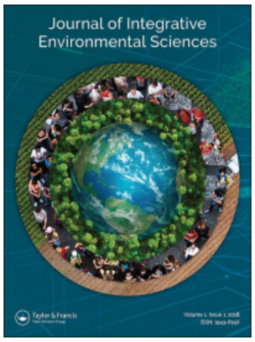

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Challenges and strategies for agricultural green development in the Yangtze River Basin

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ABSTRACT

The Yangtze River Basin (YRB) has been recognized as one of the key strategic development regions in China. Agriculture p52roduction systems in the YRB have contributed considerably to China's goal of food security. Realizing Agriculture Green Development (AGD) means agriculture production systems with high productivity, high resource use efficiency and low environmental costs. However, challenges and barriers still exist for realizing AGD in the YRB. Here, we summarize four main challenges for AGD in the YRB, and identify two approaches (top-down and bottom-up) including main strategies needed to achieve AGD. The four challenges include, but are not limited to, (1) low agricultural productivity and nutrient use efficiencies, (2) an uneven agricultural production structure, (3) rapid urbanization, and (4) uncoordinated targets for environmental protection and food production. We conclude that both top-down and bottom-up approaches are needed to deliver AGD in the YRB. Top-down approaches are mainly operated by government and underpinned by research, which uses spatial planning to promote the balance between agricultural production and the ecological environment, and to optimize the proportions of cereal and cash crop production with monogastric and ruminant animal production. The bottom-up approach needs strategies to close the yield gap of various cropping and livestock systems, improve resource use efficiencies to control environmental impacts. Furthermore, training and education are needed to increase awarenessand improve skills for farmers and advisers. Our review can serve as example for other global regions that are in transition from unsustainable agriculture production towards sustainable withclean environment and healthy economies.

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Introduction

The Yangtze River (YZR) is the longest river in Asia and the third longest in the world (World Wide Fund for Nature or World Wildlife Fund, (WWF), 2019). Its source is in the Tibetan Plateau and it meanders about 6,300 km eastwards before its outlet at the East China Sea (SCC, 2014; figure 1). The Yangtze River Basin (YRB) comprises 2.1 million km^2 and 11 provinces, and contributes to >40% of China's economy via only 20% of the nation's land area (NBSC, figure 2). Significant progress has been made over the past 50 years in terms of delivering food security for the YRB population (and beyond), especially in rice, oil crops, vegetables and pork production, for which the YRB contributes almost 50% of the total production in China (figure 2). Hence, the YRB is one of the most intensive farming regions in the world, and has become an indispensable part of China's ability to maintain food security for its population.

However, existing studies illustrate that the long-term efforts to produce sufficient food in this region have impacted on the health of its natural ecosystems and polluted water systems (e.g. rivers, lakes, reservoirs) (WWF). For example, diffuse pollution from agriculture contributes 43–85% to dissolved inorganic nitrogen (DIN) export in spring, summer and fall (Chen et al. 2019), and the net annual phosphorus (P) input into the Yangtze River (YZR) has increased constantly from 1970 to the present day (Powers et al. 2016; Liu et al. 2018b; Dong et al. 2020). Meanwhile, the YRB, especially the lower reaches,

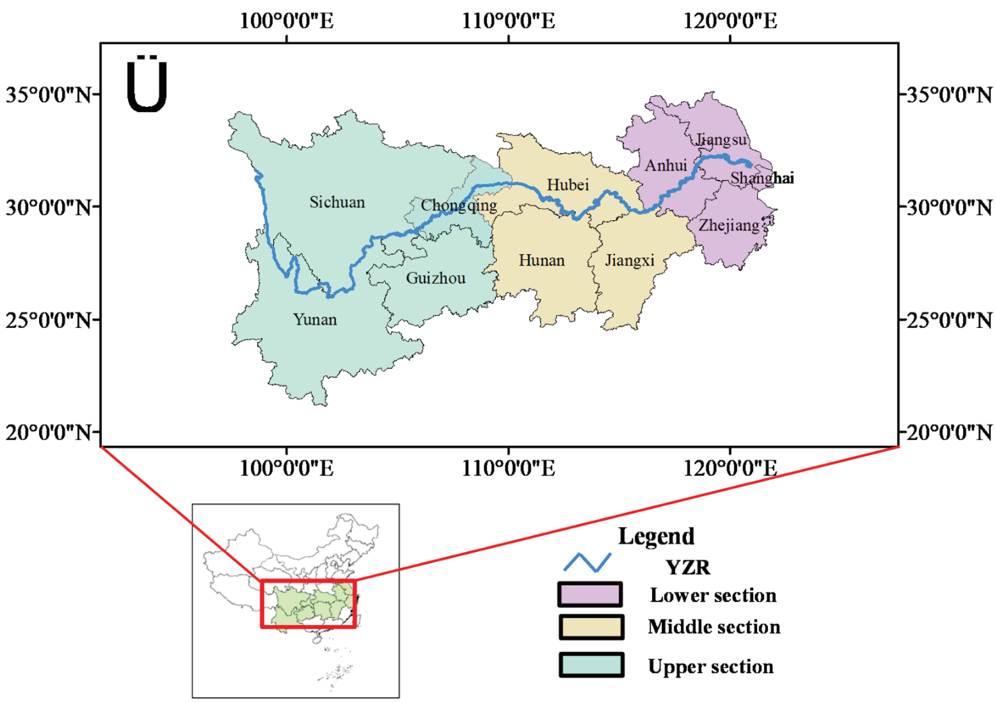

Figure 1. Location of the Yangtze River Basin (YRB) and its three sections. **Note**: The upper section includes Yunnan, Sichuan, Guizhou and Chongqing; middle section includes Hunan, Hubei and Jiangxi; lower section includes Anhui, Zhejiang, Jiangsu and Shanghai. Data for allocation of three sections were obtained from the State Council of the People's Republic of China for 2016 (http://www.gov.cn/zhengce/content/2014-09/25/content_9092.htm).

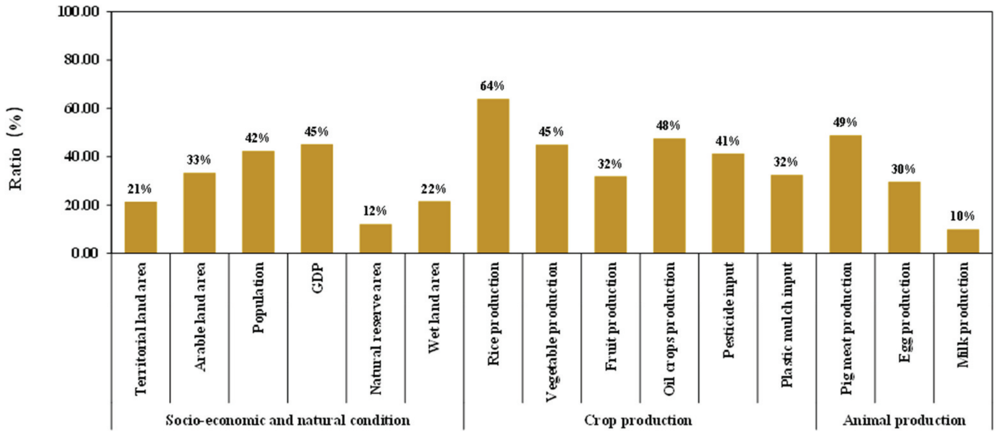

Figure 2. The ratios of the YRB to China on socio-economy and natural condition, crop and animal production in 2016. **Note**: Socio-economic and natural condition includes territorial land area, arable land area, population, GDP, area of natural reserve zones and wet land; Crop production includes total production of rice, vegetable, fruit and oil crops, and input of pesticide and plastic mulch; animal production includes production of pig meat, egg and milk. Source: Data for area of territorial land and arable land, population, GDP, crop and animal production were obtained from NBSC (National Bureau of Statistics) for 2016 (http://www.stats.gov.cn/tjsj/ndsj/); data for area of natural reserve and wet land were obtained from Ministry of Ecology and Environment for 2016 (http://g.mnr.gov.cn/201705/t20170502_1506593.html).

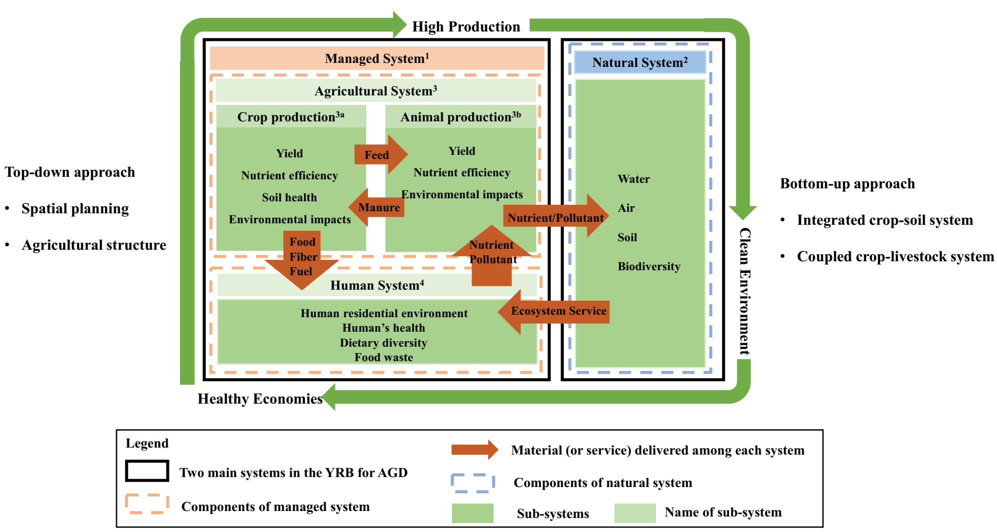

Figure 3. The concept of agricultural green development (AGD) for the Yangtze River Basin. Source: The concept was inspired by the national definition of the AGD for China (Shen et al. 2020). **Note**: The superscript number means the main systems considered in AGD for the YRB, namely Managed system (1) and Natural system (2). Agricultural system (3) and Human system (4) are sub-systems included in Managed system; Crop production (3a) and Animal production (3b) are included in Agricultural system.

has suffered from high ammonia emissions and related human health problems (Bai et al. 2019). There are also serious concerns about the loss of biodiversity in the YRB, especially of the unique indigenous fish (Fu et al. 2003; Fang et al. 2006). Many of these problems are the result of the intensive agricultural production in the region, so sustainability and net societal benefits of intensive agricultural production require more attention by scientists and policy makers (Tilman et al. 2002). The YRB is a typical subtropical intensive agricultural production region of the world, which contributes 18%, 30%, 33% and 15% to global rice, tea, orange and rapeseed production, respectively. Improving agricultural productivity and ecosystem service function in the YRB will not only benefit the region and China to realize UN sustainable development goals (SDGs), but will have wider consequences for the world.

Agricultural Green Development (AGD) is a novel concept for improving agricultural production systems in developing countries with millions of smallholder farmers (Ma et al. 2020; Shen et al. 2020). AGD links directly with the UN SDGs, as well as sustainable intensification goals. For example, implementing sustainable intensification of agriculture within AGD will support the achievement of SDG2 (food security), 6 (clean freshwater) and 14 (clean water for coastal waters). Whilst there is now an outline framework and a strategic programme for AGD in China, and several studies have reviewed strategies to solve specific challenges (Chadwick et al. 2020; Cui et al. 2020), there has been no systematic study that addresses regional solutions of the multiple and interacting challenges of AGD in the YRB. Yet this knowledge is essential in developing effective strategies to deliver sustainable agricultural production systems, whilst protecting and improving natural ecosystems. Hence, the purpose of this study is to systematically review the challenges of AGD in the YRB, and propose strategies to sustainably increase yields of various crops and livestock with reduced environmental impacts. Moreover, this case study should be seen as an illustrative example for other regions around the world where intensive agricultural production and rapid urbanization is taking place, and where there is an urgent need for eco-environmental protection to realize AGD.

Challenges for AGD in the Yangtze River Basin

Agricultural green development (AGD) means the coordination between "green" and "development". "Green" means sustainable agriculture with a clean environment, and "development" means that agriculture develops towards sustainable practices with high yield and efficient use of resources. AGD for the Yangtze River Basin considers three main components: high production, clean environment and healthy economies (see figure 3). These are reflected through crop and animal production systems in relation to human systems and the natural environment (see figure 3). We identify several challenges for implementing AGD in this enormous river basin. These challenges are described below.

Low agricultural productivity and nutrient use efficiencies

The main crop production systems in the YRB are rice, vegetables and oil crops, which accounted for 60% of total harvest area in the YRB in 2016 (National Bureau of Statistics of China (NBSC) 2017). Although yields of these dominant crops are similar to, or somewhat higher, than the average for China or developed countries (Table 1), yield gaps still exist.

For instance, rice yield in the YRB can be as high as 7.1 t·ha^{-1}, which is at a high level compared with global leading rice-producing countries (Vietnam and Thailand), but only represents 74% of the yield potential in China (Deng et al. 2019). In addition, input intensity of chemical fertilizer (N and P) in the YRB are much higher than developed countries, whilst the PFP_N (partial factor productivity of N fertilizer, Ierna et al. 2011) in the YRB is only 52.3 kg·kg^{-1}, and is significantly lower than countries such as the US (Table 1). From the perspective of animal production, livestock rearing systems in the YRB are also less productive than in other parts of the world. For example, the pork production per head of slaughtered pig is 79 kg per head in the YRB, and is much lower than that in the US (96 kg per head) and the EU (91 kg per head) (Table 1). Similarly, milk yield per cow in the YRB is 10% higher than the average level in China, but still 284% and 154% lower than the US and EU (Table 1). In addition, the mean feed conversion ratios, that is the amount of feed needed to produce a unit of animal products, are lower in China compared with the world leading producing countries (Bai 2015). N and P use efficiencies (NUE, PUE) in animal production system in the YRB are only 17% and 14%, respectively, and are lower than the average value for China and some developed countries (Ma et al. 2012; Bai et al. 2016).

Low productivity and high resource inputs for agricultural production result in the waste of agricultural resources and increased environmental footprints, and need to be addressed to deliver AGD in the YRB. Balancing productivity with resource use efficiency is a priority, and successful strategies have been reported at field and regional scales in China that result in increased grain yields with lower environmental costs (Cui et al. 2020). Furthermore, increasing yield on the existing land area of the YRB can “spare” land for delivery of other ecosystem services, including the promotion of biodiversity.

Uncoordinated agricultural production structure

Rapidly increasing proportion of cash crops

There is a large area of cash crop (vegetables, fruits, oil crop and tea) production in the YRB, representing around 38% of the total harvest area (National Bureau of Statistics of China (NBSC) 2017), which is considerably higher than the global average of 27% (Food and Agriculture Organization (FAO) 2019). The recent shift from cereal crop production towards vegetables, fruits and tea has been driven by the higher profits compared to grain production (Meng et al., 2020). However, the result has been an increase in serious environmental damage in the YRB (Li et al. 2018). One of the problems associated with cash crops, especially fruit, is that the harvested products do not remove great quantities of N and P, but farmers often use excessive fertilizer and manure nutrients to ensure maximum production (Yang et al. 2020). For example, Yan (2015) reported that the average input of chemical N fertilizer to citrus trees was 485 kg·ha^{-1} in the YRB, while only 260 kg·ha^{-1} for rice. Also, shallow-rooted crops and little ground cover in vegetable fields during the rainy season results in greater risk of sediment and nutrient loss, compared with grassland or grain production (Liang et al. 2013). This is important as the YRB is the suffering greatly from soil erosion, which associated N and P loss to watercourses (Zhang et al. 2003). This is particularly important in the upper section of

Table 1. Crop and animal productions and environmental status in the Yangtze River Basin (YRB) in 2016, compared with China, the United States of America (US) and European Union (EU). The respective sections of the YRB are included, namely upper- (Upper), middle- (Middle) and lower-section (Lower).

Item	Unit	Upper	Middle	Lower	YRB	China	US	EU	Reference
Rice yield	$t \cdot ha^{-1}$	6.93	6.89	7.54	7.14	6.92	8.11	6.20	NCBS; FAO
Vegetable yield	$t \cdot ha^{-1}$	23.4	28.3	32.4	28.0	23.0	35.0	29.0	NCBS; FAO
Oil crop yield	$t \cdot ha^{-1}$	2.01	1.91	2.57	2.18	2.07	2.27	1.14	NCBS; FAO
Chemical N fertilizer	$kg \cdot ha^{-1}$	215	283	315	263	225	75.0	107	NCBS; FAO
Chemical P fertilizer	$kg \cdot ha^{-1}$	86.6	145	121	115	94.1	25.8	24.5	NCBS; FAO
PFP-N	$kg \cdot kg^{-1}$	51.8	55.1	52.6	53.1	52.3	136	50.9	NCBS; FAO
Pesticide	$kg \cdot ha^{-1}$	7.2	27.7	21.9	17.7	14.8	2.59	3.47	NCBS; FAO
Meat productivity	$kg \cdot head^{-1}$	79.5	76.1	80.1	78.8	78.7	95.7	91.0	NCBS; FAO
Milk productivity	$kg \cdot head^{-1}$	2645	1225	3881	2707	2439	10,348	6879	NCBS; FAO
Mature N return rate	%	25.4(2010)	—	—	25.8(2010)[a]	32.9(2010)	73.5(2002)	80.7 (2000)	Liu et al. 2018a; Environmental Protection Agency (EPA) 2011; Leip et al. 2011
River export of N	$kg \cdot km^{-2}$	—	—	—	945(2012)	—	335(2014)	1490(2001–2005)	Tong et al. 2017; Environmental Protection Agency (EPA) 2011; Billen et al. 2011
River export of P	$kg \cdot km^{-2}$	—	—	—	49.9(2012)	—	53.7(2014)	136(2001–2005)	Tong et al. 2017; Environmental Protection Agency (EPA) 2011; Billen et al. 2011
Forest land ratio	%	50.5	55.3	22.5	41.6	21.6	33.1	23.1	NCBS; FAO

[a]Data in brackets represents the year or period of the items.

the YRB where there has been a rapid substitution of the cereal cropping area by cash crops over the past 30 years (National Bureau of Statistics of China (NBSC) 2017).

Concentration of pig and poultry production

Livestock density expressed per unit of arable land in the YRB is 5.1 LU·ha^{-1}, which is much higher than the average for China (4.2 LU·ha^{-1}), the US (1.7 LU·ha^{-1}), Europe (2.6 LU·ha^{-1}) and Australia (1.2 LU·ha^{-1}) (Food and Agriculture Organization (FAO) 2019). Monogastrics animals (pigs and poultry), which represent >90% of total livestock units in the YRB, are highly dependent on concentrate feeds, which comprise huge amounts of maize and soybean (Cowieson et al. 2017). Currently, the average farm size in the YRB is 65 head per farm for pigs, 1162 head per farm for poultry, and 251 head per farm for dairy cattle production, which are all greater than the average level in China (National Bureau of Statistics of China (NBSC) 2017). Meanwhile, the number of large pig and poultry farms, i.e. farm size >50,000 head per farm for pigs, and > 100 million head per farm for poultry, continues to increase dramatically, e.g. by 1.5 times and 8.8 times, respectively, between 2010 and 2015 (National Bureau of Statistics of China (NBSC) 2017).

Concentrated livestock production systems are highly reliant on the input of antibiotics and China is the world biggest antibiotic producer and consumer, with 23% of these antibiotics being used in livestock production, mainly for monogastric animals (Van and Brower, C. et al. 2015). Much of these antibiotics are excreted by animals and are at risk of contaminating watercourses, soils and crops following application of manures to the soil, or direct discharge of manures to watercourses (Larson 2015; Sun et al. 2020). Recent studies have showed the increase in abundance of antibiotic resistance genes in soil and water (Liu et al. 2017; Zhou et al. 2019). In addition, specific heavy metals have been used as dietary supplements for promoting pig and poultry productivity, with most being excreted and contributing to heavy metal accumulation in soil in the YRB (Yang et al. 2018).

The geographical decoupling of crop and livestock production

The YRB is witnessing a transformation in its livestock production systems from traditional household production (mainly for self-consumption or distributing to local-markets) to intensive industrial production systems, which results in weaker integration between crop and livestock production (Bai et al. 2018a). Manure N and P production was estimated to be around 7.9 Tg N and 18 Tg P in the YRB in 2010 (Liu 2018c). However, the rate of collected manure returned to crop production was only 26% (Table 1). This indicates the poor integration between livestock and crop production systems in terms of nutrient and organic matter recycling.

The rapid increase in numbers of monogastric animals means there is less opportunity and capacity to recycle the large quantity of crop, vegetable and fruit residues that are produced by farms in the YRB. The YRB produced 336 million tons of crop residues in 2016, containing an estimated 3.5 million tons N and 0.5 million tons P (Liu 2018c). Because of the lack of ruminant livestock in the YRB, many of these residues are discarded or burned, with only a small proportion of these residues being recycled to fields. Hence, the high ratio of monogastric animals to total livestock in the YRB has become an obstacle to achieving local and regional circular crop-livestock integration. However, there is still considerable opportunity to recycle more animal manure to cropping land to supply nutrients and organic matter, reducing the reliance on synthetic fertilizer (Liu 2018c). But this will require investment in infrastructure (for manure storage and processing), transportation (from animal farm to cropping farm, and for manure spreading), labour, education and training, and advice/guidance on recommended rates and timings of manure applications to optimize nutrient use efficiencies (Chadwick et al. 2020).

Rapid urbanization and its impacts on nutrient flows

The YRB is one of the regions with fastest rate of urbanization in China, with a current rate of 57% (National Bureau of Statistics of China (NBSC) 2017). Decreasing agricultural productivity and increasing food consumption in cities are two main ways for threatening food security in China from urbanization (Gu et al. 2019). Because large numbers of farming household members working in towns and cities, putting more pressure on the remaining crop areas to provide the same (if not more) food with less able-bodied labour (Lu et al. 2019). Moreover, rapid urbanization is linked to an increased demand for animal-based food products (Satterthwaite et al. 2010) and greater quantities of food waste (Knorr et al. 2017), both of which contribute to high environmental costs. Annual protein consumption *per capita* per day is higher in urbanized areas, i.e. around 36 kg per day in mainland China (FAO, 2019), not accounting for the associated 15 to 50% food losses before the food reaches the plate (Ma et al. 2019). In Shanghai, a city in the lower section of the YRB, food waste in households and restaurants is as high as 40–80% (Gu et al. 2019).

In addition, there are many other types of nutrient inputs to the city, such as paper, cotton and deposition. None or few of these nutrients are finally recycled to agricultural land, contributing to the increasing reliance on external nutrient (e.g. chemical fertilizer) inputs in crop production systems. Rapid urbanization has also resulted in increased nutrient flows through sewage treatment systems. In China, little sewage sludge is applied back to agricultural land, because of public perception of health issues (Li et al. 2010). Therefore, the government has invested heavily to improve sewage treatment infrastructure, e.g. to remove reactive N as N_2, and to dispose of the collected P in landfill (Zhang et al., 2016a). However, despite this, recent studies show that sewage treatment systems contribute to a significant proportion of N losses to water systems in China, and are partly responsible for decreasing the quality of water systems (Jin et al. 2014). Overall, large and densely populated cities are an obstacle to recycling nutrients to crop production in the YRB.

Uncoordinated targets for environmental protection and agriculture production

The conflict between biodiversity protection and economic development

Intensive agricultural production together with rapid urbanization has greatly reduced the habitat for plants and animals in the YRB (Li et al. 2019). There have been considerable losses of plants, invertebrates, and migratory birds in the YRB during the past five decades (Jia et al. 2018). This is not helped by the uncoordinated targets for environmental protection and agricultural production between the upper, middle, and lower sections of the YRB. Currently, the upper section accounts for >70% of the natural reserve area in the YRB (MEE, 2018). These regions only contribute to ca. 20% of the total GDP in the YRB, and farmers in the upper section are poorer than in the lower section (National Bureau of Statistics of China (NBSC) 2017). The desire to improve the income of these poor farmers may conflict with the targets for higher biodiversity by other stakeholders in the middle and lower sections of the YRB. Although, the upper section may benefit from attracting more tourists because of its high biodiversity, the economic benefit is clearly not sufficient to pay back the efforts of local government to protect its natural capital (Liu et al. 2018b).

Importantly, the natural reserves are fragmented and scattered throughout the YRB (Ministry of Ecology and Environment (MEE) 2015). There is much discussion about the ability of fragmented (small) areas of natural conservation land to deliver water conservation, soil retention, carbon sequestration, biodiversity and food supply (Xu et al, 2018b; Zheng et al. 2020). In the Netherlands, a country with strict natural conservation polices and some of the highest livestock densities in the world, there are 162 nature reserves, and in 118 of these the N deposition levels now exceed the ecological risk thresholds by an average of 50% (Erik 2019). To protect these fragile ecosystems, the Dutch high court has implemented a series of policies which prohibit many agricultural and construction activities in the Netherlands (Stokstad 2019). The YRB and the Netherlands share many similarities, i.e. higher livestock densities, hotspots for N deposition and biodiversity loss, and high water intensities. China can learn from examples of the co-ordinated strategies to protect nature and agriculture production, e.g. in the Netherlands, but it is more difficult to solve these challenges in the YRB because of the more complex environmental and economic situation.

In addition, many of the natural wetlands and lakes that linked to the YZR in the middle- and lower-sections have disappeared in the past decades, as a result of agricultural production and urbanization (Cui et al. 2013). This has greatly decreased the capacity of the YRB to hold flood waters. Hence, farmers have faced both flooding and drought within the same year and subsequent reductions in crop yields, and even losses of livestock production during severe flood events (Xiao et al. 2015).

Severe environmental pollution

Large quantities of inorganic N and P have been transported into the YZR or lakes, leading to widespread declines in water quality (Chen et al. 2020). The current status of eutrophication in lake water has become the most important environmental problem in the YRB, especially in the middle and lower sections (Wang et al. 2019). As well as diffuse pollution, point sources, e.g. direct discharge of animal manure, are also impacting on water quality in the YRB (Tong et al. 2017). According to model estimates, direct manure discharge (caused in part by the dis-location of livestock and cropping systems) was the dominant source of nutrients (N and P) in the watercourse, accounting for about 22%–69% in the YZR and Huai Rivers during 1970–2000 (Strokal et al. 2016b).

Although not as poor as in the North China Plain, the air quality in the YRB, especially in the middle- and lower-sections also exceeds WHO thresholds (Wu et al. 2016). High $PM_{2.5}$ (atmospheric particulate matter with a diameter of <2.5 μm) concentrations have led to greater mortality rates in post-65 year olds, and it is known that increases in $PM_{2.5}$

concentrations are associated with the high ammonia emissions from the overuse of urea fertilizers and intensive livestock production (Bai et al. 2019). The YRB is known to be a hotspot for ammonia emissions (Wu et al. 2016). N deposition related to these high ammonia emissions has also been measured in the YRB, via comprehensive monitoring from different sources (Xu et al., 2018a), and represents a risk of impacting the stability and biodiversity of the natural ecosystems in this region.

Strategies for AGD in the Yangtze River Basin

The YRB is a hugely important agricultural production (crops and livestock) region for China, and is based on a watershed that differs from other agricultural regions, e.g. the North China Plain, as the terrain falls away sharply from west to east. Therefore, agricultural production in the YRB is much more sensitive to human activities and easier damage to the environment by nutrient/waste flows than other agricultural region (Peng et al. 2018; Zhang et al., 2019b). As mentioned above, the key challenges to AGD for the YRB include: high resource input, low yields of crop and animal system, decoupling of crop and livestock production, rapid urbanization and agri-environmental pollution. Hence, the feedback between agriculture and the surrounding eco-environment should be considered in the design of a future sustainable strategy for AGD in the YRB (figure 3).

There are two main “systems” that need to be considered in AGD within the YRB, namely the “managed” system (figures 3, 1) and the “natural” system (figures 3, 2). In this paper, we define the managed system as a system that does not exist in nature itself and is created by human activity (for reproduction and survival). The natural system is the necessary environment on which managed system depends, and includes water, atmosphere, soil and biodiversity. The managed system not only uses nutrients (extracted/manufactured from the natural system) and circulates nutrients (to a limited some extent), but also benefits from ecosystem services from the natural system (e.g. pollination, flood water storage, environmental purification). The managed system comprises both the Agriculture sub-system (crop and animal production, figure 3, 3a and 3b) and Humans sub-system (figure 3, 4). Agriculture provides food, fibre and fuel for Humans, and receives nutrient or pollutant (waste) generated by human living simultaneously. At the same time, crop and animal production can exchange nutrients in terms of feed and manure. The agriculture and human components of the managed system have evolved together and developed over thousands of years.

Agriculture delivers materials and energy for humans, but is also an important contributor to agricultural-based pollution in the YRB, as stated above. Therefore, strategies towards achieving AGD for the YRB should not only focus on improving yield levels and nutrient use efficiencies of different farming systems, but also on reducing their environmental impacts. This includes sustaining and increasing soil fertility in many cropping systems (figure 3, 3a). Improving the human residential environment, including human health and dietary diversity, and reducing food waste caused by rapid urbanization in the YRB are key goals for AGD (figure 3, 4).

Based on demands for AGD and challenges in the YRB summarized above, two complementary strategies are suggested for achieving AGD in the YRB (figure 3): i) top-down designated strategies to redesign the structure and spatial distribution of agricultural production systems that optimize land use across the climate, topography and soil in the YRB to deliver sustainable food, fibre and energy whilst protecting the environment and enhancing local and regional economies, and ii) bottom-up technologies that include improvement of crop-soil and crop-livestock production systems for high productivity, high resource use efficiencies and reduced environmental pollution.

The top-down strategies

Biodiversity loss and severe environmental pollution caused by agricultural production, rapid urbanization and uneven structure of cereal and cash crop production, and mono-gastric and ruminant animal production are the main factors constraining AGD in the YRB. Uncoordinated use of land for different purposes contributes significantly to these problems (Su et al. 2016). Hence, a priority top-down strategy in the YRB should include government-led improved spatial planning of agriculture production systems, especially to facilitate improved coupling of cropping and livestock systems, within a wider land-use strategy to deliver fibre, energy as well as biodiversity and other ecosystem services.

Spatial planning of agriculture across the municipality borders in the YRB

It is essential to coordinate region-specific production, environmental and economic requirements for the upper, middle and lower sections of the YRB. The top-down strategies need to consider the three high priority "Ecological redline" policies proposed by the central government in China (Ministry of Ecology and Environment (MEE) 2014). The three redline policies are: guarantee baseline of ecological function, bottom-line in terms of environmental quality and safety, and maximum utilization of natural resources. These three types of areas need to be mapped at high spatial resolution, and used to provide clear guidelines for local government to use in coordinating priority areas for different agricultural production zones (or not, if there are vulnerable watercourses, habitats, heavy air pollution regions). There is opportunity to include spatial Nitrate and P Vulnerable Zones, as suggested by Bai et al (2018b), together with identified regions that are sensitive to ammonia emission and deposition (Bai et al. 2019), where specific management practices and permission to farm need to be prescribed. Through spatial co-ordination, and co-ordination across agriculture and environmental policies and targets, it should be possible to provide guidance to farmers and owners of livestock production facilities that promote sustainable agricultural production (e.g. via formal coupling of cropping and livestock systems) highlighting the co-benefits, and reducing the risk of unintended consequences (i.e. pollution swapping).

Top-down designation of the agriculture green production structure

There is an urgent need for the YRB to optimize the structure of crop and animal production systems, and to promote improved coupling of these sectors from the respective of increasing agricultural resource efficiencies, reducing environmental footprints and improving economic benefits. To fully understand the impacts of a new agricultural production structure on food production, multiple pollutants and biodiversity protection, a high-resolution spatial modelling framework that addresses the complex interactions between agriculture, the environment, biodiversity and delivery of wider ecosystem services, should be developed, to assist policy makers and local governments to prioritize land use for different outputs (agriculture, forestry, clean air, clean water, biodiversity/conservation). Scenarios of different spatial areas and intensities of grain and cash crops, monogastric and ruminant livestock production systems need to be assessed in terms of optimizing material flows, production efficiencies and minimizing impacts on the environment. These scenarios will need to consider the different soils, climates and topographies throughout the YRB, and may result in region-specific agricultural production structures, that still deliver agriculture green production. For example, the long-distance between livestock farms and cropland areas limits opportunity for manure transport and manure application on cropping land (Chadwick et al. 2020). Thus, it is important to determine the amount and species of livestock production based on the areas of available croplands and types of cereal or cash crops that could receive manure nutrients (Zhang et al., 2019a; Jin et al. 2020).

Bottom-up strategies

In addition to regional planning to promote AGD, specific technical management practices to improve crop and livestock production are needed in the YRB. Bottom-up strategies include integrated crop-soil systems and integrated crop-livestock systems, as described below.

Green crop-soil integrated production systems

A series of agronomic and breeding technologies should be developed and integrated to help farmers close the yield gaps in crop production with lower environmental footprints. Integrated Soil-Crop System (ISSM) is an approach to make maximum use of solar radiation and periods with favourable temperatures, and synchronize nutrient supplies from soil, environment and in season application with the dynamic demand of crop demand (Chen et al. 2011). Although ISSM has been shown to improve resource use efficiency in China, it relies on region- or site-specific conditions and currently ignores animal manure application (Cui et al. 2020). As mentioned earlier, because the area of cash crop production is high in the YRB, organic resources should be taken account in designing ISSM for the main crops grown in the YRB, e.g. citrus, tea and vegetables. Increased farm size has also been shown to improve nutrient use efficiency in China (Ju et al. 2016; Wu et al. 2018). Hence, designing optimized farm size, use of novel rotations and intercropping with integration of new crop varieties, new fertilizer formulations and green pesticides will be necessary for achieving AGD in the YRB.

Integrated and coupled (green) cropping and livestock production systems

Animal manure is associated with environmental pollution in the YRB (Strokal et al. 2016b), but it represents an opportunity for recycling nutrients for crop production, and is an excellent opportunity to meet the Zero Increase Inputs Policy target regionally (Chadwick et al. 2020). Retaining nutrients in manure and substituting chemical fertilizer by manure for crop production are key to improve integration of crop-animal systems (Zhang et al., 2019a). However, nutrient loss occurs throughout the different stages of the manure management chain (livestock housing, manure storage, manure processing and application), contributing significantly to the deterioration of soil, water and air quality. Many individual technologies have been proposed to mitigate these impacts (Cao et al. 2018). However, integrated technologies that include all stages should be developed on a regional basis. In particular, these technologies need to be cost-effective and applicable in the hilly and mountainous areas in the upper section of the YRB, as well as in the plains of the lower sections. To promote field-scale optimization of manure nutrient resources, a manure nutrient recommendation system should be developed, which takes account of differences in soil type, rainfall, crop species and manure types throughout the upper-, middle- and lower sections of the YRB (Chadwick et al. 2020).

Implementation of top-down and bottom-up AGD strategies

To fully achieve these two main strategies (top-down and bottom-up), monetary incentives (subsidies, payments for ecosystem services, access to loans) and policing (e.g. via fines) need to be coordinated across the region to promote positive action by government. These should promote adoption of new technologies that have been developed by researchers and new products produced by industries that support sustainable intensification of crop and livestock production (reducing the yield gaps via improved resource use efficiencies), reduce environmental losses (e.g. GHG and ammonia emissions, nitrate and P transfers to water, pesticides, plastic and antibiotics), and protect vulnerable habitats. To supplement this policy, a monitoring, reporting and policing system will need to be developed by cooperation between government, industry and researchers.

The adoption of new management practices for AGD will also require improved education and training of farmers, small-scale service providers, agricultural extension officers, livestock producers and local policy-makers about the concept of AGD and related high technologies and management practices. The Science and Technology Backyard (STB) programme is an example of a successful approach to communicate new management practices to farmers and promote adoption of these (Zhang et al. 2016b). This approach to knowledge exchange and farmer training has been effective in many parts of China, and could be rolled out across the YRB.

Conclusions

In this paper, we have reviewed the major challenges and strategies for the Agricultural Green Development (AGD) in the Yangtze River Basin (YRB). AGD in China is best delivered via a regional application, taking account of regional geoclimatic conditions, topography and natural ecosystems. The aims of AGD in the YRB are to achieve high production via resource-efficient farming systems, reduce environmental consequences and support healthy economies. We believe that this regional AGD approach for the YRB serves as an example for other global regions wanting and needing to transition from unsustainable agriculture production towards more sustainable resource-efficient production systems that are part of a wider land-use strategy that protects biodiversity and the environment. Importantly, the regional AGD approach can help deliver to Sustainable Development Goals (SDGs).

We have identified four main challenges for implementing AGD in the YRB. These challenges are (1) low agricultural productivity and nutrient use efficiencies, (2) uneven agricultural structure, (3) rapid urbanization, which causes increasing demand for animal-based food and environmental footprints of food production, and (4) uncoordinated targets for environment protection and agricultural production in the YRB, and have resulted in significant environmental pollution.

We have proposed AGD strategies for the YRB, based on an analysis of the key challenges. Our strategies are related to two complementary approaches: top-down and bottom-up. The top-down approach includes strategies such as the redesign of the structure of agricultural production coupled with improved spatial planning. The bottom-up approach includes strategies that promote adoption of existing technologies that can improve crop-soil and crop-livestock production systems. Examples of such technologies are ISSM for improved resource use efficiencies on farm, and the use of STB to promote new knowledge and encourage farmer adoption. We argue that realizing AGD will require the cooperation of all stakeholders (farmers, governments, extension bureaus, and advisors, educational institutions, researchers and industries) and cooperation across municipality borders and boundaries in the YRB. The insights of our review are useful for other global regions that are in transition from unsustainable agriculture production towards sustainable production systems that deliver a clean environment and healthy economies.

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