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LETTER

GREEN AGRICULTURE AND BLUE WATER IN CHINA: REINTEGRATING CROP AND LIVESTOCK PRODUCTION FOR CLEAN WATER

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KEYWORDS

agriculture green development, China, clean water, crop-livestock reintegration

HIGHLIGHTS

- AGD aims for a green environment, sustainable agriculture and clean water.
- Presenting examples of the impact of agriculture on water quality.
- Presenting examples of solutions for sustainable agriculture and improved water quality.
- Integration of livestock and cropping systems is possible on a farm or among farms.
- Providing recommendations for further development of sustainable agriculture.

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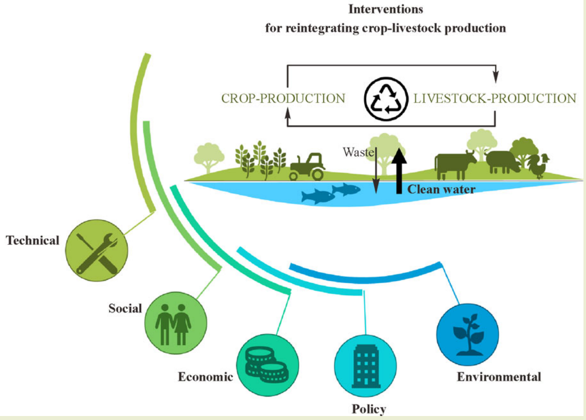
GRAPHICAL ABSTRACT



ABSTRACT

Crop and livestock production are essential to maintain food security. In China, crop and livestock production were integrated in the past. Today, small backyard systems are still integrated but the larger livestock farms are landless and largely geographically separated from crop production systems. As a result, there is less recycling of animal manures and there are lower nutrient use efficiencies in the Chinese food production systems. This, in turn, results in considerable losses of nutrients, causing water pollution and harmful algal blooms in Chinese lakes, rivers and seas. To turn the tide, there is a need for agricultural "green" development for food production through reintegrating crop and livestock production. An additional wish is to turn the Chinese water systems "blue" to secure clean water for current and future generations. In this paper, current knowledge is summarized to identify promising interventions for reintegrating crop and livestock production toward clean water. Technical, social, economic, policy and environmental interventions are addressed and examples are given. The paper highlights recommended next steps to achieve "green" agriculture and "blue" water in China.

1 INTRODUCTION

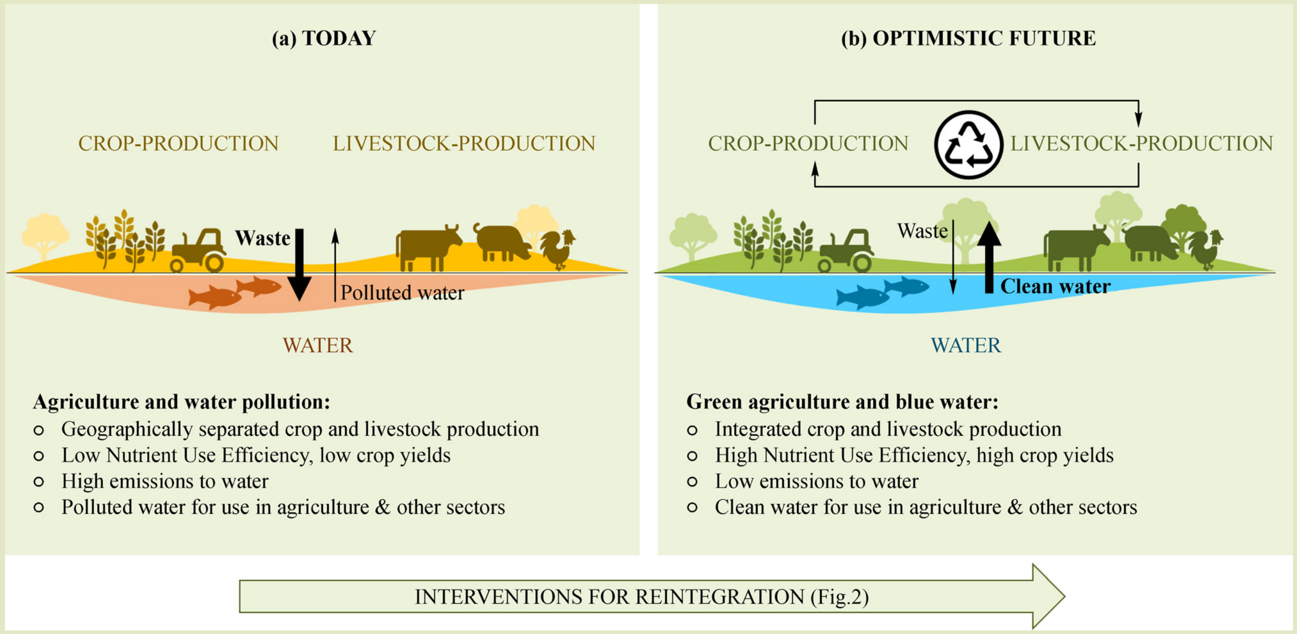
In China, the most populous country in the world, food production is of crucial importance to maintain national food security. National guidelines for Agriculture Green Development (AGD) were introduced in 2017 to achieve future food security[1,2]. AGD aims to transform the current, unsustainable agricultural practices[3,4] toward "green," sustainable agricultural production[1]. The guidelines focus largely on the coupling of crop and livestock production, green and nutritious food provision, natural resources governance, and a healthy environment. In 2018, the National Academy of Agriculture Green Development and the International School of Agriculture Green Development were established[1]. They seek innovative and smart solutions toward the sustainable transition of Chinese agriculture for current and future generations. Sustainable agriculture includes high crop and livestock productivity with limited environmental impact by using limited resources.

Another important goal is to turn Chinese water systems "blue" to provide clean water for nature and society[5,6]. "Blue" refers to water in rivers, lakes, seas and aquifers[7]. In our study we refer to these "blue" water systems that need to be clean for human activities and nature. Lakes, rivers, groundwater and seas are important sources of water for human activities[8,9]. Agriculture is an important user of water resources[10]. Water resources have become scarcer in the northern and western areas of China due to high water withdrawal. Additionally, many water systems are polluted in China[11–15]. This includes pollution associated with nutrients[12,15], pathogens[16], plastics and pesticides[17]. Pollutants cause multiple impacts on society such as impeding drinking water production by toxic algal blooms caused by nutrients, diarrhea caused by pathogens, and the spread of antibiotic resistance caused by antibiotic resistance genes.

In China the geographical separation of crop and livestock production is an important cause of water pollution[18,19] (Fig. 1, see Section 2). Reintegration of crop and livestock production is essential to achieve clean water in the future. There are also challenges with providing sufficient income to farmers, labor shortages, low educational attainment, low water use efficiency and low productivity. Here, we identify potential interventions for "green" agriculture and "blue" water in China, with a focus on reintegrating crop and animal production. This will help to achieve UN Sustainable Development Goals 2 "Food production" and 6 "Sanitation and clean water"[20]. First, we explain how separating crop and livestock production can cause water pollution (Section 2). Next, we identify and describe interventions for reintegrating crop and livestock production toward clean water (Section 3). We give examples to support these interventions. Finally, we provide recommendations to achieve "green" agriculture and "blue" water in China.

2 SEPARATION OF CROP AND ANIMAL PRODUCTION CONTRIBUTES TO WATER POLLUTION

In the past, crop and livestock production were integrated, with animal manure used to grow crops and crop residues to feed animals. In this way, nutrient losses to water were low because nutrients were cycled efficiently between crop and livestock production[18]. Today, crop and livestock production are often located far from each other (Fig. 1). An important reason is that the number and size of livestock farms have increased to maintain food demand, especially in urban areas. Smallholder crop production versus intensive livestock production is one of the major causes of separated crop and livestock production. Large distances between intensive livestock farms and crop production challenge the recycling of animal manures and crop residues[18,21]. As a result, 30%–70% of the nitrogen and phosphorus in animal manures was directly discharged to rivers in 2000 whereas this was only 5% in 1970 in 26 sub-basins[18]. Wang et al.[3] estimate that < 30% of the nitrogen in animal manures was recycled to croplands in 2010. Reduced recycling of crop residues and animal manures resulted in lower nutrient use efficiencies[4,21–24]. Bai et al.[24] estimate a decrease in the nitrogen use efficiency of the feed-pig-consumption chain from 46% in 1960 to 11% in 2010. Wang et al.[4] estimate a decrease in phosphorus use efficiency in agriculture from 38% in 1990 to



Agriculture and water pollution:
- Geographically separated crop and livestock production
- Low Nutrient Use Efficiency, low crop yields
- High emissions to water
- Polluted water for use in agriculture & other sectors

Green agriculture and blue water:
- Integrated crop and livestock production
- High Nutrient Use Efficiency, high crop yields
- Low emissions to water
- Clean water for use in agriculture & other sectors

Fig. 1 Overview of crop and livestock production in relation to water pollution in China today (a) and an optimistic future with interventions to develop green agriculture and thus contribute to "blue" (clean) water in the future (b). Interventions are shown in Fig. 2 and discussed in Section 3.

24% in 2012. Furthermore, nutrient use efficiencies in crop and livestock production differ across regions[3,19,25]. Low nutrient use efficiencies are driven by separated crop and livestock production resulting in the overuse of synthetic fertilizers and poor manure management. Geographically separated crop and livestock production is thus an important driver of water pollution in many areas of China[3,18].

Separated crop and livestock production contributes to pollution of lakes[26,27], groundwater[3,8,15], rivers[28] and seas[3,11,18]. Nutrient pollution (eutrophication) leads to blooms of harmful algae. This is mainly because excessive amounts of nutrients are lost from crop and livestock production, often through direct discharges of animal manures to water and overuse of synthetic fertilizers. In urbanized areas, wastewater also contributes to increased pollution levels in lakes[29]. Many lakes with great economic, cultural and ecological value have become eutrophic such as lakes Taihu[13,30,31], Chaohu[32] and Dianchi[29,33]. Chang et al.[27] estimate that 60%–90% of Chinese lakes (water quality class V or higher) in urban landscapes experience nutrient pollution and also physical, chemical, and bacteriological pollution and are unsafe for human use. Another example is groundwater pollution with nutrients on the North China Plain[8,34] contributing to water scarcity[35]. Inputs of nitrogen and phosphorus to Chinese rivers have increased by a factor of 2–45 between 1970 and 2000 (range for nutrients and sub-basins in China)[18]. The most important sources are direct discharges of animal manures to rivers in 2000 caused by a lack of manure recycling in crop production[18]. Wang et al.[12] quantified that 12 large Chinese rivers exported in total 3287 kt of dissolved inorganic nitrogen, 1567 kt of dissolved organic nitrogen, 295 kt of dissolved inorganic phosphorus, and 411 kt of dissolved organic phosphorus to seas in 2012. Between 15% and 76% of these nutrient exports to the seas originated from direct discharges of animal manures. The contribution of the synthetic fertilizers was generally higher to the southern rivers (Yangtze, Pearl) than to the northern rivers (Yellow, Huai, Hai)[12]. Wastewaters[11] and aquaculture[36,37] are also important pollution sources but their contribution varies with scale (e.g., national, basin, sub-basin)[11,37]. At the national scale, livestock and crop production are dominant sources of nutrient pollution in water systems in 2012[3,12].

Clean water is essential for irrigation and livestock. Sustainable agriculture is needed to achieve clean water (Fig. 1). However, clean water availability is decreasing in many regions within China[8,34] with the most dramatic losses on the North China Plain[38–41]. Groundwater is often used for human needs[8]. Climate change is expected to influence the availability of surface water and groundwater. This may increase water stress (less water, more pollution) in regions such as the North China Plain. Reintegration of crop-livestock production is a crucial step in both "green" agriculture and "blue" water to achieve sustainable food production. Reintegration refers to actions restoring the connection between crop and livestock production toward sustainable agriculture and clean water. This can be done through five main interventions (Section 3) and requires a transdisciplinary effort.

3 INTERVENTIONS FOR GREEN AGRICULTURE AND CLEAN WATER

Interventions are actions facilitating successful transitions such as a change toward sustainable agriculture and clean water. We have identified five categories of interventions for reintegrated crop and animal production toward clean water. Combining the five interventions will lead to an optimistic future with green agriculture and clean water (Fig. 2). We give examples for China below (Fig. 1 and Fig. 2).

3.1 Technological interventions

Technological interventions are actions to support the reintegration of crop-livestock production with lower environmental impact and with the use of advanced technologies. Closing the distance between crop and livestock locations is important to facilitate the recycling of manures to agricultural land and the use of crop residues for animal feeds. In addition to emission mitigation measures, manure management is key to facilitating closing nutrient loops between crop and livestock production sectors. Return of animal manures to arable fields instead of directly discharging them to water is essential in manure management. This will facilitate nutrient recycling between crop and livestock production and avoid nutrient losses to water.

Closing the physical distance between large-scale livestock farms and crop production may, however, be impractical in many Chinese regions for geographical reasons, the high cost of transport, and the social desire to locate livestock farms in the vicinity of high food demanding cities. Advanced technologies

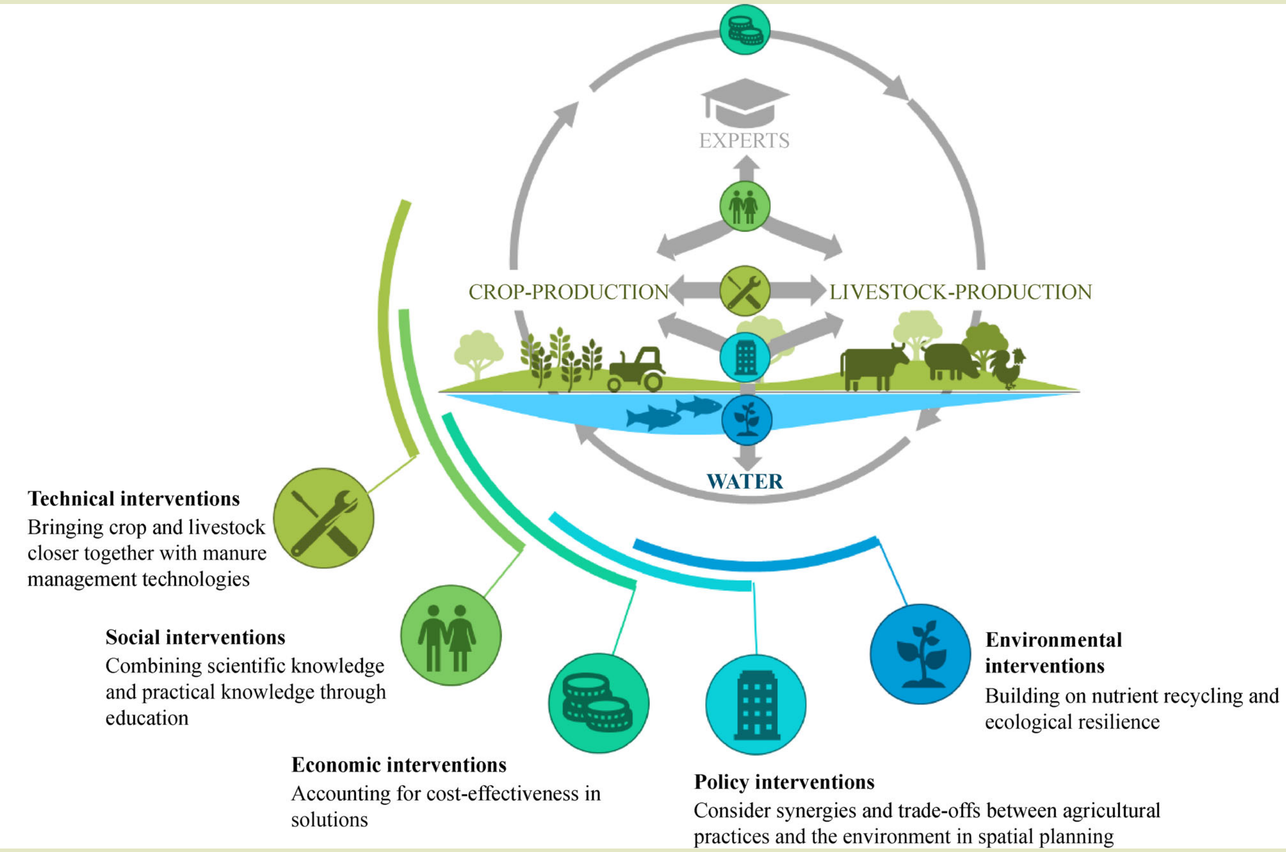


Fig. 2 Five categories of intervention for reintegrated crop and animal production toward clean water. The five interventions are technical, social, economic, policy and environmental. Examples are given for each intervention (see the main text for more information and the definitions of the interventions).

can help to bring crop and livestock production closer together without reducing their physical distance (Fig. 2). Technologies such as composting can make manure suitable for transportation over longer distances. Manure treatment can facilitate the reuse of (liquid) manure in agriculture. For instance, manure composting with bioreactors can remove odors and bacteria, does not compete for land, and makes manures suitable for transportation over longer distances to agricultural areas[2,42–44]. Technologies for anaerobic digestion exist to make manures suitable for application to land[45–48]. Advanced treatment technologies can recover over 80% of nutrients (e.g., reverse osmosis, anammox and phosphate precipitation) in liquid manures[49–52]).

Small-scale livestock farms have the potential to bring manure back to crop fields that are located nearby. Methods such as soil injection (liquid manures) and broadcasting (solid manures) can help arable farmers to apply manures efficiently to avoid nutrient losses. Technologies improving animal feeds and reducing emissions from manure storage[52,53] are also effective and have the potential to reduce nutrient losses by up to 30%[54,55]. In crop production, farmers should avoid overfertilization and replace synthetic fertilizers with animal manures. Agricultural infrastructure such as manure injection equipment can facilitate manure application[56]. This will maintain high crop yields and high nutrient use efficiencies. Implementing these technologies will require social, economic and policy interventions.

3.2 Social interventions

Social interventions include actions to deliver social benefits to farmers such as better welfare and education. Extending the knowledge co-operatively developed by experts and field practitioners can potentially increase sustainability in agriculture (Fig. 2). An example of this is the development of the so-called *Science and Technology Backyard* (STB) model in China in which experts (e.g., scientists from different related disciplines) work together with different stakeholders (particularly smallholders) in rural areas[57]. Knowledge and farming techniques co-developed with experts and different stakeholders in sustainable crop production are communicated with the farmers via training, field consultation and demonstration. Farmers, in turn, share their experiences of farming practices with the experts, and this promotes technological innovation. Since 2009 the productivity and nutrient use efficiencies in crop production have increased considerably in rural areas where the STBs have been located[58–61]. Cui et al.[58] show that yields of maize, rice and wheat in 452 Chinese counties increased by almost 12%, while application of nitrogen decreased by up to 18% between 2005 and 2015 by adopting the STB model. Nutrient use efficiency in STBs increased. STBs thus contribute both to the application of scientific knowledge and the social acceptance of new technologies. Taking the STB as an example, we could apply a similar model to both smallholder and industrialized farmers to allow knowledge exchange on manure recycling and crop production. This would contribute to the reintegration of crop-livestock production.

3.3 Economic interventions

Economic interventions are actions to reduce inequities in the market environment through regulation, taxation and subsidies in relation to sustainable agriculture and clean water. Reintegrating crop and livestock production requires economic incentives on different administrative scales (county, province and national)[62]. Subsidies for recycling animal manures can facilitate arable farmers to replace synthetic fertilizers with animal manures[63]. Costs and benefits associated with different interventions need to be economically balanced at different scales to develop successful solutions (see Interventions 1, 2 and 5). Furthermore, economic interventions preferably account for equality in implementing solutions such as considering regional disparities in socio-economic development (Fig. 2). This requires integrating economic incentives, equality and natural resource utilization for sustainable food production[62]. However, progress in this regard is still limited in China[62,64]. Strokal et al.[65] have developed an approach to identify cost-effective management options for reducing coastal eutrophication in China in the future using the Yangtze basin as an example. They show that recycling animal manures could be a cost-effective solution to avoid future water pollution. This finding supports the current policies promoting manure recycling (see also Policy interventions).

3.4 Policy interventions

Policy interventions are actions to develop information measures to facilitate the reintegration of crop and livestock production. In recent years China has introduced several important policies on livestock production and manure management[2,66–68]. Most of these focus on improved manure treatment and recycling and the reallocation of livestock production. These policies are effective initiatives for reintegrating crop and livestock production to reduce water pollution. However, some policy interventions contribute to reducing water pollution in a vulnerable region but transfer the pollution to other regions. An example is a policy on the reallocation of pig production from watercourse-intense southern regions to the south-west and north-east provinces. Bai et al.[25] show that this reallocation may reduce nutrient losses to waters in south-east China by 27%–48%. However, it also transfers nutrient pollution to south-west and north-east China and threatens forests and grasslands. Future policies should focus on spatial planning, taking into account the synergies and trade-offs between agricultural practices and the environment (e.g., waters, soils and air) under rapid urbanization (Fig. 2). Future policies could consider increasing the size of arable farms through land transfer or agricultural services for reintegrating crop and livestock production. Such policies could facilitate the implementation of innovative technologies (Technological interventions) taking into account the social aspects (Social interventions) and the economy (Economic interventions).

3.5 Environmental interventions

Environmental interventions are actions to improve the environmental health of natural surroundings to support sustainable agriculture (Fig. 2). For instance, nutrient recovery by harvesting aquatic plants or fish from polluted water systems could help to reduce eutrophication in surface waters[69]. Examples of nutrient recovery by aquatic plants are for instance found in Chinese aquaculture[69,70] and also show some promise in crop and livestock reintegration. Aquatic plants that assimilate large amounts of nutrients can be harvested for the production of fertilizers and animal feeds[68–70]. In this way, semi-natural systems such as artificial lakes and wetlands can be used to trap nutrients and avoid nutrient transport downstream. Harvesting aquatic biomass can link the ecological restoration of eutrophic waters by nutrient removal with sustainable animal and crop production[68]. Environmental interventions can be a part of synergetic solutions that combine the other interventions described above.

4 CONCLUDING REMARKS AND FUTURE OUTLOOK

We present five categories of interventions for reintegrated crop and animal production. They focus on (1) technological (e.g., bringing crop and livestock production closer together through technology), (2) social (e.g., combining scientific knowledge from experts and practical knowledge of farmers through education), (3) economic (e.g., accounting for cost-effective solutions), (4) policy (e.g., considering synergies and trade-offs between agricultural practices and the environment in spatial planning), and (5) environmental (e.g., building on nutrient recycling and ecological resilience) interventions (Fig. 2). The interventions can be practiced at different scales (e.g., administrative such as counties and provinces). For example, at the farm scale the Science and Technology Backyards can be instrumental in the transition toward sustainable agriculture. At the national and local scales, economic incentives (e.g., subsidies) can stimulate farmers to transport and apply manures to arable fields. Furthermore, increasing the size of arable farms through land transfer may help to reintegrate crop and livestock production. Such policies could facilitate the implementation of innovative technologies taking into account the social and economic interventions. However, reintegration of crop and livestock production may involve trade-offs. Transportation of manures over longer distances may increase emissions of greenhouse gasses and air pollutants. Re-allocation of livestock farms closer to arable farms may move the pollution from one place to another.

To avoid trade-offs we call for a better synthesis of existing knowledge of the five types of interventions in China to develop an optimistic vision of the future with green agriculture and clean water. Scientists and stakeholders can collaborate in the reintegration process through co-operative creation of new ideas, designs or values by integrating their expertise and tools. This will help in the co-development of actionable solutions with the involvement of stakeholders (e.g., local farmers). A successful transition thus requires the active participation of both scientists and local farmers. Inter- and transdisciplinary research is essential to support the societal changes toward “green” agriculture with reintegrated crop-livestock production and clean water. China is unlikely to be the only country for which this is a promising strategy.

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Compliance with ethics guidelines

Maryna StrokaL, Annette B.G. Janssen, Xinping Chen, Carolien Kroeze, Fan Li, Lin Ma, Huirong Yu, Fusuo Zhang, and Mengru Wang 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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