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REVIEW

FULL TIME-SPACE GOVERNANCE STRATEGY AND TECHNOLOGY FOR CROPLAND NON-POINT POLLUTION CONTROL IN CHINA

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KEYWORDS

4R chain technology system, agricultural non-point source pollution, case study, full time-space governance strategy

HIGHLIGHTS

- Full time-space governance strategy for AGNPS pollution was proposed.
- The 4R chain technology system including source reduction, process retention, nutrient reuse and water restoration was reviewed.
- The strategy and 4R technology system was successfully applied for AGNPS pollution control at administrative village scale.
- Future challenge include the monitoring system, new smart fertilizer and intelligent equipment, governance standards and supportive policies.

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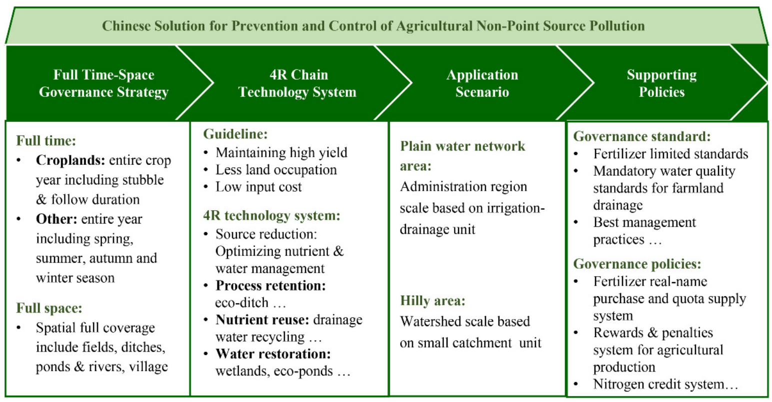
GRAPHICAL ABSTRACT



ABSTRACT

Ensuring food safety while reducing agricultural non-point source pollution is quite challenging, especially in developing and underdeveloped countries. Effective systematic strategies and comprehensive technologies need to be developed for agricultural non-point source pollution control at the watershed scale to improve surface water quality. In this review, a proposal is made for a full time-space governance strategy that prioritizes source management followed by endpoint water pollution control. The 4R chain technology system is specifically reviewed, including source reduction, process retention, nutrient reuse and water restoration. The 4R chain technology system with the full time-space governance strategy was applied at the scale of an administrative village and proved to be a feasible solution for reducing agricultural non-point source pollution in China. In the future, a monitoring system needs to be established to trace N and P transport. Additionally, new smart fertilizer and intelligent equipment need to be developed, and relevant governance standards and supportive policies need to be set to enhance the efficacy of agricultural non-point source pollution control.

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1 INTRODUCTION

Feeding a growing population and preventing environmental degradation are major global challenges. The problems are worse in China, as the country accommodates 20% of the global population but has only 9% of arable land[1,2]. According to the second national pollution census in 2017, the total nitrogen (TN) and total phosphorus (TP) loads from agricultural non-point sources (AGNPS) accounted for 57.2% and 67.4% of the total emissions in China. Among AGNPS, croplands contribute 39% of TN and 36% of TP, and they significantly contribute to water pollution[3]. The Chinese government implemented the “Zero Growth Action for Fertilizer Use” initiative in 2015, and the efficiency of chemical fertilizer use increased progressively from 35.2% in 2015 to 41.3% in 2022[4]. Still, more than half of the N applied is lost to the environment as a result of gaseous emissions (NH_3 and N_2O), leaching and runoff to water bodies[5], causing severe air pollution, water pollution (especially eutrophication), soil acidification and climate change. Springmann et al.[1] stated that between 2010 and 2050, the negative externalities of the agricultural environment may increase by 50% to 90%, exceeding the safe tolerance limits for planetary bodies, if technological measures are not taken to reform the ongoing practices. To promote the development of green agriculture and mitigate AGNPS pollution, the Chinese government set the goal of maintaining the staple production yield while improving the efficiency of chemical fertilizers above 43% by 2025. The government also proposed to establish 200 demonstration counties for AGNPS pollution control in the Yangtze and Yellow River basin by 2025. An integrated system solution for controlling AGNPS pollution in China is urgently required.

The topography, land use, surface water system, precipitation, soil type and fertility, crop cultivar, and water and fertilizer management vary greatly across China. The massive size of the country and the typical small-scale farming system make it difficult to monitor and manage AGNPS pollution[6,7]. The main AGNPS pollutants are N and P. Depending on the rate of precipitation and fertilization time, the concentrations of N and P can range from around 1 to 30–40 $mg \cdot L^{-1}$[8,9]. AGNPS pollution is managed by implementing single strategies, such as the best nutrient and water management practices, ecological ditches, buffer zones, vegetation filter strips, constructed wetlands and ecological floating beds[8–10]. However, developing strategies to increase agricultural production while improving water quality at the regional and watershed scales is a major challenge. For this, researchers need to determine the following: the technological and engineering measures that are effective and economically feasible, ways to integrate these measures in a region or a small catchment to cover the entire time-space, and the effectiveness of the implemented strategies along with their outcomes. In this review, we proposed a full time-space control strategy at a regional or watershed scale, screened and identified available technologies for controlling AGNPS pollution, introduced a representative case of AGNPS pollution control at the scale of an administrative village and discussed challenges that might arise in the future.

2 FULL TIME-SPACE GOVERNANCE STRATEGY AND TECHNOLOGY

Considering that China faces the problems of highly intensive agriculture, excessive fertilizer input, high nutrient loss, and discharge of complex pollutants, it is argued that the full time-space governance strategy should be implemented by prioritizing source management, followed by endpoint water pollution control. The term, “full time”, means the entire year covering four seasons or the entire crop year, including the stubble stage and the fallow duration. The term, “full space”, means that all pollution sources are included and the entire pollutant transport path is considered. Yang et al.[7] proposed a strategy involving source reduction, process retention, nutrient reuse and water restoration (4R). The best strategy for minimizing AGNPS pollution while ensuring crop yield is source reduction. Using this strategy, the loss of N and P from the fields can be reduced by optimizing water and nutrient management. Process retention, which combines physical, biological and engineering measures like ecological ditches, acts as the second line of defense against water pollution by trapping and filtering pollutants that leave the field before entering water bodies. Reusing nutrients and water in farmlands, known as nutrient reuse, is an inexpensive and effective strategy to decrease water pollution. Ecological restoration is an endpoint water pollution control strategy, achieved by implementing ecological and engineering measures, including wetlands, eco-ponds and eco-floating beds[10]. The 4R technology is a chain system that helps manage pollution throughout the pollutant transport path. It can be integrated in time or process, and used to create a network system at a watershed or regional scale. It can be used to achieve full time-space coverage of the management of AGNPS pollution, thus ensuring considerable improvement in water quality (Fig. 1). However, the difficult is managing the integration and design the 4R technology in time and space based on the characteristics of local pollution and natural conditions to achieve the most effective and optimal control of AGNPS pollution at the lowest cost.

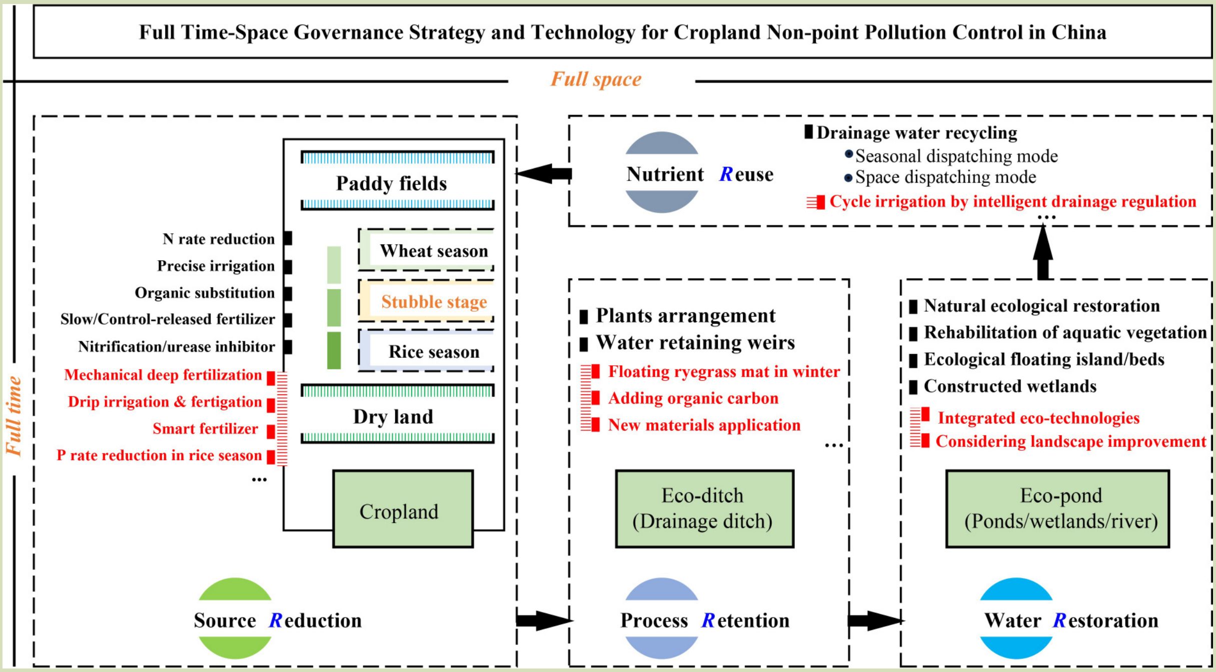

Fig. 1 Conceptualization of the 4R technology system involving source reduction, process retention, nutrient reuse and water restoration (red text indicates the newly developed technology in recent 10 years).

2.1 Source reduction technology

Mitigating farmland nutrient loss is an effective way to reduce AGNPS pollution and is also the best strategy to improve governance effectiveness and reduce costs[11]. Several studies have shown that optimizing fertilization by adjusting fertilization strategies, applying smart fertilizer (e.g., slow/controlled-release fertilizer) and reasonable organic fertilizer substitution can significantly improve nitrogen use efficiency (NUE) and enhance crop yield.

2.1.1 Optimized fertilizer N and P rate balancing the crop yield and environmental loss risk

Typically, the crop yield response to the N rate has a quadratic relationship[12,13]. However, N runoff or leaching loss increases as the N rates increase for paddy and upland crops[14,15]. Hence, excessive application of N fertilizer may reduce crop production and increase N loss. Several studies that performed meta-analyses using national or regional level data found that reducing N fertilizer by 10%–25% did not affect crop yield but decreased N loss by 16%–40%[12,13,16–20]. Cai et al.[20] evaluated the risk of yield loss among smallholder farmers by applying the economic N rate (ON) and ecological N rate (EON) to a large on-farm data set. They found that the area-based N input in rice and N loss decreased by 18%–32% and 12%–27% without decreasing crop yield. Their findings showed that the yield of rice might exceed demand in China in 2030 while reducing nationwide N application by 10%–27%, and also decreasing N loss by 7%–24% for ON and EON[20]. In China and other Asian countries, N fertilizer is often applied at three different stages (basal, tillering and panicle fertilizer) to meet the N demand of the crops at various growth stages. According to N-15 trace results, more than 50% of N applied during the basal and tillering stages was lost, but only 20% of N applied as panicle fertilizer was lost to the environment[21]. After reducing basal and tillering N fertilizers by 30%, crop yield and NUE improved[22]. Therefore, the following three steps are proposed to ensure high crop yield in paddies while decreasing the N rate. Firstly, the theoretical N rate needs to be determined based on the target yield and N requirement per unit grain. Secondly, the N split ratio needs to be decreased at the basal and tillering stages to 50% for medium soil fertility and 40% for high soil fertility. Finally, the panicle topdressing N rate needs to be adjusted based on the rice growth status, determined by non-destructive diagnosis techniques, such as measuring the leaf color or canopy reflectance spectra[23]. The multi-site-year practice showed a similar or 7% higher yield with 8%–23% lower N rates, higher NUE, and higher net profit[8,24].

The content of soil P was found to increase after the application of P fertilizer due to high soil P affinity, which increased the risk of loss of P[25,26]. Considering the limited P resources, enhancing fertilizer P use efficiency (PUE) with lower P rate might be the key to reducing the risk of P loss. By conducting a multiyear study on rice-wheat rotation in the Taihu region, Zhu et al.[27] found that the absence of P fertilization in the rice-growing season did not significantly alter the yield of rice and wheat over 4 years. However, PUE was significantly higher in the absence of P fertilization compared to P fertilization treatment in the rice- and wheat-growing seasons. Also, Gong et al.[28] conducted a meta-analysis that found both diammonium and monoammonium phosphate can increase crop yield more effectively than single superphosphate, triple superphosphate and calcium magnesium phosphate. By integrating the soil-crop system with different mineral P fertilizer types, those researchers also found that the PUE could be improved by 22%–40% and P loss could be decreased by 13%. By improving soil fertility management and using the right P fertilizer, PUE can be improved and AGNPS pollution can be decreased during crop production.

2.1.2 Shifting to deep fertilization or fertigation from broadcast fertilization

Selecting the right fertilization technique is crucial to minimizing nutrient loss. A meta-analysis showed that deep fertilization significantly increased the yield and NUE by 8.6% and 16.7%, respectively, compared to the broadcast fertilizer technique. The optimal depth of fertilization was found to be 7–13 cm, as most of the rice roots are distributed at that depth. Side-deep fertilization of basal N decreased the N rate by 20%. It also improved the rice yield[29], reduced NH_3 volatilization and N runoff loss, and increased economic gains[30]. Another meta-analysis showed that drip fertigation technology is more effective for dry crops than furrow irrigation and broadcast fertilization in improving NUE. Drip fertigation also decreases N input and the loss of N and P[31].

2.1.3 Upgrading the fertilizer product with smart fertilizer

Smart fertilizers regulate the rate, timing, and duration of nutrient release to meet crop demand based on different crops and soil types. They can greatly improve the efficiency and sustainability of crop production while reducing adverse effects on the environment[32]. Slow/controlled-release fertilizers (SCRFs) are used extensively as they can save labor and time[33]. A meta-analysis showed that the loss of N from paddies after applying SCRFs was lower than that after applying conventional fertilizers, under similar N rates[15]. SCRFs can considerably increase the production of rice, wheat and maize, and decrease nitrate leaching[34,35]. Additionally, the application of SCRF can decrease the N rate by up to 32% without reducing yield[36]. The bulk-blend controlled-release fertilizer was found to be better than single SCRF due to its greater ability to synchronize crop N demand with supply[37]. A study recommended a two-split fertilization strategy with 70% to 80% N as basal fertilizer using SCRF and 20%–30% N as panicle fertilizer using urea[37]. In addition to SCRFs, nanofertilizers, biofertilizers and other smart formulations using biodegradable polymers, lignocellulosic straw, and biochar has been suggested as a potential to improve NUE, but further research on their development is required[33].

2.1.4 Organic fertilizer substitution for combination planting with breeding

Organic fertilizers can improve soil fertility and reduce the dose of chemical fertilizer applied, as they act as nutrient sources, supplying mineral nutrients for crop growth[38,39]. A recent meta-analysis has shown that the partial substitution of chemical fertilizers with organic fertilizers increased the yield by 6.6% and 3.3% for upland crops and paddy rice, respectively, but full substitution decreased the yield by 9.6% and 4.1%, respectively[39]. The response of crop yield to manure substitution varied with the soil pH and the duration of the experiment. In which, the crop yield increased with an increase in the time (years) of organic fertilizers application[40]. Under conditions of high precipitation and temperature, a large substitution fraction (> 70%) or exclusive use of organic fertilizer may reduce crop yield and increase environmental pollution[41–43]. The substitution with organic fertilizer should not exceed 20% for cereal crops and 30% to 40% for vegetable crops[37,41]. The accumulation of P in the soil due to the application of organic fertilizer while growing cash crops, such as vegetables, should be monitored to avoid the P loss risk. Therefore, the NP ratio of organic fertilizer should also be considered based on the soil P status and crop requirements to prevent the loss of N and P.

Any reduction of fertilizer dose must be based on the balance between supply and demand for crops, after accounting for the release of nutrients from the soil. It must not affect crop yield or soil fertility. Hence, it is essential to select the best nutrient management measure combinations based on the actual conditions, such as the climate, soil properties, crop types, agronomic practices (e.g., tillage and irrigation), and the whole crop rotation year, including the field preparation stage and stubble stage.

2.2 Process retention technology focused on ecological ditches

Ecological initiatives, such as the construction of wetlands and plant buffer zones, are effective measures to reduce AGNPS pollution[44,45]. However, in China and other countries where the population density is high, no land is available for implementing such methods. Therefore, Yang et al.[46] proposed the ecological ditch (eco-ditch) technology without additional land requirements in China in 2005. Eco-ditches effectively intercepted N and P in farmland runoff[47,48]. Eco-ditches are low-maintenance management structures reconstructed from a standard drainage ditched using eco-permeable bricks with holes to support plant growth. Small water-retaining weirs are often placed at specific intervals at the bottom of the ditch to reduce the flow rate and maintain a specific water level for the normal growth of emergent and submerged aquatic plants. *Cynodon dactylon* in summer and *Lolium perenne* in winter are commonly planted on the sidewalls of the ditch. A combination of emergent plants (*Iris tectorum*, *I. pseudacorus* and others) and submerged plants (*Potamogeton crispus*, *Myriophyllum verticillatum* and others) are grown at the bottom of the ditch.

The N in the drainage water is removed by nitrification-denitrification, plant uptake, microbial assimilation, ammonia volatilization and sedimentation in an eco-ditch[49,50]. Nitrification-denitrification by microorganisms is the main pathway of N removal in ditches and wetland systems[50,51]. Depending on the topographic conditions, plant species, operation parameters and temperature, the N removal rates in eco-ditches range between 20.0% and 93.3% in China (Fig. S1). The removal of P in the eco-ditch is mainly regulated by physical and chemical processes, including sediment adsorption, ion exchange, chemical settlement, deposition of overlying water, and plant uptake[52,53]. The precipitation and retention capacities of the substrates are important factors that affect P removal. Another meta-analysis has shown that the removal efficiency of P in the eco-ditch varied from 9.5% to 94.7% depending on the substrates, hydraulic retention time (HRT) and management measures (Fig. S1).

Aquatic plants strongly influence N and P interception by sediment and overlying water in the ditch[50,51]. A study in which a vegetated drainage ditch was monitored for 2 years found that 26.3% of TN and 14% of TP load removal occurred through plant uptake[52], mainly determined by plant biomass[53,54]. A further meta-analysis has shown that N removal rates from vegetated ditches were considerably higher than those from non-vegetated ditches, but there was no difference between ditches vegetated with different plants[55].

Operational factors like the influent concentration of N and P, and HRT affect the efficacy of N and P removal by eco-ditches. Another meta-analysis found a significant positive correlation between the influent N concentration and the removal rate, which was partly contributed by substrate adsorption[56]. Longer HRT facilitates greater interaction between farmland drainage and plants or substrates in ditches, thus contributing to the removal of N and P[50]. Plants and weirs in the ditch reduce the water velocity, prolong the HRT and improve the denitrification process, promoting N and P removal[56,57].

The ambient temperature is important for the removal of N and P, as it affects plant growth, microbial activity, and the substrate adsorption rate[55]. The eco-ditch has a highly consistent interception capacity for N and P from farmland drainage in the warm season. However, the N removal efficiency decreases considerably when the temperature drops below 6 °C[58]. Therefore, to ensure effective N removal, plants that persist through winter should be selected. A floating ryegrass mat with *L. perenne* grown on the straw mat had high NH_4^+ removal efficiency of 30.5%–46.0% in the winter. Thus, it might be considered as an alternative approach for drainage purification in the winter[59].

The application of new environmental materials in eco-ditches to remove N and P from agricultural wastewater before it reaches rivers and lakes is an effective strategy for controlling AGNPS pollution. Clay minerals, such as zeolite, montmorillonite, kaolin, perlite and attapulgite, are commonly used to adsorb ammonia nitrogen[60]. For removing nitrate, adsorbents, such as zeolite, a carbon-based substance and steel slag, and biological adsorbents, such as chitosan and bacillus, are recommended[61–64]. In terms of kinetics, capacity, selectivity and stability, calcium alginate beads doped with active carbon, lignocellulose materials, spill absorbents, iron and lanthanide base materials (Fe_3O_4/$La(OH)_3$, $La(OH)_3$/C_3N_4) have performed well for phosphate adsorption[65–67]. Biochar has recently attracted the attention of researchers due to its unique physical and chemical properties, and effective adsorption. In addition to its application in the soil to regulate nutrient supply, it can also be used as an absorbent or carrier to remove pollutants from agricultural wastewater[68,69]. Different modified-biochar materials, such as FeO/biochar, were developed for removing different types of target pollutants, and have provided good performance for the interception of N and P loss[70]. Adding organic carbon, such as sawdust, rice straw and corncob, is another effective strategy to improve N removal, specifically for nitrate-rich drainage[71–74]. The C/N ratio is a key factor, and a COD/N > 3.5 has been recommended to ensure high efficiency of N removal[73].

2.3 Nutrient reuse technology: irrigation with agricultural wastewater

In certain areas of China, especially southern China, due to the scattered distribution of farmland and complex river systems, the agricultural wastewater, including those from field drainage, rural domestic sewage and livestock wastewater, is discharged into the surrounding rivers; this causes eutrophication. Although agricultural wastewater is rich in N and P, reusing it on the farm can significantly decrease the input of N fertilizer and the discharge of pollutants (mainly N and P) into the nearby water bodies[7]. This can simultaneously increase agricultural production and protect the environment. Drainage water recycling is a cost-effective method of decreasing AGNPS pollution. There are two modes, one of which is the seasonal dispatching mode, where ponds or reservoirs are used to collect the drainage and runoff from an agricultural region in the wet season and provide supplemental irrigation during the dry season. A case study conducted in eastern North Carolina, USA found that the N, P and sediment loads decreased significantly by 47%, 30% and 87%, respectively, using this strategy[75]. The other is the space dispatching mode between dry fields and paddies. The runoff from drylands, such as vegetable farms, is collected and recycled into the surrounding paddies. An unfertilized rice belt is positioned downstream and economic plant pond is recommended to retain and reuse the nutrients in the drainage. Several studies have shown that treated rural domestic sewage can be used for farmland irrigation, especially for the irrigation of paddy[76,77]. A paddy can act as a wetland and purify the surrounding river water. The N and P in the tailwater of domestic sewage can be taken up by the plants, or adsorbed and retained by the soil in the paddies, which in turn can reduce the need for chemical fertilizers[76–78]. Some researchers performed continuous water monitoring of circular irrigation in a paddy watershed in Japan and found that paddy watersheds have a purifying function for N and P during normal hydrological years and may help reduce non-point pollutants[79]. Xue and Yang[77] found that the efficiency of N and P removal in paddy wetlands was around 77% to 93% and 87% to 96%, respectively, and the TN concentrations in the discharge were less than 2 $mg \cdot L^{-1}$. Also, domestic sewage tailwater irrigation can significantly reduce the emission of NH_3 from paddies and maintain relatively high rice yields with the substitution of 15% to 45% N fertilizer[76]. Since paddies are widely distributed in China, they can effectively reduce AGNPS pollution by reusing the N and P in the agricultural wastewater.

2.4 Water restoration: integrated eco-technology

River eutrophication is a widespread problem in rural areas of China, particularly in areas around river networks. To restore the damaged river ecosystem and improve water quality, effective ecological restoration measures must be implemented. Simon and Joshi[80] reviewed the green technologies available for the rejuvenation of polluted surface water bodies and found that integrated eco-technologies are the most effective for removing different types of pollutants in a real-world scenario[80]. With the advantages of less time-space and cost, and no secondary pollution, the combination of environment restoration with landscape improvement creates a favorable setting for the coexistence of humans and nature[80]. These methods include the ecological restoration of the riparian zone using natural ecological restoration or engineering ecotype restoration approaches, ecological restoration of river channels through the rehabilitation of aquatic vegetation, ecological floating island beds and constructed wetlands[81–83].

While implementing these approaches, aquatic plant species, density and vegetation coverage, planting methods, sorption media, aeration frequency and intensity are key for the removal of pollutants and improving water quality. Additionally, environmental factors, including temperature (season), initial pollutant loading and hydraulic conditions (water depth, hydraulic loading rate and hydraulic retention time), may also affect the efficacy of the implemented approaches[84]. The selected plant species usually have a dense root system to remove pollutants effectively. Flowering plants increase the aesthetic value of the surroundings and provide a suitable habitat for various fauna. Local plant species are generally preferred to exotic species as they do not pose any risk of invasion if they escape from the water body[84]. Frequent pruning and harvesting of aquatic plants should be performed to prevent the absorbed nutrients from reentering the water body[82,85,86]. Wang et al.[87] showed that harvesting only above the water level does not remove a sufficient amount of nutrients from the water, and a large quantity of nutrients accumulate in the biomass below the water level. Thus, further studies are needed to compare the effects of partial and whole-plant harvesting. According to successful experiences, river ecological restoration should be conducted based on the principles of adaptation to local conditions. The approach should also combine engineering construction and routine maintenance, and integrate ecological restoration and pollution control.

3 DEMONSTRATION OF FULL TIME-SPACE GOVERNANCE STRATEGY AT THE SCALE OF AN ADMINISTRATIVE VILLAGE

The full time-space governance strategy for the control of AGNPS pollution was performed at the Xinkang administrative village in the Tai Lake region, China. Different combinations of 4R technology were used based on the crop type and the characteristics of the water system of each irrigation-drainage unit (IDU). For source reduction, deep fertilization was performed using a new smart fertilizer (a blend of slow/control-released fertilizer, NPK 27:10:12) with all fertilizer at transplanting (RBB1) or 70% at transplanting (RBB2), and organic fertilizer substitution technology (OCN) was used in the rice season, based on the location of the fields, soil fertility and target yield (details in Table S1). Drainage ditches, lowlands and small ponds near the croplands, and small rivers and streams that capture the cropland runoff were eco-transformed. Various emergent aquatic plants, floating plants, and submerged plants were cultivated depending on the season, water depth and other factors. The adsorption substrates for N and P were also used at the key nodes in the drainage network. A small pump station and overflow dam were constructed to retain and recycle the field drainage. The dam could block initial runoff with high concentrations of N and P during a storm, while the superfluous tailwater with low concentrations of N and P could be discharged through the dam. The details of the layout of the project are shown in Fig. 2. One IDU for Gucuntang village was selected in the study area to determine the effect of the governance of AGNPS pollution.

3.1 Source reduction: grain yield and the loss of N and P

Compared to N management by local farmers (FN), the N and P rate decreased by 26.3% and 53.3% in OCN, 26.3% and 42.2% in RBB1, and 26.3% and 60% in RBB2, respectively. OCN maintained a similar production as that recorded in the N-managed fields of farmers, whereas RBB1 and RBB2 resulted in 9.63 and 10.67 $t \cdot ha^{-1}$ grain yield, respectively, which was 4.8% and 16% more than the grain yield in FN, respectively (Table S1). In the rice growing period of 2019, five drainage events were recorded, including one artificial drainage at the late-tillering stage. The drainage of the FN field showed the N concentration ranging from 1.43 to 6.40 $mg \cdot L^{-1}$, with the highest value observed on 3 June 2019, 3 days after tillering N fertilization (Fig. S2). The average N concentration of OCN, RBB1 and RBB2 decreased by 31%, 54% and 45%, respectively (Fig. 3). A decrease in the level of P decreased the TP concentration in the drainage; the average P concentration decreased by 25% in OCN, 44% in RBB1 and 53% in RBB2 compared to the P concentration in FN (Fig. 3).

3.2 Process retention: effect of eco-ditches on N and P removal from drainage

The TN and TP concentrations in the inflow of eco-ditches (field drainage) changed substantially during the monitoring year (Fig. 4). They were higher during the growing season of green manure compared to the rice-growing season. Their peak concentrations (TN of 5.8 $mg \cdot L^{-1}$ and TP of 0.64 $mg \cdot L^{-1}$) were recorded during field preparation for transplanting after green manure was returned to the field. Using the national standard of surface water quality criteria (GB 3838-2003) as a reference, only five instances of TN among the 14 instances monitored exceeded 2.0 $mg \cdot L^{-1}$, three of which occurred during field preparation. Only one instance of TP (on 26 March 2020) was above the Class V level of 0.4 $mg \cdot L^{-1}$; the rest were all better than the Class IV level (i.e., < 0.3 $mg \cdot L^{-1}$). The concentrations of TN and TP were low in the outflow of eco-ditch throughout the monitoring year. The N removal efficiency of eco-ditches ranged from 18.0% to 56.2%, and when the TN concentrations were high (above 2 $mg \cdot L^{-1}$), the N removal efficiency ranged from 47.8% to 56.2% (average 51.3%). The N removal efficiency was higher in the summer and autumn when the temperature was relatively high (from April to November) than in the winter and spring. However, the P removal efficiency of eco-ditches was higher in the winter and spring (29.2%–68.9%, average 47.7%) than in the paddy growth period (11.1%–48.6%, average 22.6%) due to the higher concentration of P (average 0.28 $mg \cdot L^{-1}$), mainly in particle form (average 0.11 $mg \cdot L^{-1}$), but more soluble P in paddy season due to the presence of ridges.

3.3 Nutrient reuse: N and P reused through irrigation

In the rice growth period of 2020, a shallow-water irrigation mode was adopted in the demonstration fields. The total irrigation volume was 9780 $m^3 \cdot ha^{-1}$, and the water came entirely from the nearby river. The quantity of N and P added to the field via irrigation was 15.6 and 0.91 $kg \cdot ha^{-1}$, respectively. In total, 18.9 $kg \cdot ha^{-1}$ N and 1.01 $kg \cdot ha^{-1}$ P were drained to the nearest river through runoff. The efficiency of N and P recycling in farmland drainage through irrigation was estimated to be 82.6% and 90.4%, respectively, if the irrigated N and P came exclusively from the field drainage. However, the

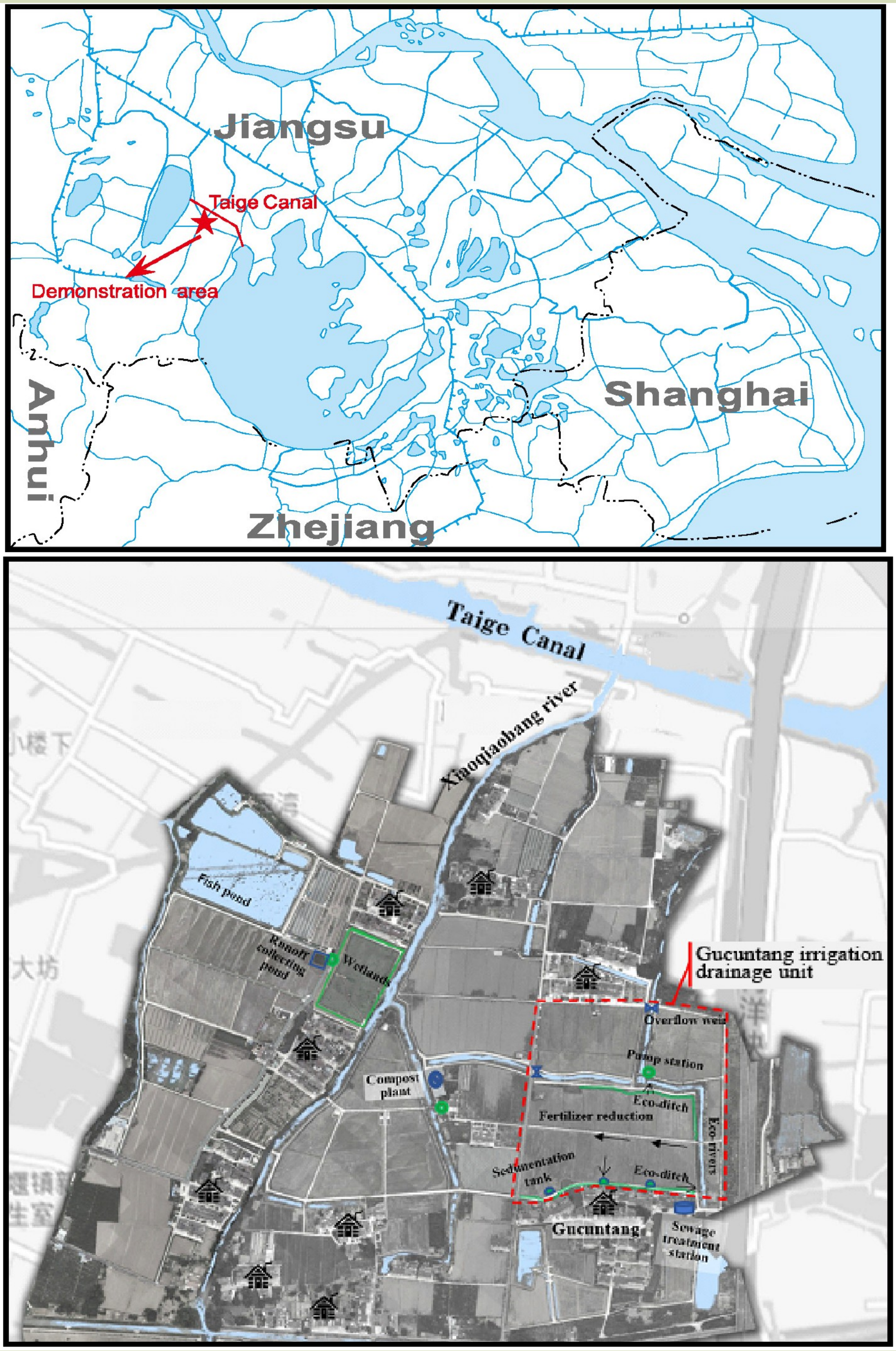

Fig. 2 The sketch of demonstration location and project engineering layout (审图号: GS 京 (2023) 2266 号).

recycled nutrients not only came from drainage but also from domestic sewage water and surface runoff from Gucuntang village. Nevertheless, circular irrigation in IDUs at paddy watersheds is an effective technique to reduce AGNPS pollution of the watershed and should be considered for all large-scale application in the future.

4 FUTURE CHALLENGE

The case study in Xinkang, Jiangsu Province, showed that the application of full time-space governance strategy and technology for controlling non-point pollution might be an effective strategy to simultaneously enhance the rice yield and

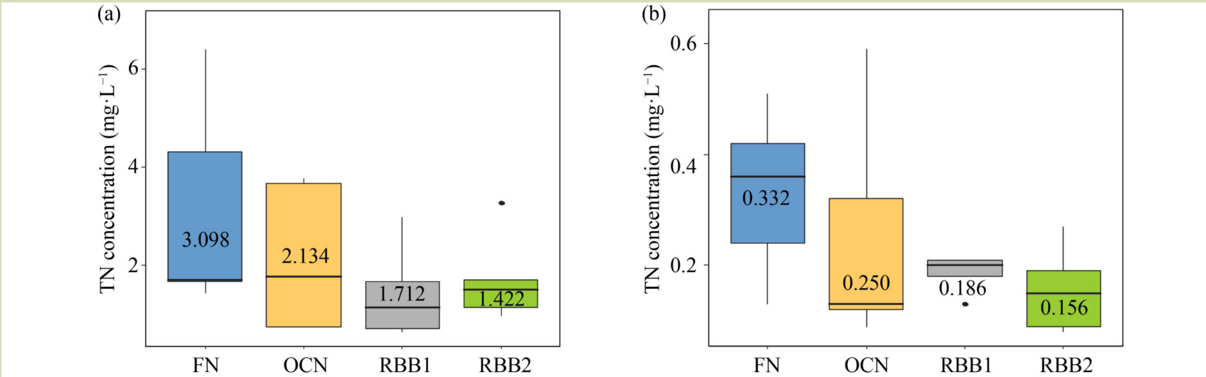

Fig. 3 TN and TP concentrations in the drainage from different fertilizer management fields in 2019 rice season (The figure is the mean of 5 samplings).

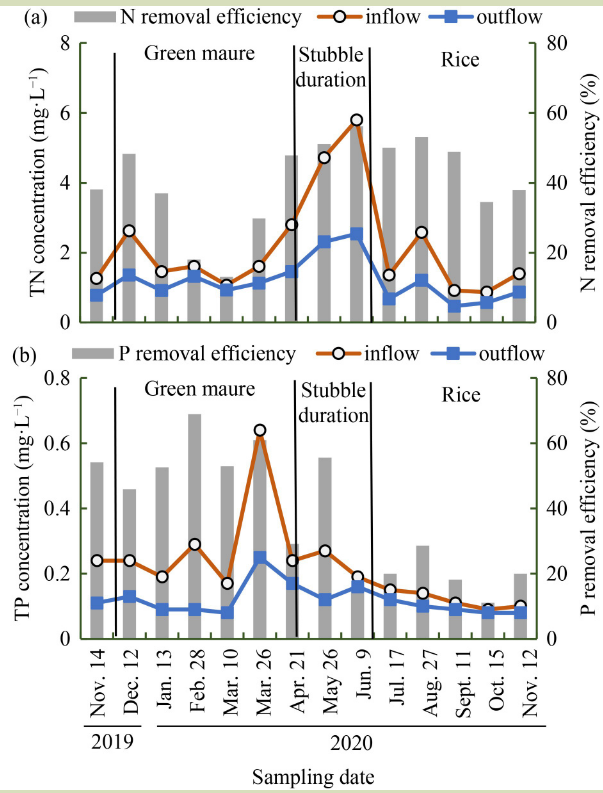

Fig. 4 Dynamic of TN and TP concentrations of the inflow and outflow of eco-ditch.

water quality in the river network region. Firstly, top-level design and system-control ideas were introduced in the strategy to combine the technologies for the full time-space coverage, which is the new development based on the 4R technical framework system proposed in Yang et al.[7]. Secondly, the detailed technology for each R was updated. In source reduction module, precise fertilization was developed using the new machinery and smart fertilizer. Some new technology was supplemented such as the application of new environmental materials in process retain module. In nutrient reuse module, cycle irrigation within IDU to reduce river pollution was proposed. Therefore, the 4R technical system became more comprehensive and effective. Lastly, the coupling of technology, engineering and ecological civilization was conducted to ensuring the effective and long-term control of AGNPS pollution. However, the following challenges need to be addressed.

4.1 Establishing a national monitoring network and source identification system for AGNPS pollution in full time-space

To effectively control AGNPS pollution covering the full time-space, a national monitoring network including farmlands, catchment units and small watersheds should be set up using contemporary monitoring technology and intelligent equipment, covering the entire process of pollution generation, transportation, and formation[20]. A database of AGNPS pollution needs to be established. Many researchers have used isotope tracing and microbial assimilation technology, along with hydrological processes and element biogeochemical process analysis to accurately identify the temporal characteristics and risk-prone areas of pollutant discharge and pollution formation. These methods can also provide data to support targeted control of AGNPS pollution.

4.2 Developing new technologies and products for controlling AGNPS pollution

Source reduction is the key to AGNPS control, green agri-inputs such as smart fertilizers based on slow-/controlled-release and/or carrier delivery systems should be developed to achieve the synergy between green and high-value agricultural production and environmental protection. Additionally, fertilization equipment needs to be improved to increase fertilizer efficiency; knowledge-based decision support system technologies need to be further developed for precise nutrient management and to address the large space-time variability of the soil, crop cultivar and climatic differences across China[4]. Intelligent irrigation and drainage regulation systems, comprising hardware and software, should be built in combination with the development of high-standard ecological farming to reduce the amount of pollutants entering the river through circular irrigation. The equipment should have a system for collecting and storing farmland drainage in existing ponds and creeks, as well as, an automatic water gauge, drainage outlet, gate, and pumping station. A software system should be installed to make intelligent decisions about when and how much to irrigate or discharge based on rainfall, crop growth demand, storage capacity, and runoff volume. Finally, researchers need to develop novel environmental materials with high N and P removal efficiency and small mobile devices for water pollution emergency processing.

4.3 Strengthen the standard and policy research of AGNPS pollution governance

To provide a suitable solution for controlling AGNPS pollution and ensure food safety, a full time-space governance strategy should be adopted, prioritizing source management followed by endpoint pollution control. Source management involves reducing fertilizer input, which requires the establishment of a quota supply system, fertilizer limited standards, and real-name fertilizer purchases. Zhejiang and Jiangsu provinces have implemented this strategy and reported satisfactory results regarding the improvement of NUE and the reduction of the loss of N and P. Secondly, mandatory water quality standards should be set for farmland discharge in sensitive watersheds, and agricultural producers and operators should be forced to control pollution discharge from farmlands. To encourage producers and operators to participate in the prevention and control of AGNPS pollution, the red-green light regulation system of agricultural production technology might be implemented. Briefly, ecofriendly technology for lower pollution and higher yield should be encouraged under the green light, and subsidies and ecological compensation should be given. In contrast, non-ecofriendly technology should be controlled under the red light, and sanctions or reduced subsidies should be enforced when adopted. To raise the necessary funding for agricultural subsidies, a nitrogen credit system (proposed by Gu et al.[88]), under which money is collected from all members of society who benefit from AGNPS pollution control, should be implemented. Finally, the best management practices that are suitable for application in China need to be established and implemented.

Supplementary materials

The online version of this article at https://doi.org/10.15302/J-FASE-2023522 contains supplementary materials (Figs. S1–S2; Tables S1).

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Compliance with ethics guidelines

Lihong Xue, Jingjing Duan, Pengfu Hou, Shiying He, Yingliang Yu, Yanfang Feng, Fuxing Liu, and Linzhang Yang 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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