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Exploring Future Food Provision Scenarios for China

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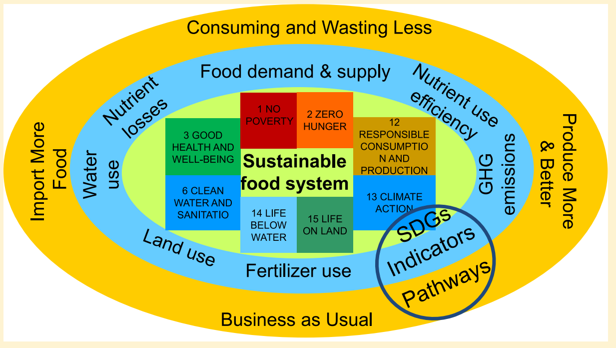
Supporting Information



ABSTRACT: Developing sustainable food systems is essential, especially for emerging economies, where food systems are changing rapidly and affect the environment and natural resources. We explored possible future pathways for a sustainable food system in China, using multiple environmental indicators linked to eight of the Sustainable Development Goals (SDGs). Forecasts for 2030 in a business as usual scenario (BAU) indicate increases in animal food consumption as well as increased shortages of the land available and the water needed to produce the required food in China. Associated greenhouse gas emissions and nitrogen and phosphorus losses could become 10−42% of global emissions in 2010. We developed three main pathways besides BAU [produce more and better food (PMB), consume and waste less food (CWL), and import more food (IMF)] and analyzed their impacts and contributions to achieving one or more of the eight SDGs. Under these scenarios, the demand for land and water and the emissions of GHG and nutrients may decrease by 7−55% compared to BAU, depending on the pathway followed. A combination of PMB and CWL was most effective, while IMF externalizes impacts to countries exporting to China. Modestly increasing feed or food imports in a selective manner could ease the pressure on natural resources. Our modeling framework allows us to analyze the effects of changes in food production−consumption systems in an integrated manner, and the results can be linked to the eight SDGs. Despite formidable technological, social, educational, and structural barriers that need to be overcome, our study indicates that the ambitious targets of China's new agricultural and environmental strategy appear to be achievable.

INTRODUCTION

Seventeen Sustainable Development Goals (SDGs) were approved by the United Nations in September 2015.[1] Food systems are linked to at least eight SDGs (1, no poverty; 2, zero hunger; 3, good health and well-being; 6, clean water and sanitation; 12, responsible consumption and production; 13, climate action; 14, life below water, 15, life on land). In short, achieving the specific targets embedded in these eight SDGs requires a more equitable distribution of nutritious food, more efficient use of resources, less pollution, and a drastic reduction of greenhouse gas (GHG) emissions and nitrogen (N) and phosphorus (P) losses. Success will therefore greatly depend on the organization and performance of food systems, particularly in those countries that account for the bulk of the global food system. Forecasts indicate that the demand for food will increase due to an increasing human population, while urbanization will lead to consumption of more resource-intensive food.[2] Unless drastic improvements are made in resource use efficiency and emission mitigation in our food systems, there will be increasing scarcity of productive land[3] and fresh water resources[4] as well as negative impacts on air and water quality,[5] biodiversity, and climate change.[2,6]

Transformative pathways toward more sustainable food systems are a global priority,[7,8] but policy makers and industry lack the tools and information to identify optimal choices.[9]

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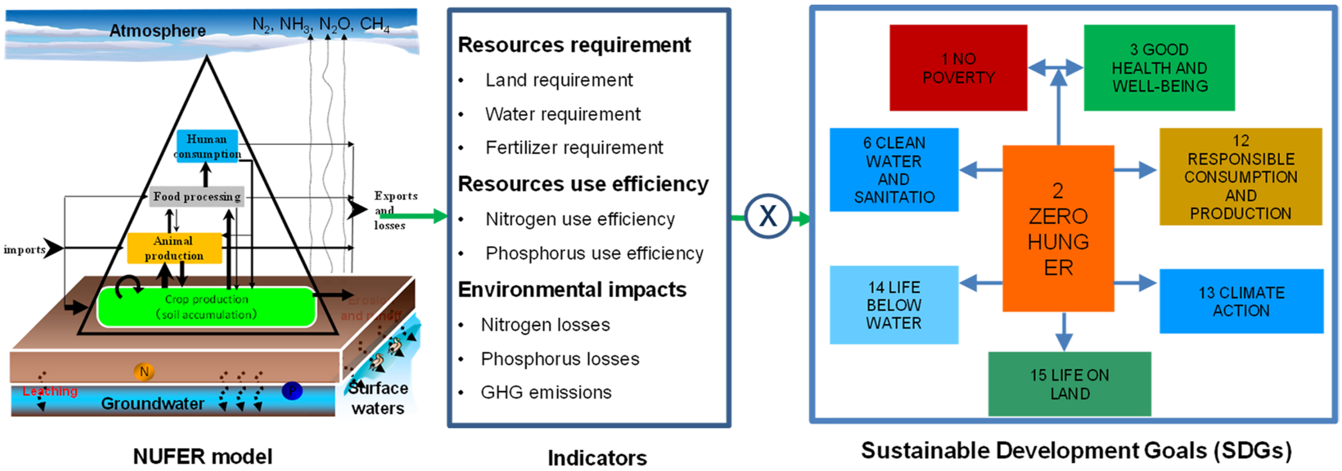

Figure 1. Linking the food production and consumption chain (left panel) to the Sustainable Development Goals (SDGs) (right panel) via a set of eight key indicators. Food production and consumption is central to at least eight SDGs (1 no poverty, 2 zero hunger, 3 good health and well-being, 6 clean water and sanitation, 12 responsible consumption and production, 13 climate action, 14 life below water, 15 life on land—hereafter SDG-8. SDG 2 is in the center). The NUFER model (Nutrient flows in Food chains, Environment and Resource use) was used to analyze the impacts of changes in the food systems. X means evaluation.

This is particularly problematic in food systems in emerging economies, which are extremely complex and are evolving rapidly over time due to the interacting effects of changes in demography, economic growth and technology development, urbanization, transnational corporations, and international trade.[9] These emerging economies are populous and large, including countries such as China, India, and Brazil and also countries in Sub-Saharan Africa. Transitions in the food systems of emerging economies have major global impacts because of the sheer size of their populations and relatively poor regulatory framework.[10,11] We argue that harmonized and quantitative analyses of possible pathways for transforming food systems will provide policy makers and industries with useful information for choosing actions to achieve more sustainable food systems.

With 19% of the world's population and a rapidly developing economy, changes in food production and consumption patterns in China have significant global implications.[12] China has increased both domestic food production and imports of both food and animal feed hugely during the past few decades in order to keep pace with the large increase in demand for food products.[12,13] Increases in food production have been accompanied by significant increases in inputs, including water, nutrients, and pesticides. Excessive inputs have, in turn, led to serious environmental damage as well as concerns about food safety and health.[14] Deterioration of soil, water, and air quality has become widespread throughout China.[15−19] These issues will become even more critical by 2030 without appropriate interventions.[11] The Chinese government has recognized the importance of sustainable food production and consumption. In March 2015, it published the "National Plan on Sustainable Agricultural Development 2015−2030", with five clear targets. Policy makers and scientists are now challenged to find the right solutions for achieving the ambitious targets of this plan, including, for example, a target to achieve further growth of agricultural production without further increases in the area of land, water, fertilizers or pesticides used from 2020 onward. However, there is a lack of quantitative analysis of the available pathways toward such a sustainable food system in China.

Here, we develop and apply a quantitative food chain approach to identify leverage points for principal interventions in the food production−consumption chain to be used at national and regional levels. Using this approach, the objectives were (1) to quantify food and resources requirements for China in 2030 and (2) to analyze the system and provide key suggestions for more sustainable food production and consumption systems.

■ MATERIALS AND METHODS

Concept of the Food Chain. The concept of a food system was formalized by sociologists decades ago.[20] Sobal et al. identified four major model concepts, food chain, food cycles, food webs, and food contexts, and developed a more integrated approach, the "food and nutrition system".[21] Recently, the concept was expanded in the context of food security and its interactions with global environmental change.[22] All of these approaches and concepts contribute to a qualitative understanding of the food production−consumption chain, but they do not provide quantitative insight. In this study, an analytical food system approach was developed to link food production and consumption and their wider environmental impacts.

Food systems consist of an interrelated set of compartments, here perceived as a "pyramid" with four main components (Figure 1), namely (i) crop production (including the rootable soil layer, i.e., the upper 1 m of soil), (ii) animal production (including managed aquaculture), (iii) food processing and retail, and (iv) households. These components are connected through flows of energy, carbon (C), and nutrients and virtual resources, i.e., land and water. Each component suffers losses of energy and C, N, P, greenhouse gases (GHGs), and other substances to the environment (Figure 1, left panel). We used eight indicators to assess the success of possible future pathways for food systems, i.e., land, water, and fertilizer N and P requirements, N and P use efficiencies, N and P losses, and GHG emissions (Figure 1, middle panel), and these were linked to the eight SDGs (Figure 1, right panel). We used the food-chain model NUFER (Nutrient flows in Food chains, Environment and Resource

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use) to analyze the current and possible future (year 2030) food systems in China.[23−25]

Modeling Food Requirements in 2030. The NUFER model quantifies land and water use, N and P flows and use efficiencies, and losses within the whole food production−consumption chain.[23−25] Seven main crop categories (rice, wheat, maize, soybeans, vegetables, fruits, and grassland; Figure S2) and six main animal product categories (pig meat, chicken meat, beef, mutton, eggs, and milk; Figure S3) were distinguished. These products were allocated to food, animal feed, industrial products, and food waste (Figures S2 and S3). In general, the main products are for consumption by humans, while the byproducts may be used as animal feed or soil amendment or are wasted. Most of the plant-based food byproducts are used as feedstuffs, such as rice chaff and wheat bran. In contrast, the byproducts of animal-based foods after processing are rarely used as animal feeds because of the risks of animal diseases such as foot and mouth. This explains in part why there is relatively more plant source than animal source byproducts used as feed (Figures S2 and S3). Allocation of the various products between food, animal feed, industrial products, and food waste were partially based on data from the FAO food balance and partially on surveys and publications on food utilization and waste in China (Tables S3−S7).

The consumption of plant- and animal-based food by rural and urban populations in 2010 was based on available statistics and literature data (Table S8). The projections of food requirements for 2030 were based on scenarios (described below). Feed requirements were estimated from the net energy and nutrient requirements of animals, as a function of animal category, production level and system, using the NUFER model (Table S9).[23−25]

Scenarios for the Food System in 2030. Six scenarios were developed to explore the effects of different possible food systems pathways. The assumptions related to the demand for domestic products per scenario are listed in Table S15 (crop production) and Table S16 (animal production).

The "business as usual" scenario (BAU) reflects the current Chinese diet. For this scenario, we assumed that there will be no changes in the diet of the urban population. However, due to rapid increase in incomes, we assume that the diets of rural and urban populations will have converged by 2030, with relatively more animal-derived food, vegetables and fruits being consumed overall. This will result in more intensive livestock, vegetable, and fruit production. As a consequence, more cereals (mainly maize and wheat) and beans (mainly soybean) will be needed as animal feed, because industrial livestock production relies highly on concentrated feeds. We assumed that the percentage of feed concentrates will increase by about 30% compared with 2010, since this corresponds to the historical rate of change in the proportion of ingredients in feed concentrates to the total animal feed intake between 1980 and 2010.

Scenario PMB (produce more and better) builds on BAU and includes substantial technical improvements in crop and animal production efficiencies. According to recent field studies, yields of rice, wheat, and maize could increase by 17%, 45%, and 70%, respectively, without using more fertilizer and other inputs[10,26] by adopting knowledge and technologies that are currently available. For soybean, vegetable, and fruit production, we assumed that crop yields could be increased by 25% relative to 2010 values.[27] Losses due to ammonia emissions and nitrate leaching can be reduced by 50%, following improved low-emission nutrient management technology.[28] Fertilizer rates used in vegetable and fruit production can be reduced by 30%, primarily by avoiding excess application of manure or synthetic fertilizers.[29]

In PMB, we expect that pig and broiler production will increase by 20% between 2010 and 2030 (Table S9). Furthermore, we expect productivity increases of 40% between 2010 and 2030 for beef cattle, dairy cattle, and laying poultry (Table S9). The performance of livestock production can be improved in China through a combination of better management of grazing systems, precision animal feeding (e.g., phase feeding in pig production,[30] total mix ration feeds in cattle production[31]), animal breeding (using high performance breeding boars and bulls), and improved herd, disease, and animal-housing management.

Significant amounts of animal manure are currently discharged into ponds and rivers[32] due to poor regulation and governance. However, the first regulations for manure management were released in 2013.[33] A recent study has indicated that N losses resulting from manure management could be decreased by 50%.[28] We assumed that the recycling rate of the nutrients in the manure (estimated via the percent of total manure produced that is recycled to crop land) will increase from 48% in 2005 to an average of 80% in 2030.

Scenario CWL (consume and waste less; i.e., healthier and less resource-intensive diets and reduced food waste) also builds on BAU; it was designed to estimate the effects of adopting the Chinese dietary guidelines (CDG), alongside a reduction of food losses and waste by 20%. On the basis of CDG, the consumption of meat will decrease and that of milk, eggs, beans, and fruit will increase compared with 2010. For CWL, we assumed that diets of both urban and rural populations will change to the recommended diet by 2030 (Table S9). Food wastes will be reduced by 20% through a combination of new technology, improved food storage facilities and education. As a result, the percentage of food produced that is consumed by humans will increase (Table S14).

Scenario PMB + CWL combines technology improvement (PMB) with dietary change and food waste reduction (CWL). It combines improvements on both the food production and consumption side.

Scenario IMF (import more food) also builds on BAU but assumes that much of the additional food required is imported from abroad. We assumed that the import of all plant-based and animal-based food and feeds will be 10% of total food demand in China in 2030, except for soybean and milk. In 2010, China imported 60% of traded world soybeans. For 2030, we assume that 84% of the total consumption of soybean in China comes from imports, based on the increase in imports between 2005 and 2010. Milk imports increased quickly after the melamine scandal in 2008. For 2030, we assumed that imported milk is 20% of total consumption in China based on the increasing imports recorded during the last 10 years (Table S9). These are likely to be conservative estimates, since China's soybean and milk import has continued to increase between 2010 and 2017.

Scenario PMB + CWL + IMF is a combination of scenarios PMB, CWL, and IMF. It represents a more integrated food system planning and management approach. In this, China would make large technical efficiency gains in food production, move toward healthier diets, and import feed and food items strategically to meet its overall food security goals.

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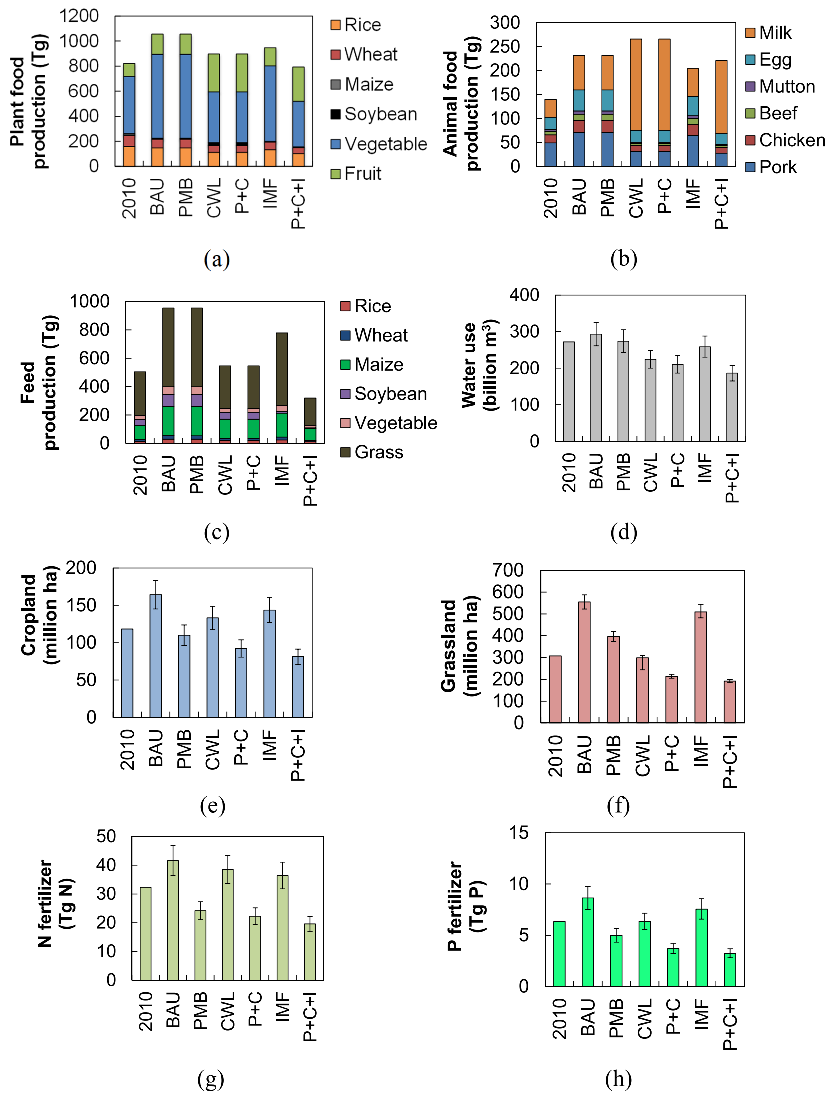

Figure 2. Demands for plant food (a), animal food (b), feed (c), fresh water (d), crop land (e), grassland (f), nitrogen fertilizer (g), and phosphorus fertilizer (h) in the food chain in China in 2010 and in 2030 for different scenarios. BAU: business as usual; PMB: Improvements of crop and animal production; CWL: diet change based on recommended Chinese dietary guidelines; IMF: Increased food and feed imports. P + C is the combination of PMB and CWL; P + C + I is the combination of PMB, CWL, and IMF. The error bars reflect the expected lowest and highest projections in 2030.

Our assumptions for the 2030 scenarios were adopted from peer-reviewed publications and are assessed as achievable and internally consistent. Recent studies indicate that crop yields and land, water, and nutrient use efficiencies can be increased greatly on smallholder farms in China through participatory research and extension.[34] However, it remains a challenge to reach the other 200 million smallholder farms. Assumptions related to improvements in animal production were based on several studies (Table S17) and on the rapid changes in livestock production systems during the last few decades.[35] Further, the NUFER model applies the mass balance approach throughout the food chain and thereby guarantees internal consistency.

Land Requirements. The total land requirement per crop in 2030 is estimated from the total food and feed demand and the average productivity per crop. Baseline average crop yields between 2008 and 2013 are derived from the FAO database (Table S9).[36]

Fertilizer Requirements. The N and P fertilizer requirements per crop in 2030 were derived from the total land requirement per crop and the average N and P fertilizer requirements per crop per hectare land. The average fertilizer N and P applications for different crops were derived from literature (Table S11).

Water Requirements. The water requirement for food production was derived from the water footprint of different agriculture products.[37] The water footprint is a measure of humans' appropriation of freshwater resources and has three components: blue, green, and gray water.[7,38] We expressed the blue water footprint as derived from water use by seven main plant-based products, including feed for livestock and food for humans (Table S11). The drinking and service water demand by animals and humans were not considered because these are relatively small compared to the blue water footprint of crops.[39]

Nutrient Losses and Nutrient Use Efficiency. The balances and use efficiencies of N and P of the food production–

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consumption chain, the gaseous loss of N via NH_3 and N_2O and N_2, denitrification and leaching, and runoff and erosion losses of N and P were calculated by the NUFER model.[23]

Greenhouse Gas Emissions. We estimated the non-CO_2 GHG emissions using the IPCC Tier 1 method. The CH_4 emission from rice production was estimated to be 43.5 kg CH_4 per ton of rice.[40] We assumed that 20% of the rice, wheat, maize, and soybean straw was burned with an emission factor of 4.6 g of CH_4 per kg burned straw.[40] The CH_4 emissions from enteric fermentation and manure management were derived from IPCC.[41] Both direct and indirect N_2O emissions from agriculture were calculated using the parameters listed in Tables S12 and S13 along with methodology reported in the relevant citations.

Contributions of China's Food System to the Global Food System. The contributions of China's food chain to the global food chain in terms of resource use and environmental impacts in 2030 were derived from a comparison of results from this study and results from the literature for the baseline years 2009/2010. Data for 2009/2010 were used, since there are no solid or widely accepted predictions for 2030 yet. At the global level, the N fixation (both industrial and biological) was 150 Tg N in 2009.[42] Reactive N losses from the global agricultural production systems have been estimated at 108 Tg in 2010.[43] The annual losses of P from freshwater systems into the ocean has been estimated at 22 Tg P at the global level.[42] The global area of agricultural land was 4893 million ha[36] and the annual blue water consumption was 2600 km^3 in 2009.[42] We used the global emissions reported by the IPCC for N_2O and CH_4, which were equivalent to 11 Gt CO_2 in 2010.[44]

Uncertainty Analysis. We used the Monte Carlo method to assess the uncertainty in resource use and emissions that result from the uncertainty in input parameters for food losses and waste management (Tables S3 and S4), as well as the uncertainty in food demand resulting from the uncertainty in population numbers expected in 2030 (Tables S15 and S16). Mean values and standard deviations were used to describe the distribution of input parameters in the random sampling procedure in the Monte Carlo simulations (Tables S4 and S5). There are also uncertainties in the assumptions underlying the suggested improvements in the food system (production, consumption and waste), but these are inherent to the scenarios and not considered further.

RESULTS AND DISCUSSION

Business as Usual. Both population (1.4−1.5 billion) and urbanization (60−80%) are expected to peak in 2030 in China.[27] If China follows current dietary trends (BAU), projected demands for animal-derived food, vegetables, fruits, and animal feed cereals and grass in 2030 will increase by 45% to 105% relative to 2010 (Figure 2a−c,f). In contrast, the direct consumption of cereals as human food will decrease by 14% (Figure 2), a compensating effect of the increasing consumption of animal products, vegetables, and fruits. The required areas for arable land and grassland will increase by a factor of 1.4 and 1.8, respectively, compared with the areas used in 2010.

A major challenge in this scenario will be satisfying the requirement for ruminant fodder (grass, alfalfa) because of the increasing size of the dairy cattle herd and the low productivity of Chinese grassland systems.[45] In addition, the demand for irrigation water and fertilizer nutrients will increase further (Figure 2d,g,h), especially in semiarid areas. The scarcity of fertile agricultural land and fresh water has already become severe over the last two decades[46,47] and will increase further in the BAU scenario.

Emissions of GHG from food production will increase by 28% in the BAU scenario. Total Nr losses will increase from 33 Tg to 46 Tg and P losses from 3.1 to 4.3 Tg between 2010 and 2030. These increases will have negative impacts on achieving SDG 13-climate action, SDG 6-clean water and sanitation, and SDG 14-life below water. NUE in the whole food system will decrease from 10% in 2010 to 8% in 2030 and PUE from 7% to 6% (Figure 3). By 2030, China's food system will consume around 30−45% of global fertilizer use and contribute 40% of global Nr losses, 16% of global P losses and 16% of global GHG emissions in the BAU scenario (Figure 4). Evidently, BAU is not a sustainable pathway.

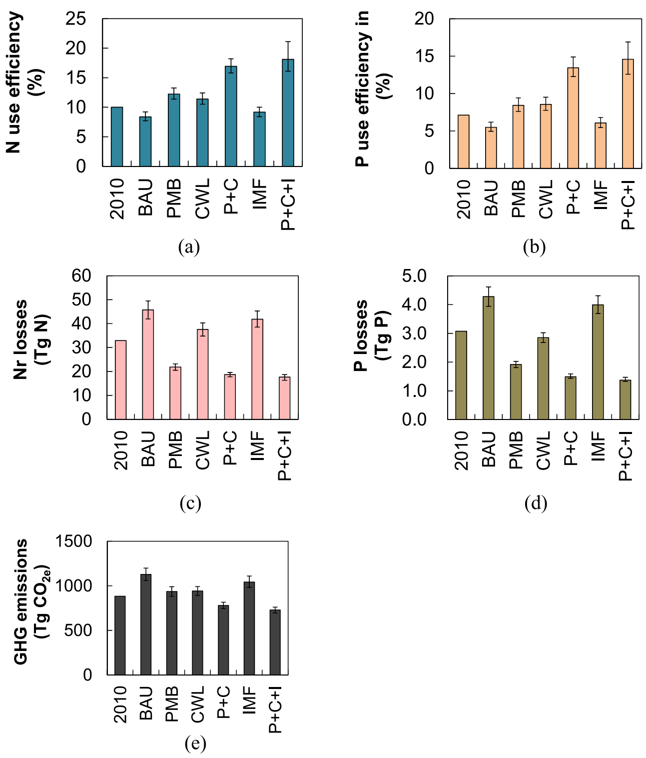

Figure 3. Nitrogen use efficiency (NUE, a), phosphorus use efficiency (PUE, b), reactive nitrogen losses (c), phosphorus losses (d), and GHG emissions (e) in the food chain in China for 2010 and projected for 2030 for different scenarios; BAU: business as usual; PMB: Improvements of crop and animal production. CWL: diet change based on recommended Chinese dietary guidelines; IMF: Increased food and feed imports. P + C is the combination of PMB and CWL; P + C + I is the combination of PMB, CWL, and IMF. The error bars reflect the expected lowest and highest projections in 2030.

Produce More and Better. In this scenario, the required cropland area will decrease from 164 Mha in BAU to 110 M ha in PMB as a result of increased productivity of both crop and livestock sectors. The required grassland area is expected to decline from 555 to 396 Mha (Figure 2). Increased crop yields and increased feed use efficiency in livestock production both contribute to achieve SDG2 (zero hunger) and SDG1 (end poverty). PMB is a powerful strategy to achieve food system related SDGs.

The increased crop and herd productivity will reduce total blue water consumption by 7% compared to BAU (Figure 2),

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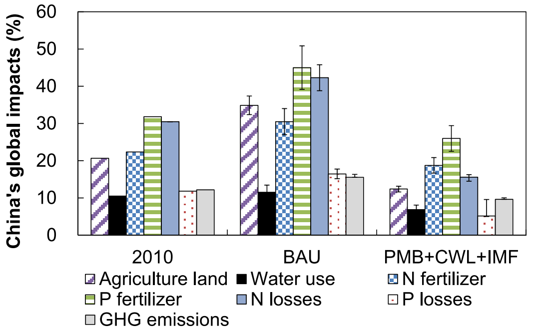

Figure 4. Relative contribution of China's food systems to the global food system in 2030, in terms of the uses of agricultural land, fresh water (blue water), N fertilizer, P fertilizer, and the losses of N and P and GHG, for the scenarios BAU and the combination of scenarios PMB, CWL and IMF. The error bars reflect the expected lowest and highest projections in 2030.

which will contribute to the alleviation of water scarcity.[47] Improvements in crop and animal productivity are associated with increases in NUE and PUE, and decreases of N, P, and GHG losses (Figures 2 and 3). This will contribute to achieving SDG6 (clean water) and SDG12−15. We do not project an increase in grassland productivity in PMB because most grassland in China has a natural character,[48] and about 90% has been degraded to a varying extent. However, sustainable grassland intensification remains an important area for further research and development.

The suggested improvements in the genetic potential of crops and animals, integrated soil-crop system management,[26] and integrated crop-livestock and manure management[28] may greatly improve the agronomic and environmental performance of the whole food production systems (Table S18). Such improvements have been achieved already in field experiments, experimental farms, and millions of small household farmers[34] but will require further integration, testing and upscaling through, for example, the Science and Technology Backyard program.[49] This requires the joint efforts of policy makers, researchers, extension services, farmers, citizens, industry and market organizations (Table 1). Chinese agriculture is already entering a transition from the current system dominated by small-holder farms to larger farms, which may enable better knowledge and technology transfer and provision of professional services.[11]

Consuming and Wasting Less. Diet manipulation and reducing food wastes are key pillars of the CWL scenario. In CWL, consumption of milk products will increase by 413%, but consumption of eggs, meat, and cereal-derived food products will decrease by 4%, 34%, and 35%, respectively, relative to 2010 (Figure 2). In comparison to BAU, this would result in a significant reduction of the requirements for cropland (19%), grassland (46%), N fertilizer (7%), P fertilizer (26%), and water (23%) in agriculture. Meanwhile, GHG emissions will decrease by 17%, and nutrient use efficiencies of the whole food system will increase from 8.4 to 17% for N and from 5.5 to 13% for P (Figure 3). These results are consistent with other findings, which indicate that dietary change can mitigate GHG emissions and benefit public health in China.[50,51] The CWL scenario directly contributes to achieving SDG2 (zero hunger) and indirectly and to SDG6 and SDG12−15. Implementing CWL requires removing the range of social barriers, listed in Table 1.

Combinations of PMB and CWL. Together, these have positive impacts on human health, resource use efficiency, and environmental sustainability (Figure 3) and might alleviate land and water scarcity.[46,52] The demand for arable land under combinations of these scenarios will reduce from 164 to 127 million ha and the demand for blue water use will reduce from 293 to 197 billion m^3 (Figure 2). This will contribute to achieving the targets of the National Plan on Sustainable Agricultural Development 2015−2030. The land saved could be used for ecological preservation.[52] The demand for N and P fertilizers will reduce to 23 and 5.5 Tg, respectively, which equals 21% and 26% of the world total N and P consumption in 2015.[36] These projected reductions will help to fulfill China's central government's target of zero fertilizer increase

Table 1. Action Plan for More Sustainable Food Production and Consumption in China

levers/barriers	actors	increasing crop productivity and resources use efficiency	increasing animal productivity and resources use efficiency	more healthy diets and reducing food wastes and losses
levers	policy makers	incentives for more sustainable cropping systems and for improved management and technology	incentives for land- and pasture-based animal production systems	incentives for choosing healthy diets and for reduction of food wastes
		enforcement of soil, water and air quality standards and regulations	incentives for improved manure management and technology	enforcement of soil, water and air quality standards and regulations
			enforcement of soil, water and air quality standards and regulations	
	researchers and extension services	design and development of high-yielding and sustainable cropping systems	design and development of high-yielding and sustainable animal production systems	research linking nutrition, diet, food wastes and behavior
		clear information and sound extension services	clear information and sound extension services	clear information and sound extension services
	farmers and citizens	innovative networks and achieving targets	innovative networks and achieving targets	innovative networks and achieving targets
	industry and market	optimized logistics and increased utilization of wastes	optimized logistics and increased utilization of wastes	facilitation of consumers associations, to reduce food wastes
		development of site-specific technology	development of site-specific technology, especially for manure utilization	
barriers		lack of entrepreneurial skills	shortage of land for feed production	western influence on food habits
		lack of education risk aversion	lack of experience with integrated crop-animal production systems	lack of political willingness to influence consumption patterns
		number and age of farmers	upscaling of innovative designs. management and technology	
		upscaling of innovative designs, management and technology		

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from 2020.[53] The formation of PM2.5 in air and water pollution will be reduced by 61% and 66%, respectively compared to BAU (Figure 3), and will fulfill China's target on controlling air and water pollution.[54,55]

Import More Food. If the food and feed demand in 2030 cannot be met through domestic production, despite the PMB and/or CWL interventions, food and feed imports may have to increase (or diets will have to change further). In the IMF scenario, it was assumed that food and feed imports will increase by 10%. This will decrease the required areas of domestic cropland and grassland, the demand for N fertilizer, as well as the water footprint and GHG emissions by 7−11% compared with those in BAU (Figures 2 and 3). This would help to achieve SDG12−15 in China.

However, large increases in food and feed imports may distort international trade balances, increase the environmental impacts of food production in exporting countries, and increase the dependency of China's food system on imports.[56] The rapid economic growth and changes in diet during recent decades has led to greatly increased soybean imports from Latin America, which in turn has contributed indirectly to the deforestation in the Brazilian Amazon.[57] The import of maize and soybean to China accounted for 6% and 58% of the global trade of these commodities in 2010.[36] In recent years, China has also emerged as a significant importer of dairy products, commodities with a thin global market base.[58] Further increases in agricultural imports may have further negative consequences for food security and environmental costs elsewhere.[56] We argue that IMF alone cannot be a sustainable pathway for large countries, especially in an era of increasing trade conflicts throughout the world.

Toward a More Sustainable Food System. A targeted combination of PMB, CWL, and IMF would result in the greatest reduction in the impact of China's food system on resources use, emissions of N, P, and GHG emissions at a global level (Figure 4). Various technologies for increasing productivity, resource use efficacy, and waste recycling have already been developed and tested (Tables S17 and S18). The adoption of improved technologies in practice will require coordinated effort across different stakeholders and sectors (i.e., policy makers, researchers, extension services, farmers and citizens, industry, and market organizations) at several points in the food chain if we are to achieve transformative change (Table 1). Such a coherent strategy must include (1) incentives to adopt improved agronomic practices and technologies, (2) incentives to support land-based animal production and pasture-based livestock systems, so as to improve manure management and meet water quality standards (which is included in the new Environmental Protection Law of China, EPL), (3) subsidy reforms to ensure that subsidies reach their target stakeholders, and (4) education and policies that promote a healthy diet and reduction of food waste. Implementing such a strategy also commits China to sound monitoring and evaluation so as to assess the impacts of action and to be able to adjust the strategy in a proactive, evidence-based manner, taking account of constraints and barriers (Table 1). Despite significant challenges, our analysis suggests that, in principle, the ambitious targets embedded in China's new agricultural and environmental strategies appear to be achievable through an integrated transformation of the whole food system.

However, there are large spatial variations within China that have not been addressed by our national-scale analysis. Different regions face different key challenges related to food security (such as resource scarcity and environmental pollution), which suggests that specific regional strategies will have to be developed and implemented. For example, identify zones that are more vulnerable to nitrogen and phosphorus loss than others in order to help control water pollution.[55] In these zones, stricter environmental control policies would be implemented than in other regions. Hence, additional high-resolution spatial analyses are needed to explore pathways for sustainable food system for different regions.

Whole Food Chain Approach. Our modeling framework permits the analysis of the effects of changes in the food production-consumption system of China in an integrated manner, and the results can be linked to 8 SDGs. Our analyses also help to identify knowledge gaps and priority innovations. The approach might be applied to other emerging economies, such as Brazil and India, which face comparable changes in demography and rapid urbanization as in China.[59,60] The necessary input data and parameters can be easily derived from FAO database and literatures. Transformative pathways toward more sustainable food systems that simultaneously increase nutritious food production and consumption, and enhance resource use efficiency and environmental quality are a particular priority for emerging economies. Future studies should address also economic and health effects.[60]

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.est.8b04375.

Detailed calculation methods, tables of additional data (Figures S1−S5, Tables S1−S18, and references and notes) (PDF)

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Notes

The authors declare no competing financial interest.

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