenges in source identification. Precise pollutant tracing technology represents a transformative approach to alleviating ANPSP by tackling ambiguous liability. As the costs of this technology declines and policy coordination improves, precise tracing will shift ANPSP control from passive response to proactive prevention, providing critical support for global sustainable development.

### 3.3.2 Fragmentation of ANPSP management systems

Currently, considerable efforts have been made in the prevention and control of ANPSP and number of effective technologies have been developed. These include ecological ditch interception<sup>[41]</sup>, constructed wetland purification<sup>[42]</sup> and energy production from livestock manure<sup>[43]</sup>, among others. However, these techniques are unable to address all aspects simultaneously and thus fail to achieve synergistic control over multiple types of pollutants. Although these technologies have achieved some success in pollutant control, the reuse of nutrients, specifically N and P, from pollutants remains unresolved.

In agricultural waste recycling, classic technologies like composting and anaerobic biogas production have addressed major waste issues, such as livestock manure and crop straw, to some extent. However, issues such as high AN levels in digestate, nutrient loss from manure and low nutrient absorption on farmland continue to persist<sup>[44]</sup>. Based on the concept of regional collaborative pollution control, Xue et al.<sup>[45]</sup> proposed a systematic and comprehensive control strategy with corresponding technologies. This ANPSP control strategy consists of four steps with four goals: source reduction, process retention, nutrient reuse and aquatic ecosystem restoration, collectively referred to as the 4R strategy. This 4R strategy constitutes a complete circular technical chain<sup>[46]</sup>. In 2018, the 4R strategy based on the comprehensive control of N and P loss from farmlands was listed as one of the leading agricultural technologies in southern China. Xue et al.<sup>[29]</sup> suggested that the systematic 4R strategy was a promising method for reducing N and P loads from agricultural fields and alleviating downstream water eutrophication. Also, it can be extended to other agriculturally intensive regions. Harnessing technological progress, maximizing cross-process integration within the 4R strategy and achieving spatiotemporal coordination in pollution control remain critical challenges in addressing ANPSP.

### 3.3.3 Low efficiency of large-scale ANPSP control

At the large regional scale, pronounced spatial heterogeneity arises from significant variations in soil types, climatic conditions and cropping patterns across subregions, making it challenging to apply uniform control measures. In a traceability analysis of pollutants across the entire Yangtze River basin, Wang et al.<sup>[41]</sup> discovered that the sources of different pollutants are diverse. The main sources of water pollution and their respective contributions are domestic pollution, hydrogeochemical evolution, water-rock interactions and ANPSP<sup>[47]</sup>. As a result, substantial disparities exist in the pollutant loads among different river basins and there is a superimposed effect of multisource pollution within large regions, which complicates source identification.

Rapidly rising management coordination and monitoring costs are also a key factor impeding large-scale ANPSP control. Collaborative efforts across administrative regions encounter significant obstacles. The coverage density of established monitoring networks, such as water quality monitoring stations, remains severely inadequate (less than 1 per 1000 km<sup>2</sup>) and operational and maintenance costs are escalating exponentially. Also, there is a response lag in large-scale ecosystem restoration, which can distort short-term policy evaluations.

## 4 Prospects

### 4.1 Develop precise N and P tracing technologies

In the control of ANPSP, developing precise N and P source tracing technologies is a key approach to addressing the ambiguity of pollution sources and improving the efficiency of pollution control. In recent years, although progress has been made in the research on N and P traceability, most studies focus on a single process, path or scale. However, agricultural pollutants migrate through multiple pathways, including soil-water migration (surface runoff, groundwater leaching and soil erosion) and atmospheric migration (volatilization of fertilizers and pesticides). Given the dynamic nature of pollutant migration, integrating diverse tracing methods is essential.

Pollutant tracing through sampling is relatively simple and efficient at the local scale. In contrast, model fitting and remote sensing technology provide better data monitoring at the regional scale where spatial variability occurs due to the

interaction of pollutants. At the national scale, it is necessary to combine metadata with algorithms to simulate and monitor pollutants effectively. In particular, AI technology can collect real-time environmental data of farmland through multisource devices such as sensors, drones and satellites. By integrating models trained on historical data, AI can also provide early warnings of pollutant emission peaks<sup>[48]</sup>. Therefore, there is an urgent need to use long-term positioning observation data to analyze the multi-path, multi-process and multiscale migration mechanisms of N and P pollutants.

Using current and historical data from long-term field observation stations, combined with on-site investigations, it is possible to analyze the spatiotemporal distribution characteristics of ANPSP and identify key thresholds for its variation. This process involves clarifying the migration and loss processes of N and P in watersheds, screening tracing indicators for N and P across different processes, and developing appropriate tracing methods. The goal is to create a comprehensive tracing technology that tracks N and P pollution from agricultural inputs to watershed water bodies. Also, by considering regional characteristics, it is possible to analyze the source-flow-sink processes of agricultural N and P pollutants, quantify the response relationships between receiving water bodies and major agricultural sources, and identify key parameters for these responses. This will enable the construction of an integrated temporal-spatial-process precision tracing and assessment system for ANPSP, which can be applied and promoted in multiple regions.

## 4.2 Integrate effective technologies and conduct cost-benefit evaluation

Over the years, many effective technologies and methods have been developed for controlling ANPSP and promoting the use of agricultural waste as a resource. However, the lack of

seamless integration among these technologies, resulting in suboptimal operational outcomes, remains a critical challenge in ANPSP management. Managing ANPSP should follow the 4R strategy, implementing a systemic approach that coordinates multiple technologies and links various stages of the process. In the Taihu Lake 4R demonstration area, the implementation of precision fertilizer application recommendations have achieved source *Reduction* of nutrient inputs, reducing fertilizer application by 10%–20% in the rice-wheat cropping system and significantly mitigating N and P losses to the environment<sup>[49]</sup>. Ecological ditches, as part of the *Retain* system, are effective control measures, with average removal efficiencies of TOC, TN and TP in the converted ecological ditch of 20.8%, 37% and 44.4%, respectively<sup>[46]</sup>. For *Reuse*, ecological floating beds are commonly adopted, achieving a recovery rate of over 80% for N and P<sup>[50]</sup>. Establishing ecological wetlands at river or estuaries is a widely used approach to *Restore* polluted water bodies. As a result of the integrated 4R process in the Taihu Lake 4R demonstration area, N and P losses have been reduced by 31%–54% and 25%–53%, respectively<sup>[51]</sup>. When integrating technologies, factors such as spatial adaptability, technological complementarity, and economic feasibility should be considered. Some typical technology integration models are shown in [Table 1](#).

While the 4R strategy can be effective at larger scales, the strategy may not be easily applicable to smallholder farming, as it requires the development of region-specific measures tailored to the local socioeconomic and natural conditions. To assess the feasibility of technologies, comprehensive consideration should be given to environmental factors, economic factors (including cost per unit area for management and carbon sequestration potential) and social factors (including technology adoption rates, farmer satisfaction and job creation). Methods such as model simulation, field

**Table 1** Typical technology combination models

Scene		Integrated solution		Suitable region	Efficiencies (%)
Intensive cropping area	Precision fertilizer application	Ecological ditches	Constructed wetland	Plain	30–66 <sup>[52,53]</sup>
Intensive poultry and livestock farming area	Solid-liquid separation of manure	Biogas project	Intelligent irrigation with digest	Basin <sup>[54]</sup>	50–80 <sup>[55]</sup>
Sloping farmland	Contour farming	Hedgerow system	Sediment basins	Highland	12–65 <sup>[56]</sup>
Suburban agricultural area	Green pest control	Ecological interception ditches	Sewage treatment plants	Suburb	70–90 <sup>[57]</sup>

monitoring and cost-benefit analysis should be used to optimize technology selection. Gu et al.<sup>[58]</sup> quantified the potential of available measures, calculated the implementation costs and analyzed the social benefits of these measures, to subsequently categorize them into three tiers to suit different regions. Through the technology integration and the establishment of an evaluation system, the management of ANPSP can shift from passive response to proactive prevention and control. This approach can ultimately achieve the green development goal of controllable pollution, increased land productivity and higher incomes for farmers.

### 4.3 Adopting advanced technologies

Given the current emphasis on ecological protection and green sustainable development, promoting the widespread adoption of medium- and large-sized self-propelled plant protection machinery and agricultural technologies is imperative. Implementing technologies such as precision targeted spraying and variable rate spraying can help reduce pollution at the source<sup>[59]</sup>. Additionally, by combining long-term positioning data from station observations, satellite remote sensing, ground sensors, information from the literature and field monitoring data, a high-resolution pollution source database can be established. This database would enable real-time, comprehensive monitoring across water-land-air.

Machine learning combined with blockchain or Internet of Things technology can be used to develop an integrated metadata platform and decision-making model. This would enable full-process automation for tracing and management for pollutant tracing. In recent years, using machine learning-based techniques for runoff<sup>[60]</sup>, sediment<sup>[61]</sup> and water quality<sup>[62]</sup> simulation have gained popularity. Ehrlich<sup>[63]</sup> suggested using blockchain technology to optimize water pollution monitoring and strengthen supervision.

AI systems can provide tailored solutions for different application scenarios. The ideal model for integrated ANPSP monitoring and prevention-control from the perspective of temporal-spatial-process is presented in Fig. 3. This model comprehensively implements the 4R strategy to achieve the reduction, interception, removal, tracing and recycling of pollutants throughout the entire process. AI employs remote sensing, sensor technology and image recognition to capture terrestrial pollutant data. After preprocessing these multisource data sets, it extracts critical features for model training, using root mean square error as a validation metric. Real-time monitoring via Internet of Things supported by algorithms like support vector machine feeds measured data into trained models for analysis. Through this closed-loop workflow, AI enables precise monitoring, scientific assessment, and intelligent ANPSP early warnings. This technology provides

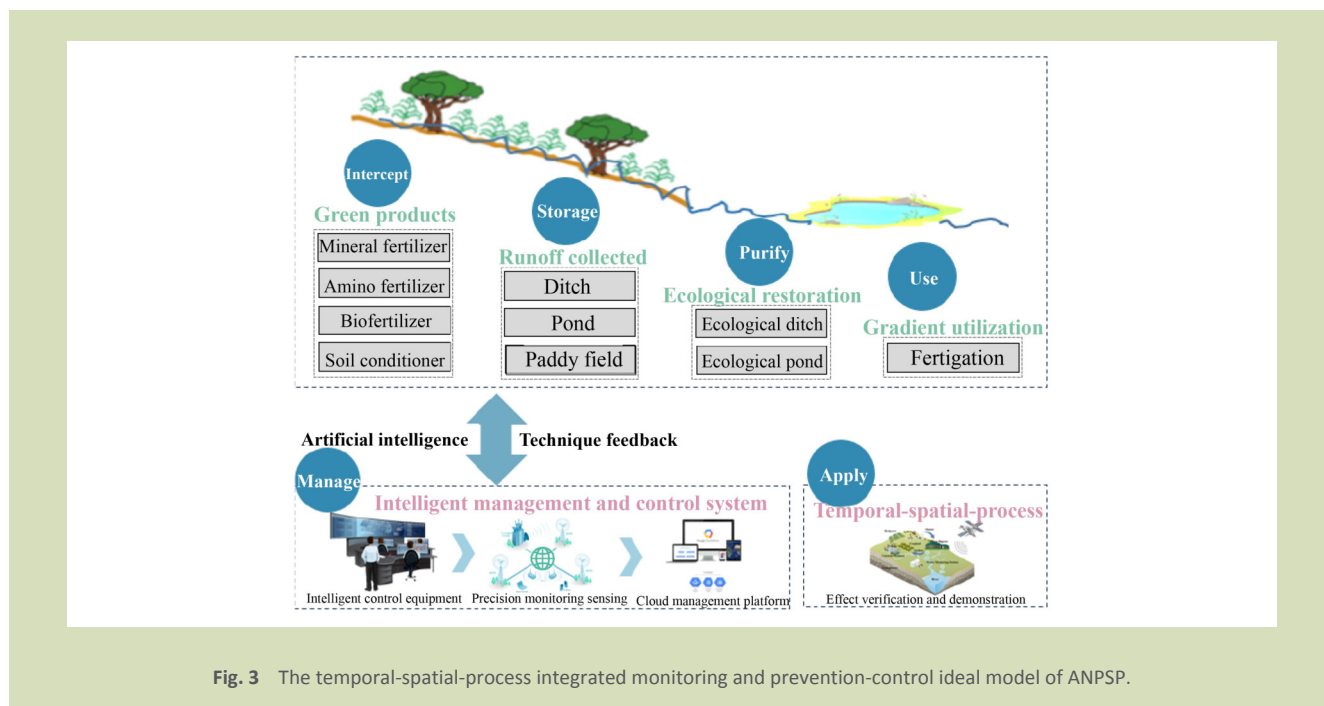


Fig. 3 The temporal-spatial-process integrated monitoring and prevention-control ideal model of ANPSP.

crucial technical support for watershed pollution control and the reduction of fertilizer/pesticide inputs. Developing portable and rapid pollution source detection devices could also help to lower the adoption threshold for small- and medium-sized farming operations.

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#### 4.4 Enhancing social and economic support

In addition to technological advances in ANPSP control, governments should establish innovative policy frameworks to support ANPSP management. One key approach is to integrate the AGD indicators (e.g., reductions in fertilizer and pesticide application rates, and increase in livestock manure utilization rate) into local performance evaluation systems, while strengthening regulatory measures. Complementary central fiscal subsidies should be implemented to incentivize and compensate farmers for their investments in green production. For example, in 2023, subsidies in Shandong Province led to an 18% increase in organic fertilizer usage, resulting in a 1.2% rise in soil organic matter concentration in the plow layer. This not only improved soil health, it also effectively boosted farmer enthusiasm for energy conservation and emission reduction<sup>[64]</sup>.

China should strengthen international cooperation by drawing on experiences from developed countries, such as precision agriculture in the USA and greenhouse gas monitoring technologies the Netherlands. By adapting these technologies for domestic use, China can improve its own green agricultural practices. Through the Belt and Road agricultural assistance programs, China can also share its expertise in pollution control with other developing countries helping them tackle

their own sustainable agriculture challenges. Finally, China should actively participate in global initiatives like the Global Environment Facility and Green Climate Fund, while launching a global ANPSP governance alliance to share data, practices and strategies for effective ANPSP control. These combined efforts will contribute to advancing global targets for ANPSP prevention and furthering the goals of AGD and SDGs.

## 5 Conclusions

Green and sustainable development are fundamental pathways to achieving agricultural modernization. In the face of global challenges such as climate change, ecological degradation, and food insecurity, these principles have become the core drivers of modern agriculture. Effective management of ANPSP is a critical breakthrough in this transformative process. This paper identifies three main challenges in current governance practices: the ambiguous traceability of pollution sources, disconnect between prevention technologies and the low efficiency of large-scale pollution control technologies. This study emphasizes the need to enhance precise tracing technologies for pollutants and implement location-specific prevention measures integrated with the 4R strategy. It underscores that ANPSP governance should transition from source reduction to resource recycling to drive green transformation across the entire agricultural chain. Finally, this study not only puts forward technical recommendations but also presents insights for government and society. Future technological innovation, institutional reform and global collaboration will enable agriculture to evolve from being a mere consumer of ecosystems to a restorer and value creator.

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#### Compliance with ethics guidelines

Jing Tao, Haibing Xiao, Feng Liu, Yanfang Feng, Shunchang Yang, Lei Zhou, and Yonghong Wu 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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