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EDITORIAL

INTEGRATING CROP AND LIVESTOCK PRODUCTION SYSTEMS—TOWARDS AGRICULTURAL GREEN DEVELOPMENT

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1 INTRODUCTION

This special issue contains a collection of papers dealing with various aspects of Integrating livestock and crop production systems in different parts of the world. Drafts of some papers were presented and discussed at a 2-day international workshop in Quzhou, Hebei, China, during October 9–12, 2019. The workshop was combined with a 2-day field trip to visit dairy and poultry farms and rural villages in Hebei. The workshop was organized by the National Academy of Agriculture Green Development of China Agricultural University. There were 13 Chinese and 11 international scientists (from five continents) and 20 Chinese postdoctoral researchers and PhD students participating in the workshop.

The objectives of the workshop were (1) to discuss experiences with integrated/integrating crop and livestock production systems across the world, (2) to discuss institutions, markets and technologies needed for integrating crop and livestock production, and (3) to discuss and identify knowledge gaps, and to explore opportunities for joint research.

Integrating livestock and crop production systems is one of the four research themes of the National Academy of Agriculture Green Development of the China Agricultural University in Beijing. The overall objective of this research theme is “*To lay the scientific foundation for integrating crop and livestock production systems in China, which are (a) productive and competitive, (b) ecologically sound and (c) accepted by the society*[1].” The research theme reflects the need of developing more sustainable livestock production systems in China, where the changes in livestock production have been huge over recent decades[2,3]. Livestock production has strongly increased, and production systems have dramatically changed over the last 20 years (Fig. 1). The dependence on feed imports has greatly increased, while manure management practices pollute the environment, and biosecurity is often at stake. Integrating livestock and crop production systems is seen as a way to develop more sustainable livestock and crop production.

This editorial briefly explains the broader background of the workshop, and summarizes the main experiences of participants with integrating crop and livestock production systems. In addition, it briefly summarizes the outcome of a survey of participant’s views on integrating crop and livestock production systems.

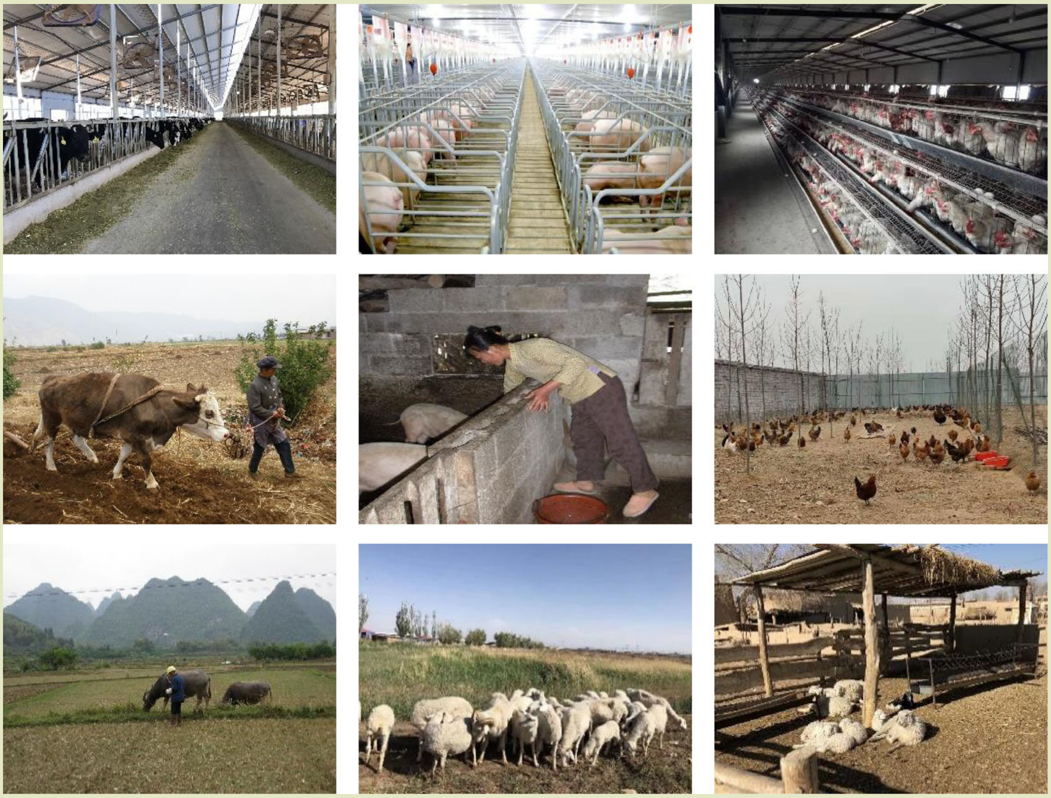

Fig. 1 Photos of mixed crop-livestock systems, household systems and specialized livestock in China.

2 MIXED CROP-LIVESTOCK PRODUCTION SYSTEMS HAVE BEEN GLOBALLY PREDOMINATE

Crop and livestock products provide more than 95% of all the food consumed by the global human population, with the remainder provided largely by fisheries. The production of crops and livestock has developed since the advent of agriculture some 10,000 years ago, and has resulted in a bewildering diversity of farming systems and practices, which are adapted to the prevailing local environmental, cultural and socioeconomic conditions[4,5]. The diversity in farming systems and practices contrasts with the limited number of plant and livestock species that have been domesticated over that time (Box 1).

Some have argued that following the original transition from hunter-gatherers to agriculturalists, arable farmers and livestock producers operated specialized farming systems[11]. A more common view is that crop and livestock production are both intimately linked to household needs in agrarian societies. In these mixed farming systems, or crop-livestock production systems, both crops and livestock provide the

Box 1 Domestication of plants and animals

Only about 100 out of 200,000 wild species of higher plants have yielded valuable domesticates, and only 14 out of 148 large terrestrial animals, weighing 45 kg or more, have been domesticated[6,7]. In practice, just three plant species (wheat, rice and maize) and just three animal species (cattle, pigs and poultry) predominate in current crop and livestock production systems; these species together provide more than 60% of all energy and protein intake by humans[8]. The success of these species is related to their high yield potential, nutritive value, versatility and to globalization. The increasing homogeneity of food sources has been implicated in decreasing the genetic resources, and is seen as a risk for future food supply[9,10].

food for the households, while leftovers from the household and the residues from cropland are used to feed the livestock. Livestock may also scavenge feed from the farmyard and communal lands. Surpluses of food are marketed (and/or taxed) to obtain other goods and services. In addition to providing livestock-source food, livestock in many agrarian societies also provides manure, wool and leather, and may perform tasks (transport, plowing) and serve as a savings bank. The manure can be used for construction, as biofuel or as a soil amendment or fertilizer. Over time, a huge diversity of crop-livestock systems have developed that produce about half of all the food across about two-thirds of the farmers in the world in the 2000s[12–14]. Farmers in mixed farming systems are most numerous in agriculture, but the agricultural area cultivated in mixed farming systems has rapidly declined over the last few decades, although there are large differences between countries[15]. The advantages and disadvantages of mixed crop-livestock farming systems depend very much on the local environmental, socio-economic and cultural context, and on the perception of stakeholders (Table 1).

The transition from hunter-gatherers to agriculturalists is commonly called the first agricultural revolution[4]. It has dramatically changed the world; almost all food is now derived from agriculture, and hunter-gatherers have almost vanished. A second agricultural revolution took place concomitant with or preceding the industrial revolution in the seventeenth to twentieth century, especially in Europe and North America. This revolution was associated with a doubling in crop and labor productivity through the introduction of crop rotation, growing legumes, improved breeds, improved plows, and land reclamation[4]. As a consequence, the population doubled, the labor surplus in agriculture became available for the industry and cities rapidly grew in population. However, this revolution was not so strong outside Europe and North America, and did not greatly affect the nature of mixed farming systems in other continents.

The Green Revolution in the second half of the twentieth century is commonly called the third agricultural revolution, and greatly influenced the nature and practices of many mixed farming systems across the world, although not as strongly in central Africa, parts of central Asia and South America[16]. The Green Revolution consisted of packages of practices including high-yielding cereal cultivars, mineral fertilizers, pesticides, improved irrigation and mechanization, combined with support programs[17,18]. As a result, cereal yields doubled or tripled, allowing the human population to rapidly grow further. Indirectly, it affected the nature of mixed farming systems, because mechanization made draft animals unnecessary and mineral fertilizers made animal manure unnecessary in crop production. Further, massive amounts of cheap cereals became available as high-density and high-quality animal feed.

The Green Revolution paved the way for the Livestock Revolution; a concept introduced by Delgado et al.[19] who identified a number of drivers for and characteristics of the Livestock Revolution: (1) rapid increases in the demand of livestock products together with increased substitution of grain and other staples for meat and milk in the human diet, especially in rapidly developing countries; (2) the emergence

Table 1 Advantages and disadvantages of mixed crop-animal systems compared to specialized crop and specialized livestock production systems[11]

Advantages	Disadvantages
Greater buffer against market price fluctuations	Greater requirement of expertise (double expertise needed)
Greater buffer against climate fluctuations	Greater investment in diverse equipment
Greater nutrient recycling due to more direct soil-crop-animal manure relations	Less opportunities for benefiting from economies of scale
More diversified income sources	
More consistent labor demand	
Better weed and disease control	
Alternative use for low-quality roughage	
Greater sources of security and savings	
Greater investment options	
Greater social functions	

of rapid technological change in livestock production and processing in industrial systems; (3) rapid rise in the use of cereal-based feeds; (4) ongoing change in the status of livestock production from a multipurpose activity with mostly non-tradable output to food and feed production in the context of globally integrated markets; and (5) increased stress on grazing resources along with more land-intensive production closer to cities. The Livestock Revolution strongly increased livestock and labor productivity in livestock production, and thereby increased total livestock production and decreased the cost of animal-derived food production[20].

The Green Revolution and Livestock Revolution together paved the way for the specialization, intensification and upscaling of crop and animal production around the world. These drivers of production increases have indirectly contributed to the spatial decoupling of specialized crop production systems and specialized livestock production systems. The spatial decoupling of specialized crop and livestock production systems is also related to location-specific (cost) advantages of crop and livestock production, and to low transport costs. Intensive livestock production systems are often located near urban areas, and source animal feed from elsewhere. About one-quarter of all crops produced in the world are now traded internationally, to satisfy the demands of the human and livestock populations in and around urban areas[21–23].

Table 2 presents estimates of the percentages of total milk, beef, pork, poultry meat and eggs produced in grazing systems, mixed farming systems, and intensive systems in 2010. Evidently, most cattle milk and beef were produced in mixed farming systems and grazing systems. This holds also for sheep and goats (not shown). Slightly less than half of all pork was produced in mixed farming systems, and slightly more than half in intensive systems. In contrast, well under 10% of poultry meat and eggs were produced in mixed farming systems, and more than 90% in intensive systems. The proportions change slightly when expressed as the number of animals in the various systems; for example, 62% of the total number of pigs were kept in mixed systems and 38% in intensive systems in 2010 (not shown). Clearly, the influence of the Green and Livestock Revolutions on specialization in the livestock sector decreased in the order poultry sector > pork sector > cattle sector. The strong influence on the poultry and pork sectors is also reflected in the changes in the number of animals in the world over the last 20 years; the number of cattle and pigs increased more or less linearly over time, while the number of chickens increased exponentially (Fig. 2).

Globalization, i.e., the spread of products, technology, information, habits and culture across national borders, has strongly influenced intensive crop and animal production systems, but differentially for different systems. The breeds, technology and production performance in intensive broiler farms in Brazil are now similar to those in China, India, Turkey and the USA, because only a few transnational corporations own, contract, and/or manage these production facilities. However, production costs, and environmental and veterinary constraints may differ between countries and that affects the competitiveness of the different countries[25]. The highly productive (per animal and unit of labor) and efficient (in terms of feed and land use) poultry factory-farms have, over the last few decades, almost completely outcompeted the raising of poultry in mixed farming systems[26] (Table 1).

The report *Livestock's Long Shadow* highlighted that current livestock farming practices place severe pressure on the environment, through emissions to air, water and soil, and through the utilization of natural resources, including land, water and fossil energy[27]. There are also concerns related to the risks of zoonotic diseases, the excessive use of antibiotics, and animal welfare. Various measures and pathways have

Table 2 Relative share of the production of livestock products in grazing (including pastoral and commercial grazing systems), mixed crop-livestock (including mixed, household and intermediate systems) and intensive systems (including industrial systems and feedlots) in 2010 (source: HLPE, 2016[24])

Livestock products	Grazing systems (%)	Mixed systems (%)	Intensive systems (%)
Cattle-milk	32.5	67.5	n.a.
Cattle-beef	30.7	57.1	12.2
Pork	n.a.	43.8	56.2
Chicken-meat	n.a.	1.8	98.2
Chicken-eggs	n.a.	7.9	92.1

Note: n.a. means not applicable.

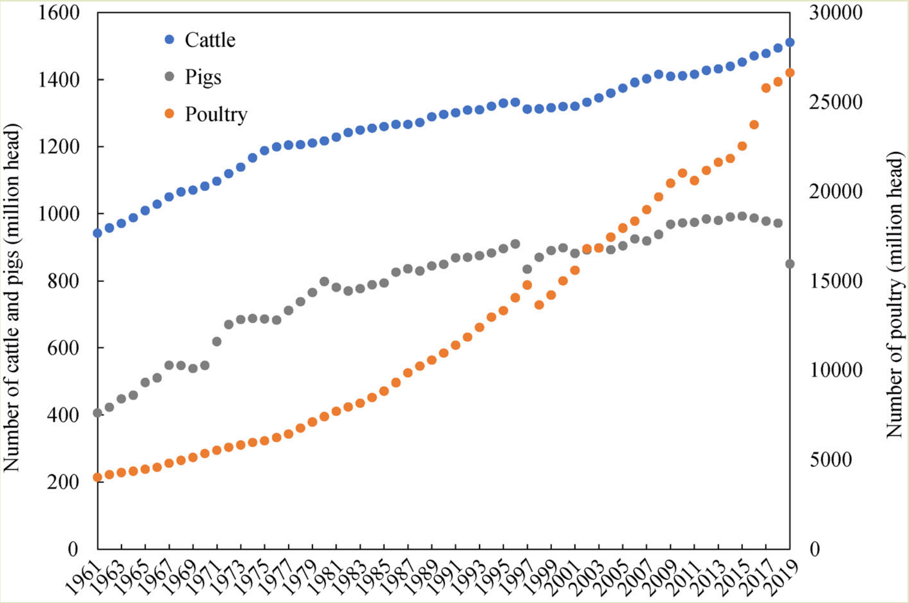

Fig. 2 Changes in the total stock number of dairy and beef cattle, pigs and poultry in the world from 1961 to 2019 (source: FAOSTAT).

been suggested to address these concerns. Governments and the livestock sector in, for example, some European countries strive for a low-emission and highly productive/efficient livestock farming, mainly through technical solutions. Others argue that mixed farming systems must receive greater support, for many reasons[12,15,28]. A decrease of the consumption of animal-derived food by especially people in affluent countries is also seen as a possible solution[29,30].

3 CROP-LIVESTOCK PRODUCTION SYSTEMS IN CHINA

Food security and food self-sufficiency have been high on the political agenda in China, ever since the Great Chinese Famine from 1958 to 1962, which the elderly still remember. As a result, the government has strongly supported the modernization of agriculture over the recent decades, especially after the opening-up policy in the 1980s. The government has also initiated programs to control the size of the rapidly growing population from the 1970s (one-child policy), which was most strictly enforced in densely populated urban areas. This policy aimed at reducing food demand and alleviating poverty, has reshaped demographic characteristics (Fig. 3). The policy has been relaxed stepwise, and from 2015 all families are allowed to have two children. Impacts of the one-child policy have been debated intensely[31]; China has now the largest population in the world (nearly 1.4 billion), and on average less than 0.1 ha of cropland per person.

Government support programs have been successful for increasing crop and animal productivity. The percentage of undernourished people has decreased steadily over time, to less than 3% in 2020. Wheat, rice and maize production have increased and vegetable and fruit production have strongly increased (Fig. 4). The production of pork, poultry, beef, mutton and fish (mainly from aquaculture) also has strongly increased (Fig. 5). China became the largest producer and consumer of pork, poultry, wheat, rice, vegetables and fruit in the world during the 2010s. The 200 million Chinese farmers (with average farm size of 0.5 ha) provide almost all food for the 1.4 billion inhabitants, although an increasing proportion of the animal feed (notably soybean, maize and alfalfa) and an increasing proportion of animal-derived food (notably milk, beef and pork) has been imported in recent years (Fig. 6). The increasing import of animal feed and animal-derived food is related to the increasing prosperity of an increasing proportion of the population; the percentage of animal-derived protein consumed has been steadily increasing over the last few decades.

The land area and the amount of animal feed needed to produce 1 kg of animal-derived food has greatly decreased

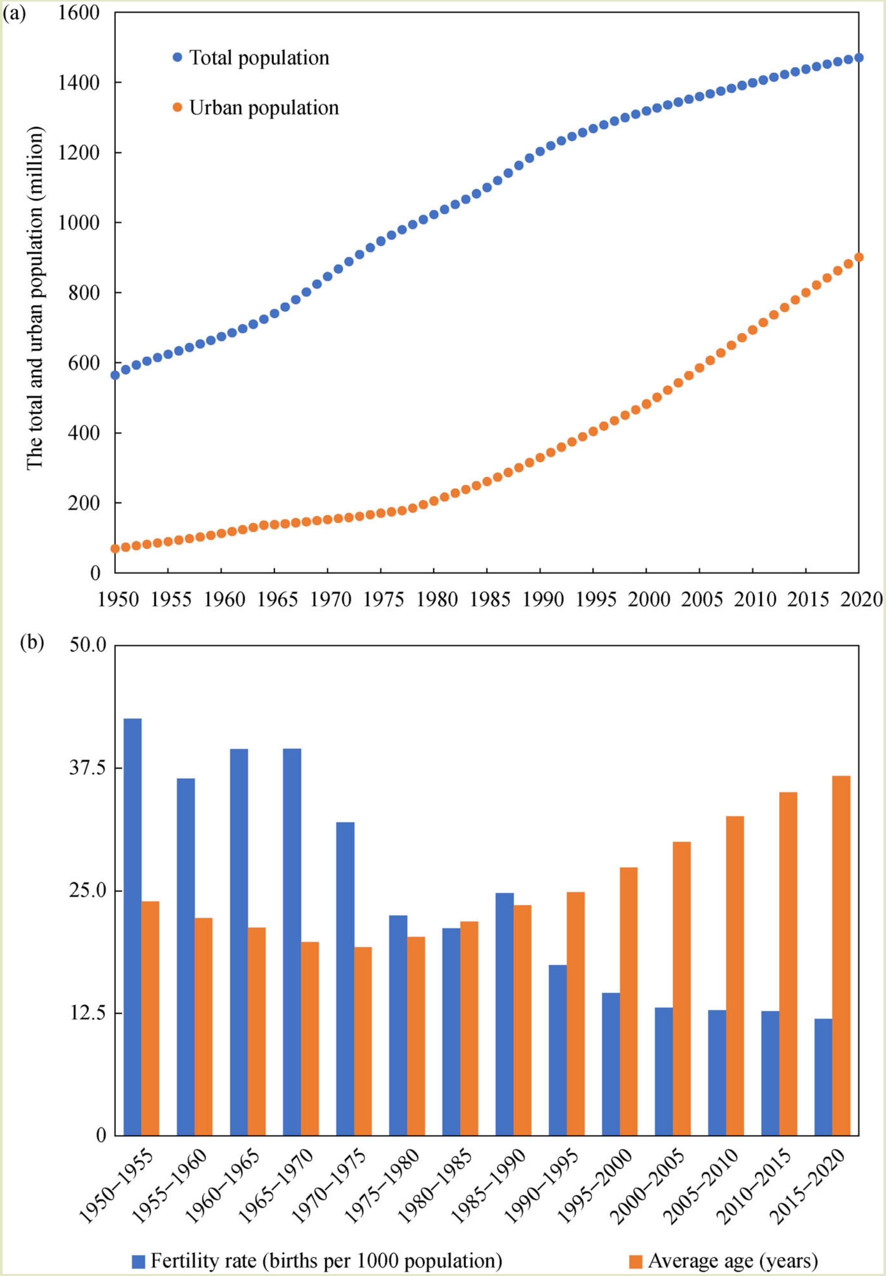

Fig. 3 Changes in the total population and urban population in China (million) (a), and fertility rate (births per 1000 population) and average age (years) (b) from 1950 to 2019 (source: United Nations, Department of Economic and Social Affairs, Population Division. World Population Prospects: The 2020 Revision).

over the last few decades[2]. Emissions of greenhouse gases (CO_2, CH_4 and N_2O) and nitrogen and phosphorus per kg of animal-derived food have also decreased, while the N and P use efficiencies at herd levels have increased. This indicates that animal productivity and the efficiency of resources use at herd levels have markedly increased over the last few decades. However, the total feed use, and the total emissions of greenhouse gases, N and P to the environment have strongly increased in livestock production[2]. Livestock production has become a main polluter of surface waters, especially in the eastern provinces where livestock densities are the highest (Fig. 7).

Concomitant with the rapid economic development in

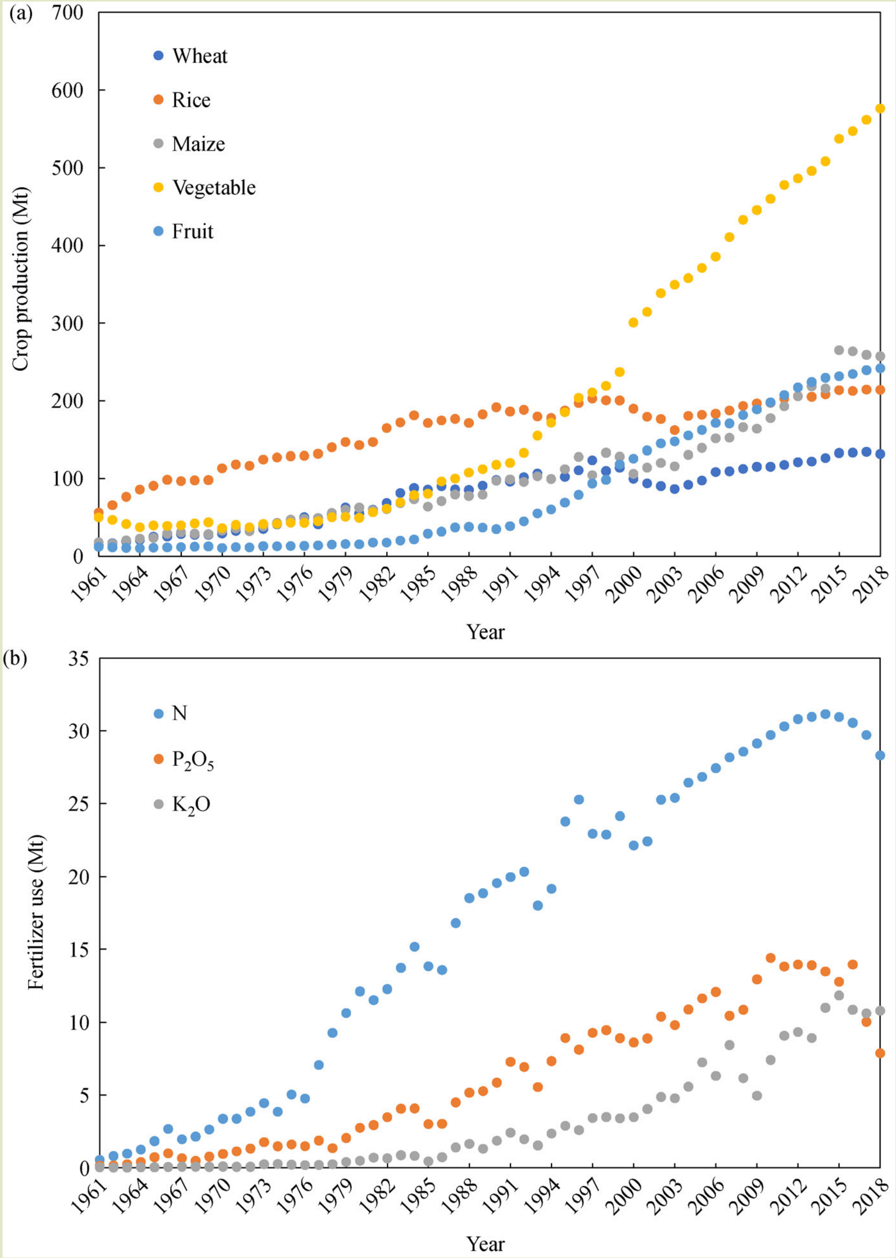

Fig. 4 Changes in total production of wheat, rice, maize, vegetable and fruit (in Mt per year) (a), and in mean fertilizer nitrogen, phosphorus (P_2O_5) and potassium (K_2O) use in China (in Mt per year (b) from 1961 to 2018 (source: FAOSTAT).

industry and agriculture, rapid changes also occurred in farming systems and practices, especially between 1980 and now. Stratified, regular surveys of more than 20,000 rural households from 1984 to 2018 reveal major trends[3]. The percentage of mixed crop-livestock farms decreased from about 71% in 1986 to about 12% in 2018. Most of these mixed crop-livestock farms had only few head of livestock. In the same period, the percentage of specialized crop farms increased from about 25% to 55%, the percentage of households without cropland and livestock increased from about 2% in 1984 to 35% in 2018, while the percentage of specialized livestock farms remained more or less constant at a level of about 1% to 2%. Large intensive (industrial) livestock farms were not included in these surveys; the percentage of industrial farms is reported to be less than 1% of the farms with livestock. Yet, these industrial farms were

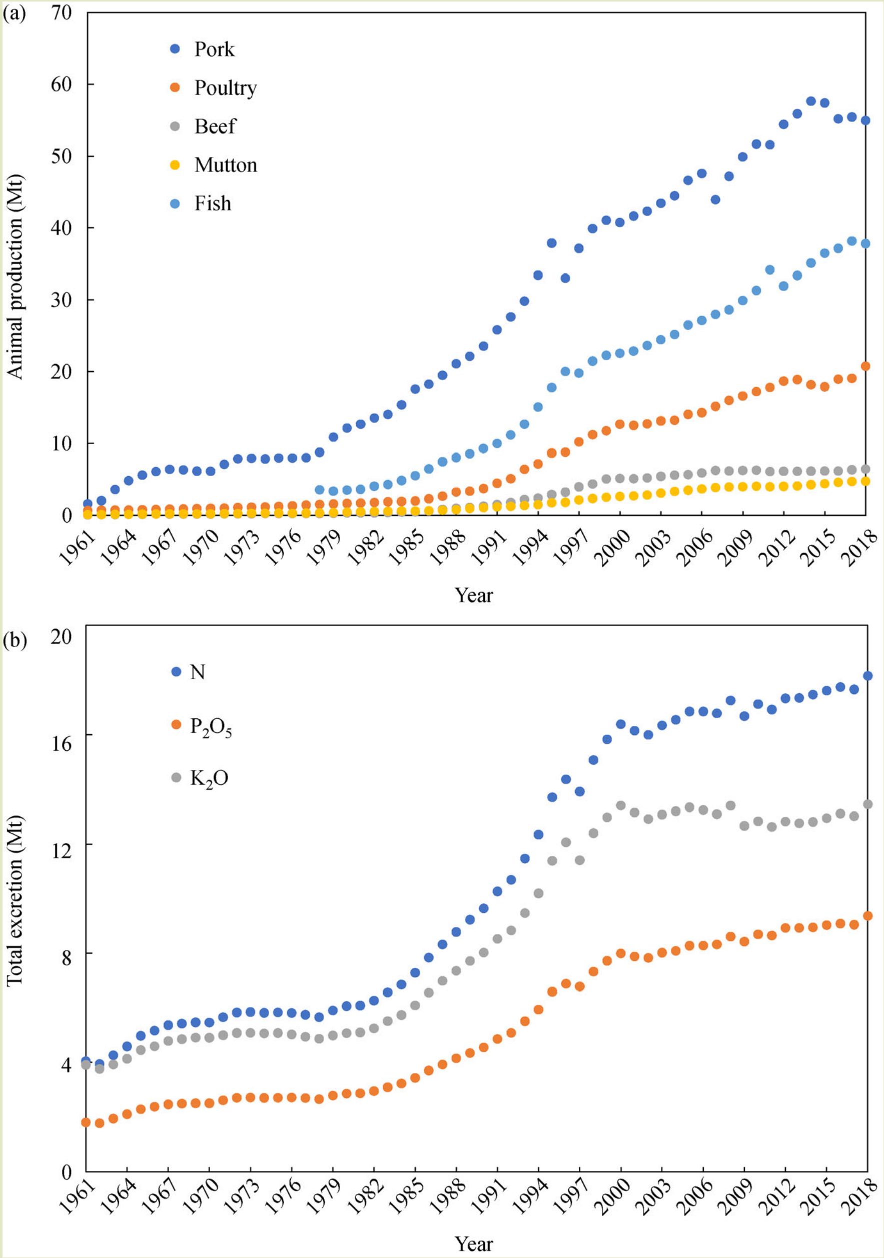

Fig. 5 Changes in the total production of pork, poultry, beef, mutton and fish (in Mt per year (a), and in total excretion by livestock of manure nitrogen (N), phosphorus (P_2O_5) and potassium (K_2O) in China (in Mt per year) (b) from 1961 to 2018 (source: calculated from FAOSTAT).

reported to produce 65% of all pork, 70% of all milk, 80% of all beef, 80% of all mutton, 40% of all eggs, and 30% of all broiler meat[3]. The authors plea for recoupling of livestock and cropland to address the substantial livestock-related environmental pollution, which was inferred from the low use of manure in cropland. Recoupling of livestock and cropland is also seen as measure to reduce the large mineral fertilizer use, through substitution for manure.

Government policies and subsidies have been a major driver for the livestock transition in China over the last three decades, next to the growth of the population, the economy, and urbanization (Fig. 3). Three types of policy positions have been important[2]. First, the liberation of markets and removal of barriers for producers and consumers. Second, the economic incentives for livestock producers, processing industry and retail that strongly promoted industrial

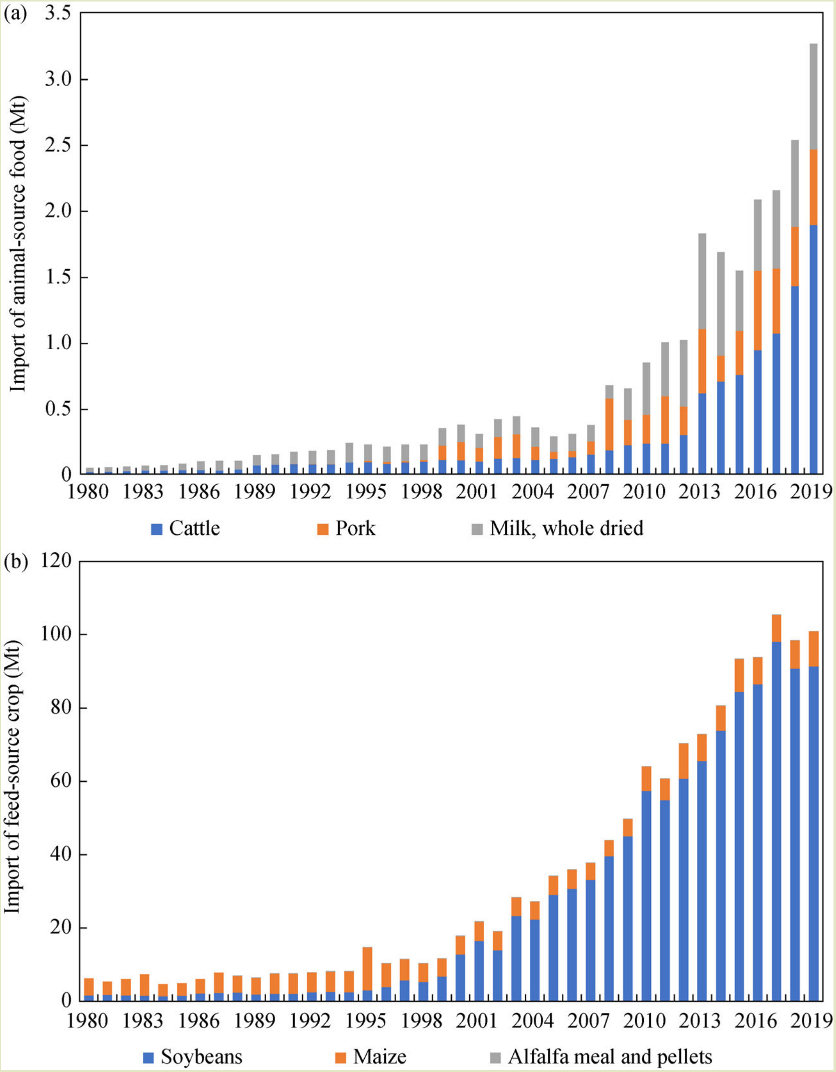

Fig. 6 Changes in the import of animal-source food (milk powder, cattle beef and pork) (a) (in Mt per year) and the import of feed-source crop (soybean, maize, alfalfa meal and pellets (b) in China from 1980 to 2019 (source: FAOSTAT).

livestock farms around cities, and facilitated the processing and transport of animal products. Third, the loose environmental protection regulations, which indirectly boosted large-scale and landless livestock production with poor manure management.

Scenario analyses for 2050 suggest that the consumption and production of animal-derived food will continue to rise[2]. As a consequence, total feed demand and total emissions of greenhouse gases, N and P to the environment will continue to rise further in livestock production, unless drastic improvements are made. Four main proposal have been made for achieving a more sustainable livestock production[2]: (1) targeted spatial planning of livestock production, (2) coupling of crop and livestock production, (3) improved grassland management and concentrate feed production, with reduced competition with human edible food, and (4) improved manure management. Evidently, recoupling of crop and livestock production is a key recommendation in several studies[2,3].

4 OVERVIEW OF THE SPECIAL ISSUE

This special issue contains nine papers that were also presented at the workshop in Quzhou and six papers from

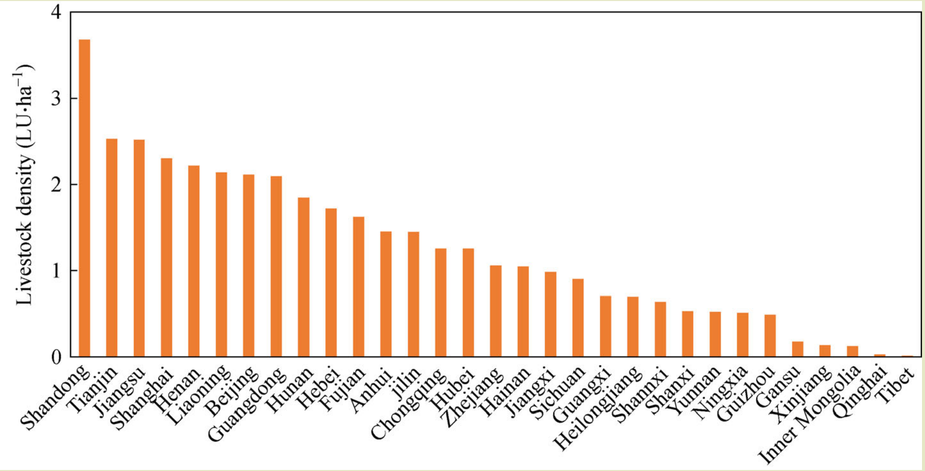

Fig. 7 Livestock density in livestock units (LU) per ha of agricultural land per province in 2013 (source: China Statistical Yearbook).

authors who were invited to provide reflections on various aspects of mixed crop-livestock production. Here, we provide a brief overview.

Three papers provide in-depth background information about livestock production in China. Shuai Zhang and colleagues discuss the changes in the pork production sector, including the impacts of the African Swine Fever in 2018–2020 (https://doi.org/10.15302/J-FASE-2020377). Ning Yang discusses the developments in the layer hen sector, which now produces more than 40% of the total mass of eggs in the world (https://doi.org/10.15302/J-FASE-2020363). Fujiang Hou and colleagues provide an overview of grazing systems used for cattle, sheep and goat production. Large areas of China cover marginal grassland areas with low productivity, but with potential for improvement (https://doi.org/10.15302/J-FASE-2020378).

Sha Wei and colleagues discuss current manure management practices, with a focus on manure treatment techniques and governmental incentives needed to drastically improve manure management (https://doi.org/10.15302/J-FASE-2020369). Yifei Ma and colleagues estimated nutrient use efficiencies and losses from livestock production in mixed crop-livestock systems and specialized livestock production systems in the North China Plain, on the basis of farm survey data and model calculations. They found that nutrient use efficiency at herd level and nutrient losses at system levels were higher in specialized livestock farms than in mixed farms, and that mixed farms had also shortage of land for feeding all animals and for proper disposal of all manure (https://doi.org/10.15302/J-FASE-2020371). Maryna Strokal and colleagues argue that current agricultural systems in China result in considerable losses of nutrients, which cause water pollution and harmful algal blooms in Chinese lakes, rivers and coastal waters. To turn the tide, there is a need for agricultural green development through reintegrating crop and livestock production, and additional technical, social, economic, policy and environmental interventions (https://doi.org/10.15302/J-FASE-2020366).

Nine papers present results of case studies from different continents. Two papers deal with Africa, where most farming systems are mixed subsistence farming systems. The need for increasing productivity is emphasized in both papers, due to the expected huge increase in human population in Africa over the next few decades. Mariana C. Rufino and colleagues argue that there is ample room for the development and improvement of crop-livestock farms; keeping integration as part of the development will help prevent many of the mistakes and environmental problems related to the intensification of livestock production observed elsewhere in the world (https://doi.org/10.15302/J-FASE-2020362). Solomon Tulu Tadessa and colleagues present a scenario analysis of urban and peri-urban agriculture in a rapidly expanding city in Ethiopia for the year 2050, using results of farm surveys and model calculations. They argue that slowing down population growth, improvements in crop and animal productivity, and exchanges of manure and household wastes between urban areas and rural areas are needed for achieving food self-sufficiency, high resource use efficiency, and greater environmental sustainability (https://doi.org/10.15302/J-FASE-2020375).

Alan Franzluebbers and colleagues present three case studies from North America, with different levels of integration between livestock and crop producers in British Columbia (Canada), New York and southeastern USA. They argue that effective solutions for integration should recognize that (1) manure has value and is not just a cost, (2) farmers, farm advisors, regulators, and university researchers all need to be active participants in the development of solutions, and (3) change to a sustainable future requires a combination of government regulation and outcome-based incentives (https://doi.org/10.15302/J-FASE-2020365). Paulo César de Faccio Carvalho and colleagues discuss experiences of mixed crop-livestock systems in South America (Argentina, Brazil and Uruguay), where highly specialized agriculture has decoupled livestock from croplands over the last few decades (https://doi.org/10.15302/J-FASE-2020380). Carvalho and colleagues emphasize the importance of designing multi-functional landscapes with integrated crop-livestock systems, to improve nutrient cycling and other ecosystem services, economic performance indicators and the resilience to climate-market stresses. The area under mixed crop-livestock farming is now increasing in Argentina and Brazil[15].

Antonius G. T. Schut and colleagues discuss the opportunities for recoupling crop and livestock in Europe, where farming systems have become more specialized, especially in western Europe. They discuss the various socioeconomic barriers and opportunities of coupled crop-livestock systems, and argue that recoupling crop and livestock production will not happen without policy support and institutional incentives, as specialization seeking the benefits of scale is an ongoing driver. They urge for a long-term vision at landscape scale to encourage a regional mix of farm types, and to reduce the environmental challenges associated with strong regional specialization (https://doi.org/10.15302/J-FASE-2020373).

Two papers deal with grassland-based dairy farming. Jiafa Luo and Stewart Ledgard discuss the characteristics and performances of dairy farms in New Zealand, where dairy cows graze year-round in low-cost systems with little external inputs. Market incentives, due to the increasing milk demand in Southeast Asia, have driven milk production to increase through increases in stocking rate and inputs of fertilizer N and externally-sourced feeds. As a consequence, N and P leaching and greenhouse gas emissions have increased (https://doi.org/10.15302/J-FASE-2020372). Jouke Oenema and Oene Oenema present characteristics of dairy farms in the Netherlands, where dairy production and N and P use at farm level are tightly regulated. The N and P surpluses remained constant and N and P use efficiencies at herd and farm level increased with milk production per unit of land. This was related in part to externalization effects; increased milk production per unit of land required greater import of feed from elsewhere and greater export of manure to other farms (https://doi.org/10.15302/J-FASE-2020376).

Zhengxia Dou discusses the role of livestock in upcycling crop and food residues generated along the food chain that are otherwise unfit for human consumption. She emphasizes the critical role of livestock in promoting a circular food system toward sustainable food security, using data from the USA. Innovative technologies and enabling policies are needed to convert food waste into safe and nutritious animal feed (https://doi.org/10.15302/J-FASE-2020370). The latter is indeed important as recently shown by cases where swill has contributed to the spread of African Swine Fever in China[32].

Daan Verstand and colleagues present a global framework with four quadrants along the axes of human population density and livestock density. This framework helps to identify regions with nutrient accumulation and nutrient depletion. These authors argue that there are two possible solutions for redressing nutrient accumulation and depletion, i.e., (1) organizing return flows of manure and excreta from high-density (population and livestock) areas to low-density areas, and/or (2) transfer livestock production from high-density areas to low-density areas (https://doi.org/10.15302/J-FASE-2020364).

5 DISCUSSION

All participants of the workshop received background information about current livestock production and manure management in China, and were requested to complete a questionnaire about (re)coupling crop and livestock production, the main theme of the workshop. The questionnaire consisted of a number of subtopics, and for each subtopic, 7 to 12 short statements/propositions were included. Participants were invited to indicate whether they agree or disagree with these statements/propositions. The questionnaires were completed by almost all participants prior to the workshop, and the results were summarized and discussed during the workshop. Some main results are presented below:

- Participants had different opinions about many statements;
- Opinions were partly related to the country of origin—

opinions of international participants tended to differ from those of Chinese;
- Differences in opinions were partly related to experiences of the participants and to the possible spatial scales of (re)coupling—farm scale versus regional scale;
- Integrating crop-livestock production was thought to be beneficial for resource use and nutrient use efficiency, animal welfare, and social acceptance of livestock farming, with a near-neutral effect on productivity and farm income.
- Integrating crop-livestock production was thought to be supported by research institutes and governmental organizations, but not by suppliers and processing industry;
- Influence on integrating crop-livestock production was thought to be strongest from governmental organizations;
- There was no consensus about the main barriers for integrating crop-livestock production;
- The spatial scale of integration was thought to be important, with greater perspectives at regional scales than at the farm level.

In the discussion, it became clear that the farm visits prior to the workshop and the information discussed during the workshop greatly helped in provide understanding of the background of the Chinese case—how to improve the recoupling of crop and livestock production. The recoupling in China is mainly aimed at restoring the nutrient recycling between crop and animal production, to decrease the pollution caused by inefficient use of manure, and to replace mineral fertilizers with manure in cropland. An eye-opener for many international participants was the difference in size of current specialized crop farms and livestock farms; one livestock farm often produces more manure nutrients than 100 crop farms can use in agronomically and environmentally sound ways.

The policy framework and institutions needed for recoupling crop and livestock production were not specifically discussed, although many participants emphasized in their presentations the need for government incentives. It was felt that government regulations applied in Europe and North America cannot be directly applied in the Chinese situation, as farming systems, culture and institutions are completely different.

By the end of the workshop, participants agreed on the following conclusions and recommendations:
- There is a wide diversity in livestock production systems, and in mixed crop and livestock production systems around the world. Unfortunately, there is little quantitative information about the organization, management and the economic and environmental performances of these systems in different countries. There is also little empirical information about the governance of linking specialized crop production systems and specialized livestock production systems, especially related to the exchange of manure nutrients, in different countries.
- Future research needs include the development of institutional frameworks related to the smart coupling or integrating crop and livestock production systems in China. Such frameworks must include multiple dimensions (space and time) and sustainability indices (resource use, environment, economy, food safety and governance). There is also need for monitoring data on the economic and environmental performances of coupled, mixed and integrated crop and livestock production systems, and there is need for modeling and optimization tools to explore opportunities for the near future.
- A greater understanding is needed of the key technical, economic and social drivers and barriers for coupling of crop and livestock production systems in China. The current roles of stakeholders, actors and agencies are often unclear, and the skills and competitions needed by these actors for coupling of crop and livestock production systems have not been articulated.
- There is great need for demonstrations in the field, to inspire stakeholders. New-style coupled, mixed and integrated crop and livestock production farms have to be developed and the performances of these farms have to be discussed among and demonstrated to stakeholders. This must be a joint effort of all stakeholders. Such experimental/demonstrations farms can be used also to examine and demonstrate new technologies and management approaches related to for example animal feeding, manure management and emission mitigation.

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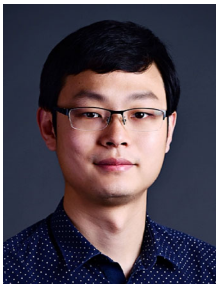

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