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REVIEW

AGRICULTURAL GREEN DEVELOPMENT IN THE ERHAI LAKE BASIN—THE WAY FORWARD

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KEYWORDS

agriculture, farmer income, nitrogen, phosphorus, water pollution

HIGHLIGHTS

- Erhai Lake basin faces the duel challenge of enhancing water protection and increasing farmer income.
- A new framework indicates the key strategies for tackling the multiple challenges of agricultural green development in Erhai.
- The needs for interdisciplinary research innovation and smallholder enabled technology transformation identified.
- Building trust and partnerships between farmers, citizens, local government, industry and extension services should be prioritized.
- Agricultural green development in Erhai can serve as a model for other high-altitude lake basins.

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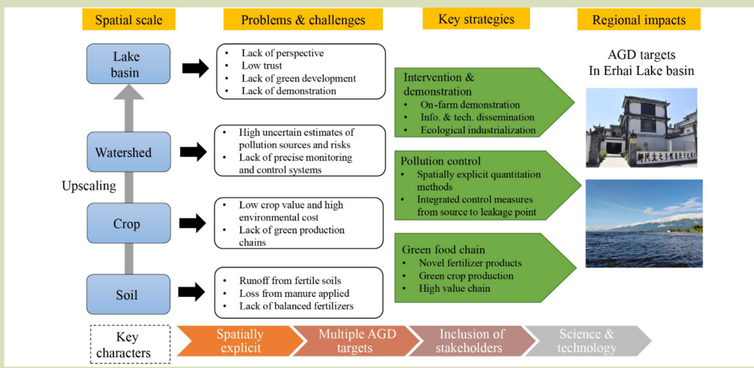
GRAPHICAL ABSTRACT



ABSTRACT

Pollution of high-altitude lake basins by agriculture and rural activities, and the control of this pollution, have received increasing attention from academic research and government policy in China. Series of restrictions and regulations have been implemented to protect the surface water quality. These restrictions and regulations have greatly impacted and transformed the agricultural systems and rural livelihoods surrounding these lake basins. Using Erhai Lake basin in Yunnan Province as a case study, three main challenges were identified for concurrently decreasing pollution in the lake and increasing farmer income. It is contended that scientifically-sound environmental protection policies and agricultural green development practices are key to reversing the current situation. This will help to protect the lake from pollution while smallholder farmers will be able to produce healthy food in an environmentally sustainable manner, and with a fair remuneration for all the services farmers provide to the society.

1 INTRODUCTION

Pollution of surface waters by nutrients, notably by nitrogen and phosphorus, but in some cases also by micronutrients such as copper, is a worldwide concern, as it degrades water quality and biodiversity[1]. Anthropogenic activities are generally the main cause of the nutrient loading of water bodies[2]. Eutrophication of major lakes in China by nutrients from agriculture and households is a main problem. Among the 180 monitored lakes, 90% have an intermediate or high eutrophication status[3]. The Yangtze River Economic Belt in China includes the five of the largest freshwater lakes, which are key contributors to the economic and social functioning of the basin[4,5]. However, many lakes in the Yangtze River Economic Belt have damaged ecological functioning, deteriorating water quality, and shrinking biodiversity[4,6]. The lakes situated on high altitude plateaus generally have high ecological value[7], but are also vulnerable to degradation[8], due to economic development and exploitation of natural resources[9].

Erhai Lake is the second-largest plateau lake in Yunnan Province and had an outstanding ecological status until recently. It is said to be the *Mother Lake* of the Dali people (Box 1). However, population growth, intensification of agricultural production and increased tourism have affected the overall water quality of Erhai Lake, which has changed over the past 30 years from Class I to III in national standards for surface water quality[10,11]. In response, a series of measures have been implemented in surrounding areas to decrease pollution of the lake, including waste collection and treatment, adjustment of agricultural structure and fishery, restoration of submerged vegetation and emergency treatment of water blooms[12]. These government undertakings have substantially decreased nutrient loading of the lake and have contributed to improved water quality. Between 2018 and 2021, 85% of the 27 major rivers that flow into the lake reached water quality Class I or II. The total loading of phosphorus in the rivers decreased by 59%, total nitrogen by 46%, and ammonia-nitrogen by 62%. Chemical oxygen demand decreased by 11%[13,14]. However, the amounts of N and P entering the lake still exceed the environmental limits of Erhai Lake by 26% and 50%, respectively[15]. The mean N and P concentrations of Erhai Lake are still near Class II, indicating a risk of algal blooms.

However, the initiative have seriously impacted agricultural industries. Economically high-value cash crops, such as garlic, and livestock production have been banned on the coastal flood plains around Erhai Lake. These situation means that farmers need a new a perspective. Therefore, it is essential to explore development pathways that concurrently protect Erhai Lake and enhance farmer income[16,17].

In 2021, China Agricultural University, Yunnan Agricultural University and the Dali Government signed an agreement for collaboration to develop an innovation and demonstration site in the Erhai Lake basin. Subsequently, over 30 research institutes and over 300 scientists from a range of disciplines are working jointly in the region. From this context, we outline the major challenges and perspectives toward agricultural green development in the Erhai Lake basin. We propose new systematic strategies to address agricultural pollution with interdisciplinary research and advocate the incorporation of farmer-enabled technology transformation approaches. Our approach may serve also as a model for catchments of other high-altitude lakes in China.

2 CHALLENGES FOR AGRICULTURAL PRODUCTION IN ERHAI LAKE BASIN

Agriculture in the catchment of Erhai Lake is key contributor to local food supply, rural livelihood and pollution of the lake[19,20]. Following the release of the Thirteenth Five Year Plan, a range of policies have been implemented to reduce discharge and leaching of pollutants from agriculture into the lake[14]. However, the underpinning of these policy measures remains weak. There is still a lack of data and information on (1) the contributions of current agricultural practices and rural landscape to the loading of pollutants to the lake, (2) best management practices and techniques that decrease emissions of pollutants to the lake and increase farm income, and (3) perspectives for farmers regarding the future of farming. These problems have limited a variety of major agricultural practices and have led to a reduction in farm incomes.

Thus, a consortium of universities and research institutes, together with local governments, organizations and companies have taken the initiative to address this lack of data, information, tools and perspectives. The overall objective of the consortium is to provide the knowledge base for further concurrently decreasing the pollution of Erhai Lake and enhancing farm income. This paper provides perspectives of the consortium on the challenges and strategies to greening agriculture in the Erhai Lake basin.

Challenge 1: The need to mechanistically understand and precisely quantify non-point source pollution from agriculture, as function of farming practices, rural landscape and environmental conditions. Currently, there are

Box 1 Erhai Lake and catchment

Erhai is a tectonic lake (developed in a geological fault) in Dali, Yunnan (25°45′48″ N, 100°11′15″ E) at 1972 masl. It has a length of about 40 km, a width of 7 km, and a surface area of 250 km^2. Mean water depth is about 11 m. It is the seventh largest freshwater lake in China. The catchment area is about 2250 km^2 (Fig. 1). The lake drains out through the Xier River to the south which eventually joining the Mekong River. The lake had high biodiversity and has been a main food source for the local Bai people. However, fishing (plus boating and swimming) has been forbidden by the government since 2015, because of declining water quality and biodiversity.

The lake is surrounded by mountains that reach heights of more than 4000 masl with forests above 3000 masl. The slightly sloping floodplains on the western and northern shores are intensively cropped and also rather densely populated. The main crops are paddy rice, tobacco, maize, vegetables and beans grown in double cropping systems (2 crops per year). Most crops are irrigated, with water intercepted from the surrounding mountains and taken from Erhai Lake.

There are four towns and 52 villages in the catchment, with a total population of nearly 1 million, but most people live on the floodplains of the western shore. The lake and its surroundings are attracting millions of visitors each year. Both, the intensive agricultural practices, households and tourists put pressure on the lake. From 2015, the governments have implemented several initiatives to protect the lake from further pollution.

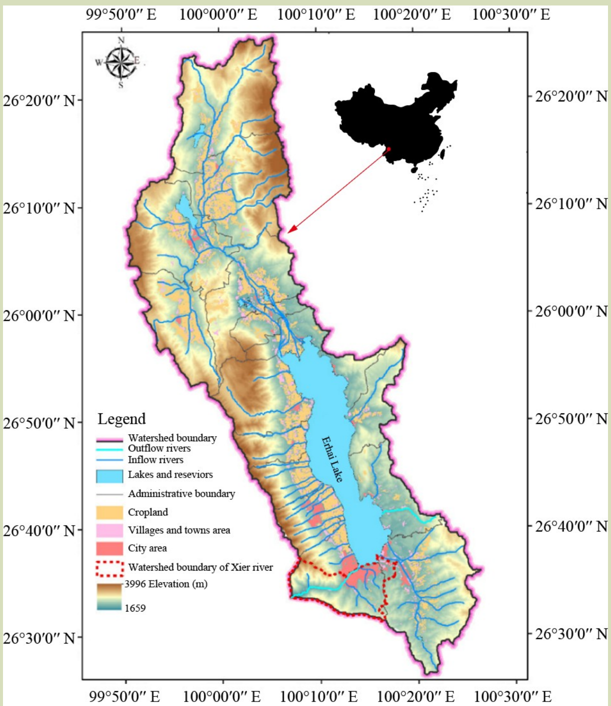


Fig. 1 Location and map of Erhai Lake basin. Adapted from Wu et al.[18] (审图号: GS 京 (2023) 2266 号).

significant uncertainties in the assessment of agricultural non-point pollution, despite recent government reports indicating that agricultural non-point pollution contributed 40% to the total N input and 30% to the total P input into Erhai Lake in 2020. We note the following shortcomings of previous studies. Firstly, many small plantings of high-input vegetables near houses have often been overlooked because they are not representative in estimating non-point pollution. However, our initial measurements in a demonstration site have indicated that these small plots account for only 5% of the total land area but contribute as much as 29% to the total N input and 54% to the total P input to the Erhai Lake through agricultural non-point pollution during the rainy season. Secondly, the contribution of concrete roads and yards in villages has been underestimated. Investment in road construction in rural areas have increased the area of sealed surfaces and thereby the rapid export of pollutants from villages during rainfall events[21]. According to our initial studies, about 17% of the total area consists of concrete roads and yards, which contribute about 21% to the total N and 17% to the total P losses via runoff in our demonstration catchment site. Thirdly, more than half of the household waste stored in villages and yards is kitchen waste. Previous studies indicated that the concentration of total N and P in the leachate from the kitchen waste was often higher than from cropland. These nutrient sources are often overlooked in estimating agricultural non-point pollution. Lastly, there is lack of monitoring spatial variations in non-point pollution by cropland. To date, monitoring of agricultural non-point pollution has focused on nutrient losses via main streams and rivers, while nutrient transport via small streams and drainages ditches and networks has been unestimated[22]. Currently, the agricultural non-point pollution is estimated indirectly from the measured total load via rivers corrected for measured point source pollution loads[23]. We argue that this approach may overestimate the agricultural non-point pollution. Clearly, there is a need to develop more systematic monitoring approaches, covering all key pollution sources.

Challenge 2: The need to increase agricultural productivity while decreasing the environmental cost of production. Following the implementation of strict environmental protection polices from 2015, high-value crops with high fertilizer inputs were banned in the catchments of Erhai Lake. For example, garlic is a profitable crop for farmers and was widely planted in the basin. Its net profit ranged from 150,000 to 300,000 yuan·ha^{-1} (25,000 to 50,000 USD·ha^{-1}), and the annual economic value of the whole garlic crop production chain was 3 billion yuan. However, the crop has a shallow root system and thus requires frequent fertilizer applications and irrigation. The annual nitrogen surplus of a rice-garlic rotation was estimated at 547 kg·ha^{-1}[24]. Based on this information, the local government deem this crop to be a polluting crop and banned its cultivation in Erhai Lake basin from 2018. This ban resulted in a substantial financial losses to local farmer and it also decreased farmer trust in officials.

After garlic planting was banned, more environmentally-friendly cropping systems such as rice-canola and rice-faba bean were promoted by local governments via subsidies. Based on our farmer survey in 2022, the annual nitrogen input of the rice-canola rotation system was about 360 kg·ha^{-1}, the nitrogen surplus was about 160 kg·ha^{-1}, and the annual output value was about 6000 yuan·ha^{-1}. Thus compared with the rice-garlic rotation, the nitrogen input and nitrogen surplus decreased by about 60%, but the economic value of the rice-canola rotation was 60% to 80% lower than that of the rice-garlic rotation.

Since 2018, the local government has also prohibited the use of mineral N and P fertilizers, while promoting the use of organic fertilizers, to improve nutrient recycling. It is been shown that the use of organic fertilizers can have advantages compared to the sole use of mineral N and P fertilizers[25]. However, there is often a temporal mismatch between the supply of essential nutrients by organic fertilizers and the demand of essential nutrients by crops over time, which ultimately leads to a decrease in crop productivity. Firstly, the N to P ratio in composted manure is often much lower than the N to P ratio of the nutrient demand by the crop. Secondly, the N in organic fertilizers is partly organically bound, and the rate of mineralization and N release often does not match with the temporal patterns of the N demand by the crop, depending also on environmental factors. As a result, there is either a shortage of available N or a surplus of P when using organic fertilizers, which lead to a risk of yield loss and to P accumulation in soil with an enhanced risk of P leaching over time[26,27]. Our initial results indicate that 45% to 50% of the nutrients applied via organic fertilizers to paddy rice are lost through runoff and leaching due to the mismatch between the supply of nutrients from soil and organic fertilizers, and the demand of nutrients by rice in the Erhai Lake basin. Clearly, there is an urgent need for the development of innovative, sustainable, intelligent fertilizers in combination with advanced application methods, timing and placement, to effectively and accurately provide nutrients to the crops and at the same time control non-point source pollution. Also, there is a need to reconsider cropping systems and cropping practices. It remains a substantial challenge to establish sustainable and high-value cropping systems with innovative nutrient management strategies and green fertilizer products.

Challenge 3: The need to build trust and partnerships for agricultural green development. Agricultural green development aims at optimizing the whole food supply and consumption chain to provide adequate amounts of healthy food to all consumers, and concurrently protect the natural environment and farmer livelihood[28]. It is seeking for the right balance between environmental protection and economic/agricultural development. This balance has shifted in Erhai Lake basin, during the last couple of years. The ecology of the lake and tourists have received greater priority than farmers and local citizens. However, local agricultural and rural development also needs to be emphasized, as they are not only about food security but the Bai culture adding value to the landscape diversity of the Erhai Lake basin.

How to spare the cabbage and the goat? Here, we argue that agriculture green development is the way forward, particularly in the Erhai Lake basin. The lake needs to be protected and healthy food needs to be produced by the local farmers. New partnerships base on mutual trust and sustainably-driven business models need to be established. New green cropping systems and technologies have to be developed. Farmers will have to adopt green cropping systems and technologies to protect the lake. At the same time, farmers have to be rewarded for the green services they provide.

However, there are a number of barriers for realizing agricultural green development in Erhai Lake basin. Here, we discuss four key barriers. Firstly, there is a lack of trust among farmers in new cropping systems and new technologies. Many farmers are risk averse, particularly because they have limited financial reserves[29]. Secondly, in the so-called red-line zone around the Erhai Lake, smallholder fields were merged in farmer cooperatives and the management came under strict government control. The idea is that cooperatives can make more effective use of machines and of multiple institutional arrangements, and thereby can better ensure the quality and safety of agricultural products and environmental protection. However, cooperatives may not be the best vehicle to promote investment in and use of dedicated assets, and to adopt green technologies. Cooperatives appeared also unable to promote green technology through training and breaking the knowledge barrier for farmers to adopt green farming technologies. Clearly, targeted support should be given to cooperatives in Erhai Lake basin, in order to strengthen the active role of cooperatives in the popularization of green production technologies. Third, smallholders and cooperatives have limited knowledge and experience with the green technology described in scientific literature. This technology is often not specifically designed for the context and may have to be adjusted and optimized first to local conditions. There is need for testing and optimizing green agricultural technology in practice, under actual farming conditions. For realizing agricultural green development, a series of tested green technologies and policies have to be developed by research institutions and extended by local governments. These technologies may include seeds of high-yielding crops, improved water and nutrient management strategies and technologies, improved pest management strategies, strategies aimed at enhancing ecosystem services, and others. Concurrently, new business models have to be developed and tested, which allow farmers an adequate remuneration for their efforts. The research on new business models should also explore opportunities for transferring money from the tourist sector to the agricultural community. Undoubtedly, this requires close cooperation between research institutions, farmers, entrepreneurs in the tourist sector and food industry, and local governments, to explore policy options and business models for agricultural green transformation.

3 FRAMEWORK OF AGRICULTURAL GREEN DEVELOPMENT IN ERHAI LAKE BASIN

We developed a framework with key strategies for agricultural green development in the Erhai Lake basin, as a possible model for other plateau lake basins in Southwest China. The framework also presents the specific challenges and associated management strategies for different geographic regions, from soil, through crop and livestock production, to the whole food chain and the society (Fig. 2). The three key strategies are detailed below.

Strategy 1: Spatially explicit quantitation of non-point source pollution. There are still large uncertainties regarding the relative contributions of emission sources (e.g., agriculture, industry and urban areas) in the Erhai Lake area (Section 2, Challenge 1). This uncertainty limits policymakers to enact adequate and precise pollution control regulations. At the same time, there is limited urgency to develop advanced production technologies aimed at achieving water quality standards and high crop yields. Adequate modeling as well as monitoring tools and instruments have to be developed and applied, as a joint effort of researchers with multidisciplinary experts and pertinent stakeholders. These tools and instruments will allow to precisely identify and quantify the primary contributions of

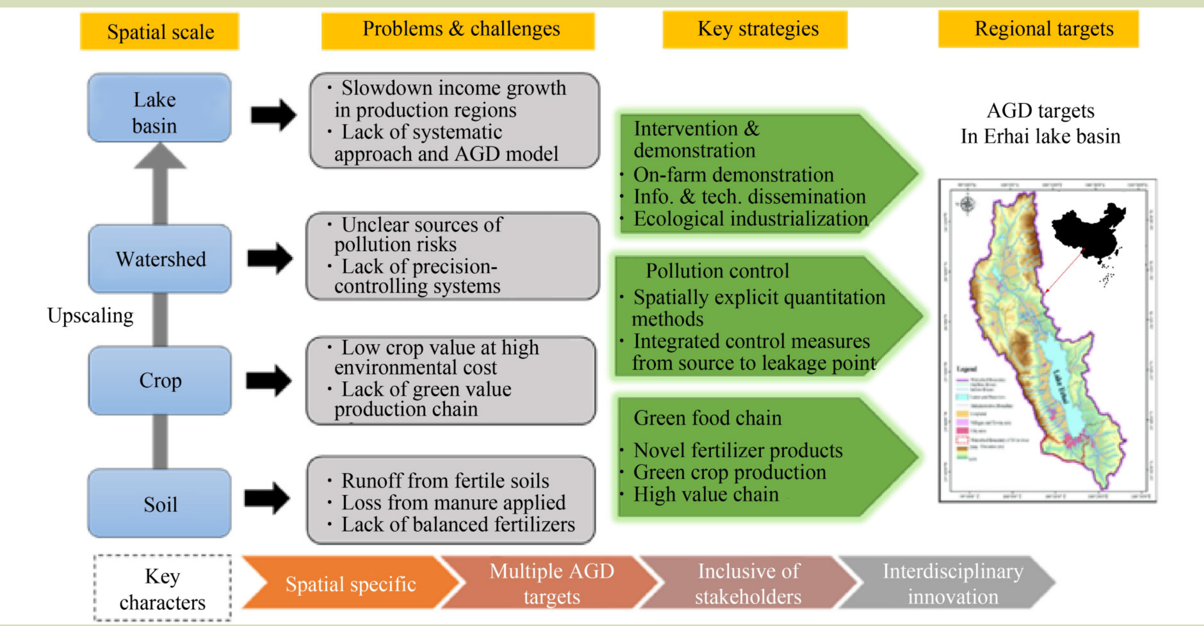


Fig. 2 Framework illustrating the key challenges and strategies for agricultural green development in a lake basin typical of Southwest China (审图号: GS 京 (2023) 2266 号).

all non-point pollution sources. Specially, field measurements should be conducted to quantify the nutrient flows in catchments, using modern monitoring technology. Also, spatially explicit modeling tools should be developed. These models should accurately incorporate all emission sources and nutrient transfer pathways, and should facilitate the estimation of the impacts of various policy measures and future developments. Next, modeling tools and empirical tests have to be developed that facilitate the establishment of environmental thresholds for agricultural pollutants. Such thresholds have to be based on a clear understanding of the relationship between emissions and the responses of water quality indexes (e.g., chlorophyll and biodiversity). In parallel, innovative green technology and management strategies have to be developed and tested to allow compliance with environmental thresholds.

Strategy 2: Technological innovation along the food supply chain to balance green (sustainability) and development. Under the strict environmental protection regulations, the area of high-value cropping systems with relatively high nutrient surplus (e.g., vegetables) have been limited. This regulation resulted in a loss of local farmer income. To address this challenge (Section 2, Challenge 2), we innovated green and high-value cropping systems to achieve the dual synergistic goals of protecting water quality of Erhai Lake and increasing farmer income. The procedures for developing such systems are discussed below. Firstly, the dynamic relationship between nutrient supply from soil and fertilizers and nutrient uptake by crops have to be established for different crop and soil types and management practices. These relationships must account for the mineralization of nutrients from soil organic matter and for the emissions of C, N and P in these contexts in Erhai Lake basin. Secondly, based on the data and information of soil-crop-fertilizer interactions, the targeted high-yield and high-efficiency technologies, such as high-yield cultivars, root-zone resource management, and environmentally-friendly fertilizers matching with the year-round nutrient uptake of crops, will have to be developed. Thirdly, based on market demand and local resource endowment, we construct a green (sustainable) high-value crop rotation systems. For example, replacing canola (used for oil production) with crops that have dual functions such as oil and vegetable production, can add economic value above the current rice-canola rotation. Our initial results on the newly developed rice-based cropping systems indicate a reduction of 20% to 50% of N and P leaching losses, and a 30% increase in farm income. Finally, we explore modifications of the whole food chain to arrive at an innovative and green high-value food chain. Taking consumer demand into consideration, we are aiming to establish a full supply chain consisting of green fertilizer and pesticide products, high-yield and high-efficiency crop production, and empowering the value of crop products with organic or green labeling and local culture of Bai people. The whole food chain from fertilizer production, crop farming, to retail and marketing should be improved substantially to tackle the unwanted trade-offs between environmental and economic benefits.

Strategy 3: Institutional interventions for implementation of agricultural green development. Rapid economic development has significantly degraded the environmental quality of Erhai Lake basin. Previous studies on the sustainability of lake basins gave less attention to the pathway toward agricultural green development through green technologies transformation, mainly because of a lack of understanding on the complex of socioeconomic interactions (Section 2, Challenge 3). To realize a greater sustainability of farming and livelihoods in the Erhai Lake basin, the insights for improving the overall sustainability in the basin through facilitating green agriculture are proposed, including empowering smallholders and cooperatives to adopt green technologies, adjusting policy and increasing farmer incomes.

The following priority actions are proposed.

(1) Closing yield gaps (i.e., the gap between attainable crop yield and actual crop yields) through minimizing the differences between farmer yields and the yields that are attainable for a given region according integrated management strategies (e.g., Zhang et al.[17]). The development of technologies that enhance crop productivity with a minimal level of fertilizer and water inputs have to be prioritized.

(2) Establishing sustainability-driven business models, in partnerships between entrepreneurs from the tourist sector, food industry, farmers (and cooperatives) and local governments. These business models have to provide remuneration to farmers who provide ecosystem services and services to protect the lake from pollution.

(3) Strengthen the training and demonstration activities that increase the knowledge/skill capacity of local farmers who are willing to adopt green technologies.

We contend that the Science and Technology Backyards founded by China Agricultural University since 2009 that are now operating in more than 100 villages[17] can be a means of building trust and for stimulating innovation among smallholders. The initiative encourages university-academies, cooperatives and smallholders work together, aiming to empower smallholders and cooperatives through zero-distance socialized services. They stimulate the willingness of farmers to actively adopt green production technologies and thereby form a mechanism for sustainable green production[30].

4 CONCLUSIONS AND OUTLOOK

In this paper, we argue that scientifically-sound environmental protection policies and agricultural green development are key to reversing the situation. When strictly implemented, the lake will be protected from pollution and smallholders will be able to produce healthy food in an environmentally sustainable manner, and with a fair remuneration for their services provide to the society as a whole.

Scientifically-sound environmental protection policies are based on (1) accurate accounts of emission sources and pathways, and (2) tested policy measures that are effective and efficient, and targeted to the specific emission sources and loss pathways. The effectiveness and efficiency of the policy measures have to be evaluated once in 4 to 5 years, to check for possible changes and inaccuracies in the underlying reasoning. In addition, the fairness of the policy measures to farmers and society have to be evaluated. Agricultural green development involves a food production-consumption system that complies with such environmental protection policies, and that delivers adequate amounts of healthy food to citizens, and provides farmers a fair remuneration for their services. Our perspective is that joint effort is needed to realize this.

The optimized benefits of agricultural production will only be possible if multidisciplinary expertise and technological advancement are integrated. The combination of knowledge-based technologies and ecological conservation infrastructure is essential to reduce the use of resources and increase circularity, and thereby the pollution risk of water bodies. Scientists from different disciplines, including agronomy, environmental science and social science, are encouraged to work together to explore the pathways that can bridge the different challenges and objectives of farmers, enterprises, academics and governments.

We advocate the development of a demonstration site in Erhai Lake basin, where technological innovations and measures are tested and demonstrated, and where farmers, entrepreneurs, researchers, extension services and local policymakers cooperate, to create innovative pathway toward agricultural green development in high altitude lake basins of China. The results of this demonstration site may be applicable to many other large lake basins in Southwest China.

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Compliance with ethics guidelines

Yong Hou, Wen Xu, Wenfeng Cong, Kemo Jin, Jiuliang Xu, Hao Ying, Shengrui Wang, Hu Sheng, Linzhang Yang, Wenqi Ma, Oene Oenema, Zhengxiong Zhao, and Fusuo Zhang 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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