Lower pork consumption and technological change in feed production can reduce the pork supply chain environmental footprint in China

Nature Food

Tong, Bingxin; Zhang, Ling; Hou, Yong; Oenema, Oene; Long, Weitong et al

https://doi.org/10.1038/s43016-022-00640-6

nature food

Article

https://doi.org/10.1038/s43016-022-00640-6

Lower pork consumption and technological change in feed production can reduce the pork supply chain environmental footprint in China

Received: 10 April 2022

Accepted: 19 October 2022

Published online: 22 December 2022

Check for updates

Bingxin Tong[1,5,6], Ling Zhang[1,5,6], Yong Hou [1] ✉, Oene Oenema [1,2], Weitong Long[1,3], Gerard Velthof[2], Wenqi Ma[4] & Fusuo Zhang [1]

Nearly half of global pork production and consumption occurs in China, but the transition towards intensification is associated with worsening environmental impacts. Here we explore scenarios for implementing structural and technological changes across the pork supply chain to improve environmental sustainability and meet future demand. Following the middle-of-the-road socio-economic pathway (SSP2), we estimate that the environmental footprint from the pork supply chain will increase by ~50% from 2017 to 2050. Utilizing technologies that improve feed crop production and manure management could reduce phosphorus and nitrogen losses by three-quarters and one-third, respectively, with modest reductions in greenhouse gas emissions and cropland area. Reducing pork consumption had substantial mitigation potential. Increased feed and pork imports would decrease domestic environmental footprints and meet demand, but increase footprints elsewhere. We conclude that farm-specific technologies and structural adjustments can support the development of rural, small-scale pig farms near cropland and promote circular economy principles.

Global pork production accounts for about one-third of global meat production, with nearly half of the global total production in 2017 occurring in China[1]. Since Chinese policy reform in 1978, specialized and intensive farming systems started to grow, with ~20% pigs being raised in large-size industrial farms by 2000 (ref. 2). Intensification has many detrimental environmental impacts. Poor manure management resulted in more than half of nitrogen (N) (5.3 million tonnes) and phosphorous (P) (0.8 million tonnes) being lost to the environment in 2010 (ref. 3). About one-fifth of cropland area in China was used for concentrate pig feed production (mainly corn and wheat) in 2017 (ref. 4). China imported 90.7 million tonnes of soybean in 2018, with about 25% going towards the pig sector[1,4], while also importing 1.1 million tonnes of pork, which is implicated in deforestation and greenhouse gas (GHG) emissions in soybean-exporting countries in Latin America, and with environmental pollution in the main pork-exporting counties in the European Union (EU)[1,5].

Actions to decrease environmental impacts can be implemented across the pork supply chain. Governmental policies can address demand and supply. Current dietary guidelines promote decreasing

[1]College of Resources and Environmental Sciences, National Academy of Agriculture Green Development, Key Laboratory of Plant-Soil Interactions, Ministry of Education, China Agricultural University, Beijing, China. [2]Wageningen Environmental Research, Wageningen University and Research, Wageningen, the Netherlands. [3]Environmental Economics and Natural Resources Group, Wageningen University and Research, Wageningen, the Netherlands. [4]College of Resources and Environmental Sciences, Hebei Agricultural University, Hebei, China. [5]These authors contributed equally: Bingxin Tong, Ling Zhang. [6]These authors jointly supervised this work: Bingxin Tong, Ling Zhang. ✉e-mail: houyong7514364@126.com

pork consumption, which would decrease environmental impacts on the demand side of the pork supply chain[6,7]. Supply-side options attempt to reduce the intensity of resource use and emissions of GHG, N and P. Technical measures reduce the environmental pressures from livestock systems through the use of, for example, feed additives, low-protein feeding, anaerobic digestion and improved manure management[3,8]. Structural adjustments require fundamental changes in production systems, such as a transition towards intensive production systems, relocation of production across regions through international trade and inclusion of demand-side adjustments[9,10]. Relocation of animal production across regions could improve manure recycling and decrease N and P emissions greatly[11,12], but the impacts of farm structure adjustments on the environmental performance of pork production are poorly explored.

Industrial farms typically outperform traditional smallholder farms in terms of productivity and farm profit, but not necessarily in terms of environmental performance. Smallholder farms amid villages and crop production farms have greater opportunity than industrial farms to recycle animal manure to cropland[13]. Pigs on small-scale farms can contribute to a circular bioeconomy by using household leftovers and agro-industrial by-products, thus recycling nutrients back into the food system[14,15]. Numerous studies have examined the environmental impacts of technological measures in pork production and manure management[3,4,16,17], but impacts of combinations of technological measures and structural adjustments for the whole pork supply chain have not been examined in an integrated manner.

In this Article, we examined unique combinations of a comprehensive set of measures and adjustments for the whole pork supply chain. First, we assessed four key environmental footprints (cropland area used for feed production, and carbon (C), N and P footprints) of the pork supply chain in 2017. Next, we estimated the pork demand in 2050, following a business-as-usual (BAU) baseline (that is, the middle-of-the-road socio-economic pathway—SSP2 (ref. 18)), and full implementation of the Chinese guidelines for healthy diets[19], estimating the cropland area, C, N and P footprints. Finally, we explored the impact of possible technical measures and structural adjustments through scenario analysis.

Results

BAU environmental footprints

In 2017, China's pork supply totalled 55.6 Mt (import accounted for 2%), contributing 63% to the total national consumption of meat products (as carcass weight). Mean meat consumption was 61 kg per capita in China (that is, 50% of the mean consumption in the United States[1]). A total of 28.0 Mha of cropland was used for the pork supply, including 7 Mha overseas (Table 1). Total GHG emissions associated with the pork supply (including imports) were 153.1 Mt CO_2-eq. Total reactive nitrogen (Nr) losses were 4.7 Mt, and total P losses were 0.24 Mt (Table 1).

In the 2050 BAU scenario, pork consumption increases to a mean of 78.6 Mt (uncertainty range 67.5–95.8 Mt) owing to population and per capita consumption increases, from 38.3 in 2017 to 54.8 (range 47.1–66.8) kg per capita per year (Supplementary Fig. 1). Nearly 90% of total pork will be produced by medium (50–3,000 heads) and large (>3,000 heads) farms in 2050 (Table 1). Pork consumption per capita in BAU will be close to the current level of consumption in, for example, Germany[1]. Footprints of C, N, P and cropland per kilogram pork (carcass weight) will increase by 2.2%, 2.4%, 7.8% and 1.1%, respectively, owing to the anticipated greater contributions from large industrial farms and lower contributions from small farms (Table 1). These farms have contrasting differences in feed use and manure management and utilization resulting in the total area of cropland needed for feed production increasing by 41.7% between 2017 and 2050 (from 28.0 Mha to 40.0 Mha), while total GHG emissions from the pork supply chain will increase by 44.5% (from 153.1 Tg to 221.1 Tg), P losses by 52.1% (from 239.1 Gg to 363.6 Gg) and Nr losses by 44.5% (from 4.7 Tg to 6.8 Tg) (Fig. 1 and Table 1). GHG emissions and Nr losses originate mainly from feed production and manure management, and P losses occur mainly through manure discharge and landfill (Fig. 1). Pork and feed imports increase alongside the associated environmental spillover in exporting countries (the EU, Canada and the United States). The required cropland area and the GHG emissions increase more than Nr and P losses in exporting countries; 28% of the cropland area needed for feed production is overseas in 2050 (Brazil, Argentina and Ukraine), and 14% of the total GHG emissions embodied in the pork supply in 2050 occurs overseas (Fig. 1).

Impacts of structural and technical changes

We explored technological measures that have been tested and applied in pilot farms and regions in China to assess how structural adjustments and technological measures impact the environmental footprints of the pork supply chain relative to the 2050 BAU scenario (Figs. 1 and 2).

In the 'Dietary guidelines' scenario, the recommended pork consumption was 13 kg per capita per year, according to the Chinese guidelines for healthy diets[19]. In this scenario, the total required cropland area, GHG emissions, and Nr and P losses from China's pork supply chain would be 64.7–66.6% lower compared with the BAU scenario (Fig. 1) and lower than for the year 2017 (Table 1).

Increasing pork imports (S1-1, assuming all additional demand will be imported compared with 2017) decreased Nr losses by 11% and P losses by 27%, but increased GHG emissions by 23% and required cropland area to increase by 36% (Fig. 2). Increasing feed import (S1-3, that is, increasing soybean import from 85% to 93% of the total domestic demand) did not have substantial impacts on the environmental footprints. Changes in intensification level (S2), that is, in the relative contributions of small, medium and large pig farms to the total pork production, have substantial effects owing to the associated differences in feed use, pork production efficiency and manure management between farm types (Fig. 2). Environmental footprints were reduced by 6–8% in S2-1 (ratio of small:medium:large farms is 25:51:24) and by 10–12% in S2-2 (ratio of small:medium:large farms is 25:18:57), relative to the 2050 baseline. However, all four environmental footprints modestly increased in S2-3 (assuming all pigs were fed in large farms).

Improvements in feed production through improved crop production practices affected environmental footprints modestly (range −11% to +3%). Balanced N fertilization (S3-1) had the greatest reduction and enhanced N fertilizer technology (S3-3) the least. A combination of technologies in feed production (S3-4) led to an 8% reduction in GHG emissions, an 11% decrease in cropland area and a 3–4% reduction in Nr and P losses (Fig. 2). The effects of combined options are not simply additive, as interactive impacts are considered in the model.

Improvements in pig production (S4) decreased the four environmental footprints modestly (range 0–9%), except for supplementing phytase in feed (S4-2, P losses decreased by 24%). Low-protein feeding (S4-1) and improved herd structure (S4-3) decreased the environmental footprints only modestly, because the genetic basis of the pig herd was close to international standards and feed protein content was relatively low on average in 2017. The combination of improved pig production measures (S4-4) decreased the four environmental footprints by 6–26% (Fig. 2).

Improvements in manure management and treatment had large impacts on the environment compared with the BAU scenario, but had no impact on the required cropland area (Fig. 2 and Supplementary Fig. 3). The C, N and P footprints decreased roughly in the order C < N < P. Improvements in manure storage and treatment (except for anaerobic digestion) reduced Nr and P losses, but increased GHG emissions. Anaerobic digestion combined with proper utilization of the digestate in cropland (S5-3) decreased GHG emissions by 14% (including the emissions associated with avoided fossil energy use through biogas production), Nr losses by 8% and P losses by 18% (digestate application to cropland may substitute 1.7 Mt N and 1.3 Mt P synthetic fertilizer). Composting decreased P and Nr losses, but slightly increased GHG emissions; the reduction in methane (CH_4) emissions was offset by increased CO_2 emissions from energy use (S5-2; Fig. 2). Some manure management measures decreased N losses to water bodies, but increased emissions of ammonia (NH_3) (S5-1, S5-3 and S5-4; Fig. 2).

https://doi.org/10.1038/s43016-022-00640-6

Table 1 | Estimated cropland area needed for feed production, and GHG emissions and Nr and P losses associated with the pork supply chain in China (differentiated for three main farm types) and in countries that export pork and/or feed to China in 2017 and in 2050 (for BAU)

Countries and farm types		Proportion of total pork supply (%)		Cropland use (Mha)		GHG emissions (Tg)		Nr losses (Tg)		P losses (Gg)	
		2017	BAU (2050)	2017	BAU (2050)	2017	BAU (2050)	2017	BAU (2050)	2017	BAU (2050)
China	**Small size**	24.6	9.8	1.9	0.6	11.1	4.9	0.48	0.25	28.6	15.9
	Medium size	50.0	34.3	13.5	12.1	86.1	77.2	2.8	2.6	144.5	140.5
	Large size	23.4	53.9	5.6	16.2	36.4	108.0	1.1	3.5	61.9	200.5
	Subtotal	98.0	98.0	21.0	28.9	133.7	190.1	4.4	6.4	234.9	356.9
Brazil		0		3.1	5.1	9.2	15.0	0.13	0.22	3.6	5.9
Europe		1.5	1.5	1.0	1.3	3.9	6.0	0.04	0.06	0.27	0.39
America		0.26	0.26	2.3	3.6	4.2	6.8	0.10	0.16	0.21	0.33
Others		0.24	0.24	0.67	1.1	2.1	3.3	0.01	0.01	0.04	0.06
	Subtotal	2.0	2.0	7.0	11.1	19.6	31.1	0.29	0.46	4.2	6.7
Sum		100	100	28.0	40.0	153.1	221.2	4.7	6.8	239.1	363.6

Data related to the total domestic pork supply in China and to imported pork and feed were obtained from the Food and Agriculture Organization Corporate Statistical Database. Data related to the differentiation over small, medium and industrial farms were collected from China Animal Husbandry and Veterinary Yearbook (2018), China Statistical Yearbook (2018) and Long et al.[4]. GHG emissions and Nr and P losses relate to the whole feed and/or pork supply chain.

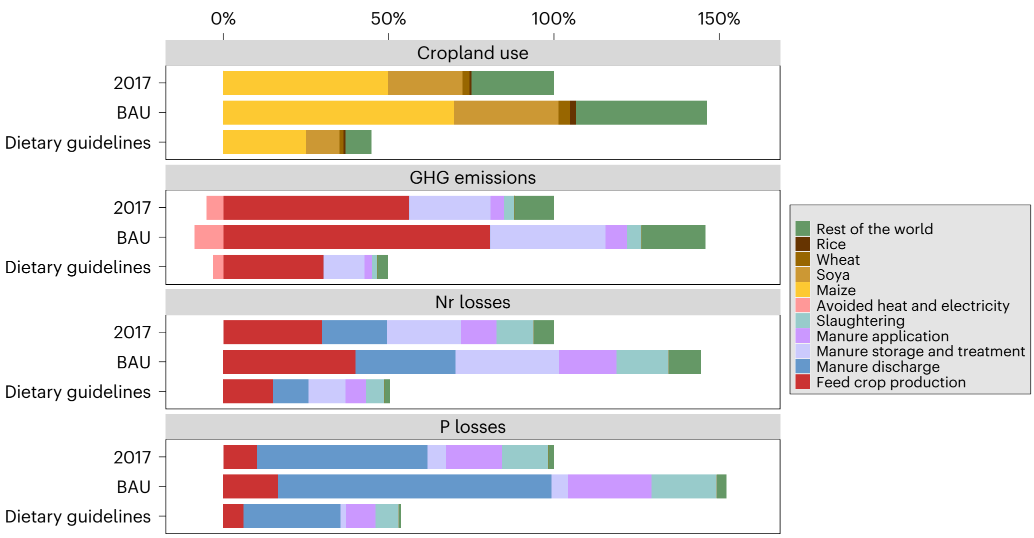


Fig. 1 | Estimated relative cropland areas used for feed production, and relative GHG emissions, Nr and P losses associated with China's pork supply in 2017 and 2050 (for BAU). Estimations are shown as percentage of the current situation (2017 is 100%). Results for 2050 are according to the BAU baseline projection (the middle-of-the-road socio-economic pathway—SSP2) without dedicated mitigation measures. Rest of the world indicates overseas impacts associated with the import of pork and/or feed. Avoided heat and electricity refers to the energy from biogas generation and utilization from anaerobic digestion of pig manure.

Trade-offs exist between emission pathways: GHG emissions increased by 4% and Nr losses by 3%, but P losses decreased by 3% in S5-1 (Fig. 2 and Supplementary Fig. 3). Overall, the combination of manure management and treatment had the greatest impacts on total GHG emissions, and Nr and P losses (S5-6; Fig. 2).

Improvements in slaughterhouse waste management and utilization had a surprisingly large impact on the total losses of Nr and P from the supply chain, but not on the cropland area and GHG emissions (S6; Fig. 2).

Impacts of integrated packages of measures

An integrated package of measures from feed production to slaughterhouse waste management (see SD in Fig. 3, SD = S3-4 + S4-4 + S5-6 + S6) gave large reductions of P losses (72%) and Nr losses (38%), with modest reductions of GHG emissions (17%) and the required cropland area (14%). Losses of Nr and P mainly decreased through improved manure management; decreases of GHG emissions and cropland area were largely associated with improved feed production.

Integration of the aforementioned technological package and increased pork import (see SE in Fig. 3, SE = SD + S1-1) reduced total Nr and P losses further, but increased total GHG emissions and the required cropland area, especially overseas as increased import leads to spillover of environmental impacts to exporting countries. The pressure on the environment decreased significantly when the aforementioned package of measures was integrated with changes

 https://doi.org/10.1038/s43016-022-00640-6

Scenarios	Variants	Cropland use	GHG emissions	Nr losses	P losses
Changed import of pork and feed (S1)	S1-1: Pork self-sufficiency (63%)	+36	+23	−11	−27
	S1-2: Pork self-sufficiency (83%)	+18	+11	−5	−13
	S1-3: Increased feed import	−1	0	0	0
Changed intensification level of pig farm (S2)	S2-1: Small:medium:large = 25:51:24	−7	−8	−6	−7
	S2-2: Small:medium:large = 25:18:57	−11	−12	−11	−10
	S2-3: Small:medium:large = 0:0:100	+1	+3	+1	+2
Improved feed production (S3)	S3-1: Balanced N fertilization	−10	−6	−6	−5
	S3-2: Manure substitute for fertilizer (40%)	0	−1	0	−2
	S3-3: Nitrification inhibitor	0	−2	+2	0
	S3-4: S3-1 + S3-2 + S3-3	−11	−8	−3	−6
Improved pig production (S4)	S4-1: Low-protein diet	−4	−2	−9	0
	S4-2: Phytase supplementation in feed	0	0	−3	−24
	S4-3: Improved herd structure	−6	−4	−6	−3
	S4-4: S4-1 + S4-2 + S4-3	−9	−6	−15	−26
Improved manure management (S5)	S5-1: Improved manure storage	0	+4	+3	−3
	S5-2: 100% solid—composting	0	+3	−4	−34
	S5-3: 100% slurry—anaerobic digestion	0	−14	−8	−18
	S5-4: 100% slurry—solid–liquid separation	0	+5	−7	−16
	S5-5: Deep placement of manure in field	0	0	−5	0
	S5-6: S5-1 + S5-2 + S5-3 + S5-5	0	−8	−22	−53
Improved slaughter waste management (S6)	S6: Improved slaughter waste utilization	0	0	−6	−7

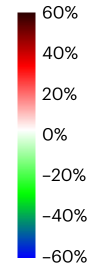


Fig. 2 | Relative changes (%) in cropland area, GHG emissions, and N and P losses following the implementation of series of technological measures and structural adjustments by 2050, relative to the 2050 BAU baseline. Dark-red colours indicate the environmental pressures increase; blue-green colours indicate the environmental pressures decrease. Scenarios S1 to S6 and their variants are further detailed in Methods.

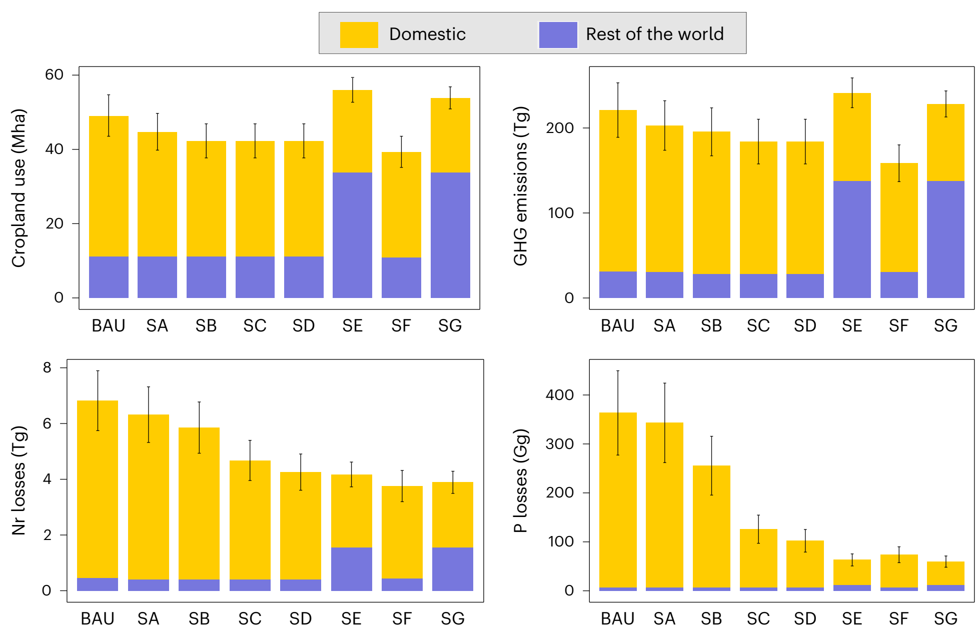


Fig. 3 | The needed cropland area, and GHG emissions and reactive Nr and P losses associated with China's pork supply chain for the 2050 BAU baseline and for various scenarios. The scenarios were constructed using a step-wise combination approach. SA = S3-4, SB = SA + S4-4, SC = SB + S5-6, SD = SC + S6, SE = SD + S1-1, SF = SD + S2-2, SG = SD + S1-1 + S2-2 (Fig. 2). Rest of the world indicates overseas impacts associated with the import of pork and/or feed. The error bars denote the 95% confidence intervals of the specific emissions (based on Monte Carlo simulations, $n = 1,000$). Data are presented as mean ± standard deviation.

in farm structure (see SF in Fig. 3, SF = SD + S2-2). Results of the decomposition analysis for scenario SF show that a reduced intensification level alleviates environmental pressures, in particular for GHG emissions and cropland area, relative to the 2050 BAU baseline. Improving manure management greatly reduced Nr and P losses (Fig. 4).

In short, total P losses may be reduced by up to 84%, total Nr losses by up to 45%, total GHG emissions by 28% and the required cropland area by 20% through integrated packages of measures (Fig. 3).

Discussion

China will probably remain the main global pork producer and consumer in the twenty-first century, even if the Chinese guidelines for healthy diets are implemented successfully (Table 1). Forecasts suggest that pork consumption will increase further by about 40% during the next three decades, but it is uncertain how much of the additional pork will be produced domestically (Supplementary Table 11). This uncertainty is related to the shortage of domestically produced feed, the surface water eutrophication and air pollution caused by current

 https://doi.org/10.1038/s43016-022-00640-6

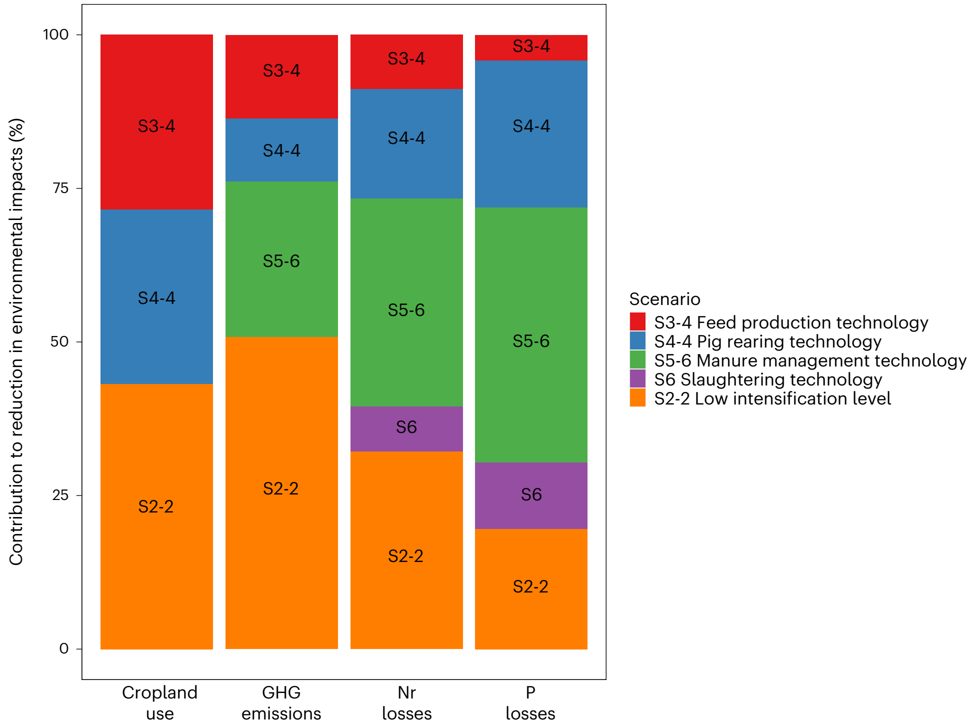


Fig. 4 | The relative contributions of technological and structural measures to the diminished need for cropland area, and to the mitigation of GHG emissions, Nr losses and P losses in the SF scenario (Fig. 3), relative to the 2050 BAU baseline. SF incorporates a combination of technological measures along the pork supply chain (S3-4, S4-4, S5-6 and S6; Fig. 2) and a low intensification level (S2-2; Fig. 2).

pork production systems and the incidence of animal diseases such as African swine fever[3,20] (Supplementary Information). Alternatives include increased pork and/or feed import, but this may lead to environmental spillovers and increased dependency on the vulnerabilities of international trade[21,22] (Supplementary Information). The third possible pathway is improved domestic production. Our results indicate that impacts of the pork supply chain on the environment can be greatly reduced, but will require investments in innovative technologies for improved feed production, pig production, manure management and slaughterhouse waste management (Fig. 5).

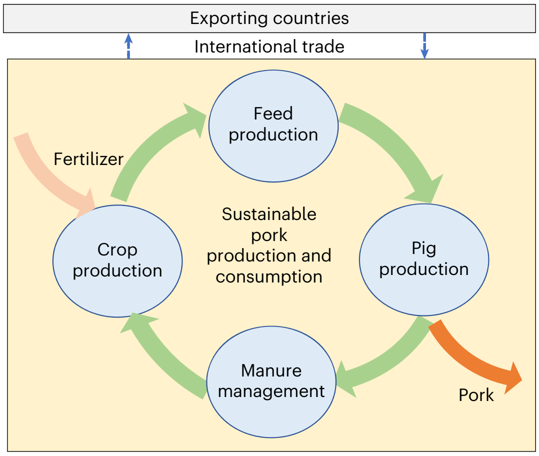
Decrease red meat consumption

We argue that demand-side measures are needed, but recognize that reducing pork consumption is not easy, especially since more rural populations reach a prosperity level where they can afford pork consumption more regularly[23,24]. The mean pork intake in 2017 was already beyond the Food and Agriculture Organization (FAO)[25] and Chinese[19] recommended red meat consumption ranges, and consumption per capita in the BAU baseline for 2050 increased by 43% compared with the consumption in 2017 (Supplementary Fig. 1). These results are similar to some earlier estimations for 2050 following the SSP2 storyline[26] (an increase of 79–99% of the pork production, relative to 2005), but are higher than a recent FAO estimation[27]. These discrepancies are partly related to differences in data sources, methods and reference years. Our forecast of pork consumption in 2050 was based on an average of various methods in a middle-of-the-road pathway (SSP2) (ref. 18). Our results indicate that four environmental footprints associated with China's pork supply chain may be reduced by 65–67% relative to the BAU scenario if the recommended low meat intake according to the Chinese dietary guidelines is implemented (Fig. 1). However, pork consumption is embedded in Chinese culture and history[6], making substantial changes to current dietary behaviour challenging[28]. Increased consumption of fruit, vegetables and nuts, and less meat are often more expensive, especially in rural regions[29]. Investments in communication are needed to promote healthy diets with less pork. In addition, the price of pork should reflect the true societal cost of pork production, for example, through imposing taxes. These mechanisms would lower pork demand in the future, but transitions of this scale require time and resources.

Integrate improvements to domestic production

Productivity in the pork sector has increased strongly since 1990s, mainly owing to improved pig breeds and feeding, especially in industrial pig farms[30]. The total production value of the pig sector amounted to 1296 billion Chinese Yuan, accounting for 45% of the total production value of the livestock sector in 2017 (ref. 31). In contrast, poor manure management and recycling led to nutrient losses estimated at 86 g Nr and 4.4 g P per kilogram pork in 2017, compared with 53 g Nr kg^{-1} and 0.3 g P kg^{-1} in the EU (Supplementary Table 13).

We show that integrated packages of measures across the whole pork supply chain can reduce Nr losses by 45% and P losses by 84% (Fig. 3), confirming results of earlier model estimations[3] and bringing Nr losses (47 g kg^{-1}) and P losses (0.6 g kg^{-1}) near to the current mean Nr and P losses in the EU. Our results may slightly overestimate the overall emission reduction potential in scenarios S1 to S4 as the emissions from the 2050 BAU may have been overestimated. The coefficients in the life-cycle assessment partially reflect current practices per farm type following the SSP2 pathway, but not necessarily future improved practices. An additional sensitivity analysis was therefore conducted (assuming that the emission coefficients will decrease by 10% or 20% owing to optimistic progress in management towards 2050), showing that the environmental footprints in the 2050 BAU scenario will decrease by 3.0–8.0% (Supplementary Table 19), which are relatively minor decreases relative to other scenarios (S1 to S4). Moreover, some combinations of measures led to increased GHG emissions (Fig. 2 and Supplementary Fig. 3), indicating a risk of pollution swapping, and the need for smart combinations of techniques and measures. Evidently, further studies and especially tests at whole-farm scales are needed.



Options/ pathways	Key advantages /benefits	Key disadvantages /barriers
Integrated technological measures	• Environmental pressure reduction • Increased domestic production	• Economic costs • Complex coordination across stakeholders
Farm structural adjustment	• Circular food system • Environmental pressure reduction	• Low productivity (small-scale farm) • Low return
Increased import of pork and/or feed	• Reduced pressure on domestic demand • Reduced pressure on environment (for example, N, P)	• Environmental spillover • Sensitive to global trade frictions
Eating less pork	• Positive effects on human health • Reduced pressures from pork supply chain	• Increased demand of pork in rural area • Difficult to change current dietary behaviour

Fig. 5 | The key mass flows in the pork supply China (left) and a summary of key advantages and disadvantages of possible pathways/options for achieving more sustainable pork production and consumption (table on the right; see Discussion). Crop production, feed processing, pig production and manure management are the main components of the pork production chain, which interacts with countries exporting pork and feed.

Though the potential for decreasing the footprints of C, N, P and cropland use are large, implementing integrated (synergistic) and farm-specific packages of measures will be challenging. Experience with single measures demonstrates ineffective implemention due to high operational cost, little technical guidance and lack of motivation and incentives[32,33]. In addition, there is a huge diversity among pig farms and among farmers' education and attitudes[34,35], which must be taken into account when developing, testing and demonstrating farm-specific packages of measures and techniques. Massive investments are needed for implementing these farm-specific packages. For example, the mitigation cost per kilogram Nr emissions from China's agricultural system was estimated at 0.8–2.1 USD[36], suggesting that implementation of the most effective packages of our study (scenario SF in Fig. 3) will require about 2.5–6.4 billion USD, equivalent to 2–6% of the total annual value of pork production in 2017 (ref. 31). Additionally, on-farm experimentation is needed to implement innovative measures at scales that are meaningful to farmers, rather than in small experimental plots[37]. The cost effectiveness of integrated packages needs to be determined, to identify the priority packages[38].

The future for small-scale farms

The structure of the pork supply chain has rapidly changed during the past two decades, with an increase in large specialized farms and a decrease in mixed smallholder farms[16], yet questions remain about the most appropriate farm size for future pork production. In 2017, small-scale farms supported one-third of the pork production in China (Table 1). These farms are important for livelihoods in rural regions, where the young and middle-aged people often go out to work in urban areas and elderly people live on smallholder farms[39,40].

The share of small-size pig farms will probably decrease further to ~10% in 2050 (BAU)[26]. Our results indicate that footprints of C, N, P and cropland use per kilogram of pork produced may decrease by 10–12% (in absolute values), when the rate of intensification is halved relative to the 2050 BAU baseline (Figs. 2 and 4). Small-size pig farms use less cropland per kilogram pork produced (2.0 m^2 functional unit $(FU)^{-1}$), emit lower GHG emissions (0.9 kg CO_2-eq FU^{-1}), and have lower Nr (36.9 g FU^{-1}) and P losses (2.1 g FU^{-1}) than medium- and large-size farms (Supplementary Table 1). Their location near villages and (small-scale) crop production farms allows for greater opportunities to recycle food waste to pigs[41] and animal manure to cropland[14], compared with the large specialized farms, which reduces the need for synthetic fertilizers[42], and contributes to improving soil fertility and to higher crop yields[43].

Returning low-opportunity-cost feed to pigs impacts feed–food competition for cropland[14]. Nearly 30% of food produced annually for human consumption in China (349 ± 4 Mt) is lost or wasted, implying a large potential for recycling this biomass as feed sources[44], meaning 11–23 Mt pork being produced, that is, 14–29% of the total pork production. Feeding swill reduces N losses at the feed production stage, and can save 16 Mha of land used by global pork production[15]. The circular bioeconomy framework also links healthy diets to healthy and local food production systems[45]. Small-scale traditional mixed farms can supply local-brand food at a relatively high price to meet increasing demand for 'regional' or 'local' food with unique flavours[46]. Small-scale farms also have their limitations. The productivity is often relatively low, and the return on investments in improved techniques is also low. Further, it is difficult for these farms to invest in epidemic prevention measures, increasing risks related to zoonoses[47]. Yet, these small-scale farms have much greater potential to intimately participate in a circular bioeconomy, and to produce healthy regional food than the large industrial farms. Thus, targeted policy incentives are needed to improve the biosecurity level and production performance of small-scale farms, and to boost the circular economy.

Conclusion

A combination of technological improvement and structural adjustment is needed to reduce the environmental impacts of the Chinese pork supply chain. Small-scale pig farms should receive greater attention than large-scale farms from policy and other stakeholders, as these small farms may harbour the appropriate mix of characteristics for the circular bioeconomy and as suppliers of healthy local food. Simultaneously, demand-side measures must aim to reduce pork consumption, particularly among affluent populations. If China would successfully secure the growing demand of animal food at a low environmental cost, it could pose an example for many developing countries that are facing similar challenges.

Methods

Footprint analyses

Footprints of the cropland area and the C, N and P used for the production of 1 kg of pork (carcass weight) were estimated for the whole pork supply chain in 2017 and 2050. The pork supply chain includes four subsystems, that is, feed production, feed processing and transport, pig rearing and manure management, and pig slaughtering (Supplementary Fig. 2). An existing environmental footprint assessment model[4] was extended by including slaughtering, and a P footprint module was developed. The cropland footprint reflects the area needed for producing the required amounts of feed for producing 1 kg of pork; the cropland receiving pig manures is irrespective of the cropland footprint defined here. The C footprint represented the GHG (nitrous oxide (N_2O), CH_4 and CO_2) emissions of the entire pork supply chain. The global warming potentials of CH_4 and N_2O were set at 25 and 298 times that of CO_2, respectively, according to Intergovernmental Panel on Climate Change guidelines[48]. The N footprint included Nr emission to the atmosphere (NH_3, N_2O and nitrogen oxides (NO_X)), and N leaching, runoff and erosion losses to water bodies[49]. The P footprint represented total P losses directly or indirectly caused in the pork supply chain[50]. The FU was 1 kg of carcass weight. Economic allocation was adopted as the allocation method in our study[4] (Supplementary Tables 7 and 8).

The life-cycle assessment (ISO14040) was established at the provincial level, and was up-scaled here at a national level. Three farming systems were distinguished, with different farm size, feed regimes and manure management practices: namely smallholder farms (<50 heads per farm), medium farms (50–3,000 heads per farm) and large farms (>3,000 heads per farm)[3,4] (Supplementary Table 6). The equations used for the estimation of the cropland use and the C, N and P footprints are detailed in the Supplementary Materials.

Estimation of pork demand in 2050

Four methods were used to forecast pork demand in 2050, using 2017 as the reference year and following the middle-of-the-road (SSP2) pathway. The total pork demand is expected to increase by 41% between 2017 and 2050, according to the mean pork consumption growth rate (1.1%), historical trajectories between 1961 and 2018, and the relationships between pork consumption and gross domestic product, and with urbanization rate (Supplementary Materials and Methods part 1). The average value of these methods was used as pork demand in 2050 (Supplementary Fig. 1).

In addition, the future pork demand was also estimated following the 'Dietary Guidelines for Chinese Residents'[19] (Supplementary Materials and Methods part 1), although healthy diets belong to the sustainability (SSP1) storyline—a dramatic (but gradual) shift towards sustainability. These dietary recommendations are based on the principles of nutrition science and preventing human health risks.

Definition of scenarios for 2050

Six scenarios with 21 specific adjustments of the pork supply chain for 2050 were defined (Supplementary Table 9). The scenarios included structural and technological changes of (part of) the pork supply chain. Structural changes related to changes in the import of feed and/or pork (varying the self-sufficiency ratio) and in the intensification level (varying the percentages of small, medium and industrial pig farms). Technological changes related to feed production, animal feeding, manure management and to slaughterhouse waste management. These scenarios are briefly explained below.

BAU. We estimated the environmental pressures of the pork supply chain for 2050 using a middle-of-the-road pathway (SSP2) (ref. 18), in the absence of the dedicated mitigation measures. China's per capita pork consumption will increase from 38.3 kg per capita per year in 2017 to 54.8 kg per capita per year in 2050 (total pork consumption 78.6 Mt). We assume a constant pork self-sufficiency percentage of 98% and feed self-sufficiency rate (soybean 15% and maize 99%) in 2050 equivalent to those in 2017 (Supplementary Table 11). Further, the relative contributions of countries exporting pork and feed to China will remain unchanged (Supplementary Table 12). According to the historical trend in pig production[51], the number of small farms will further decrease and the number of medium and large pig farms will increase. The relative contributions of small, medium and large pig farms to the total pork production in 2050 will be 10%, 35% and 55%, respectively. We assumed that the recycling rate of manure to field will increase from 17% (2017) to 30% (2050), based on expected policy interventions (for example, zero increase of chemical fertilizer use in China), and that the mean crop yield will increase by 13% (for example, the maize yield will be 8,508 kg ha^{-1} on average), because of improved crop breeding and nutrient management measures.

S1—Changed import of pork and feed. In scenario S1, we explored the impacts of increased import of pork or feed on the footprints of the pork supply chain. For the pork import variant (S1-1), we assumed that domestic pork production in 2050 will remain at the level of 2017, and that all additional demand will be imported from the same exporting countries in 2017. The pork self-sufficiency will therefore drop to 63% (Supplementary Table 11). For another pork import variant (S1-2), we assumed that half of the additional demand will be imported from the same exporting countries as in 2017, and the pork self-efficiency will drop to 83% (Supplementary Table 11). Those scenarios reflect possible future market developments, and/or environmental and physical constraints, and/or strict regulations limiting domestic pork production. All operations of domestic pork production are assumed as the same as the BAU.

For the feed import variant (S1-3), we assumed that the total domestic feed production in 2050 will remain at the level of 2017, and that all additional feed demand will come from current exporting countries. Therefore, the proportion of imported soybean to total soybean use in pork feed will increase from 85% to 93%, and that for imported maize from 1% to 36% (Supplementary Table 11). Relative contributions of exporting countries to imported feed were assumed to remain the same as that in BAU.

S2—Changed intensification level of pig farms. In scenario S2, we explored the impacts of the intensification of pig production on the footprints of the pork supply chain (Supplementary Table 11). The relative contributions of small, medium and large farms to the total domestic pork production in 2050 was varied in response to possible socio-economic developments and governmental incentives[3,52,53]. In variant S2-1, we assumed that the relative contributions of small, medium and large farms to the total domestic pork production in 2050 will remain at the level as in 2017 (25:51:24), because of stagnant economic development and a constrained labour market (S2-1). In variant S2-2, we assumed that the relative contributions of small-size farms remained unchanged, while the share of medium was halved and that of industrial farms doubled (25:18:57), because of possible incentives from the supply chain. In variant S2-3, we assumed rapid economic growth and that basically all pork will be produced in industrial farms, and none in small- and medium-sized farms (0:0:100).

S3—Improved feed production (S3). In scenario S3, we explored the impacts of improvements in domestic feed production on the footprints of the pork supply chain. In variant S3-1, we assumed improved crop husbandry practices, leading to increased crop yields with less inputs of fertilizers[54,55]. As a result, the self-sufficiency percentage of maize increased from 99% in 2017 to 100% in 2050. In variant S3-2, we assumed an increased substitution of synthetic N fertilizer by N from animal manure[43], from 14% in 2017 to 40% in 2050. In variant S3-3, we assumed the increased use of enhanced efficiency fertilizers (for example, nitrification inhibitors) to reduce N_2O emissions by 39.8% in 2050 (ref. 56). The combination of all three variants (S3-1, S3-2 and S3-3) was explored in S3-4.

S4—Improved pig production. In scenario S4, we explored the impacts of improvements in domestic pig production on the footprints of the pork supply chain. In variant S4-1, we assumed that all medium and large pig farms will adopt low-protein diets (through phase feeding; that is, the crude protein content in diets of piglets to finishing pigs will step-wise decrease from 19% to 13%, while supplementing essential synthetic amino acids)[17]. In variant S4-2, we assumed phytase supplementation of pig diets for all medium- and large-size pig farms, simultaneously with lowering feed P supplementation; this will reduce the N and P excretion by 5.3% and 31.4%, respectively[17]. In variant S4-3, we assumed that the piglet production per sow and the feed conversion efficiency on medium- and large-size pig farms will have increased to an advanced level[33,57,58], the management level in small pig farms also increased, that is, the piglet production per sow increased from 15 to 20, and feed conversion rate reduced from 3.4 to 2.7. The combination of all three variants (S4-1, S4-2 and S4-3) was explored in variant S4-4.

S5—Improved manure management. In scenario S5, we explored the impacts of improvements in manure management and treatment technologies in housing, storage and field application on the footprints of the pork supply chain. In variant S5-1, we assumed the implementation of biofilters (to reduce NH_3 emissions) on all medium- and large-scale pig farms, together with storage of pig slurries in leak-tight and covered storages[59–61]. In variant S5-2, we assumed that all slurries are separated in solid and liquid fractions, that the solid fraction is composted and that the resulting compost N and P will replace equivalent amounts of synthetic N and P fertilizers, following application to cropland. In variant S5-3, we assumed that all slurries are anaerobically digested to produce biogas, and that the resulting digestate are returned to cropland to substitute synthetic N and P fertilizers. In variant S5-4, we assumed that all slurries are separated in solid and liquid fractions, and that these are returned to cropland to substitute synthetic N and P fertilizers. In variant S5-5, we explored the effects of applying all manures to field through injection into soil, or incorporation into the soil immediately following surface spreading. The combination of these variants (S5-1, S5-2, S5-3 and S5-5) is examined in S5-6.

S6—Improved slaughter waste management. In scenario S6, we explored the impacts of improvements in slaughter waste management on the footprints of the pork supply chain. In 2017, the N and P losses were 71% and 10% of the amounts of N and P in slaughtered by-products (Supplementary Table 8), respectively[3,62]. We assume that, by 2050, the utilization of slaughtering (by-)products will have increased (for example, swine carcass trimmings, inedible offal and bones can be produced into meat and bone meal, which is an excellent source of protein and energy supplement in animal feed), and that the losses of N and P will have decreased to 30% and 5% of the amounts of N and P in slaughtered by-products, respectively.

Uncertainty and sensitivity analyses

Uncertainty and sensitivity analyses were performed to estimate the influence of possible uncertainties in activity data and parameters, using a Monte Carlo simulation[38,60]. We divided the uncertainties into five groups: (1) CAP: crop activity data and parameters, (2) LAP: livestock activity data and parameters; (3) EFN: nutrient emission factors; (4) OPA: other emission factors; and (5) SAD: slaughtering activity data (Supplementary Table 16). The uncertainty ranges are shown as error bars in Fig. 3. The C footprint ranged from 2.3 to 3.2 kg CO_2-eq kg FU^{-1}, the N footprint from 71.4 to 100.2 g N kg FU^{-1}, the P footprint from 3.3 to 5.4 g P kg FU^{-1} and the cropland footprint from 4.2 to 5.7 m^2 kg FU^{-1} in 2017, respectively. The coefficients of variation ranged from 14.7% to 24.1% for the four environmental footprints (Supplementary Fig. 4). The uncertainty contributions of individual parameters to the environmental footprints are presented in Supplementary Table 17 and Supplementary Fig. 5.

Reporting summary

Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

Data availability

Data supporting the findings of this study are available within the article and its Supplementary Information files, or are available from the corresponding author upon reasonable request.

Code availability

The statistical coding is available from the corresponding author on reasonable request.

References

1. FAOSTAT 2020. *FAO* http://faostat.fao.org/ (2020).
2. Ministry of Agriculture and Rural Affairs of the People's Republic of China. *China Animal Husbandry and Veterinary Yearbook* (China Agriculture Press, 2018).
3. Bai, Z. et al. Changes in pig production in China and their effects on nitrogen and phosphorus use and losses. *Environ. Sci. Technol.* **48**, 12742–12749 (2014).
4. Long, W. et al. Mitigation of multiple environmental footprints for China's pig production using different land use strategies. *Environ. Sci. Technol.* **55**, 4440–4451 (2021).
5. Richard, F. et al. US–China trade war imperils Amazon rainforest. *Nature* **567**, 451–454 (2019).
6. Wang, L. *Modern Chinese Pig Production* (Jindun Press, 2007).
7. Stylianou, K. et al. Small targeted dietary changes can yield substantial gains for human health and the environment. *Nat. Food* **2**, 616–627 (2021).
8. Herrero, M. et al. Greenhouse gas mitigation potentials in the livestock sector. *Nat. Clim. Chang.* **6**, 452–461 (2016).
9. Havlík, P. et al. Climate change mitigation through livestock system transitions. *Proc. Natl Acad. Sci. USA* **111**, 3709–3714 (2014).
10. Du, Y. et al. A global strategy to mitigate the environmental impact of China's ruminant consumption boom. *Nat. Commun.* **9**, 4133 (2018).
11. Bai, Z. et al. Relocate 10 billion livestock to reduce harmful nitrogen pollution exposure for 90% of China's population. *Nat. Food* **3**, 152–160 (2022).
12. Gu, B. Recoupling livestock and crops. *Nat. Food* **3**, 102–103 (2022).
13. Jin, S. et al. Decoupling livestock and crop production at the household level in China. *Nat. Sustain.* **4**, 48–55 (2021).
14. Muscat, A. et al. Principles, drivers and opportunities of a circular bioeconomy. *Nat. Food* **2**, 561–566 (2021).
15. Uwizeye, A. et al. Nitrogen flows in global pork supply chains and potential improvement from feeding swill to pigs. *Resour. Conserv. Recycl.* **146**, 168–179 (2019).
16. Bai, Z. et al. China's livestock transition: driving forces, impacts, and consequences. *Sci. Adv.* **4**, r8534 (2018b).
17. Wang, H. et al. Can dietary manipulations improve the productivity of pigs with lower environmental and economic cost? A global meta-analysis. *Agr. Ecosyst. Environ.* **289**, 106748 (2020).
18. O'Neill, B.C. et al. Meeting report of the workshop on the nature and use of new socioeconomic pathways for climate change research. *Clim. Change* **122**, 387–400 (2014).
19. Chinese Nutrition Society. *Dietary Guidelines for Chinese Residents* (People's Medical Publishing House, 2022).
20. Zhao, J. et al. China needs long-term solutions for African swine fever. *Sci. Bull.* **64**, 1469–1471 (2019).
21. Xu, Z. et al. Impacts of international trade on global sustainable development. *Nat. Sustain.* **3**, 964–971 (2020).
22. Yao, G. et al. The increasing global environmental consequences of a weakening US–China crop trade relationship. *Nat. Food* **8**, 578–586 (2021).

23. He, P. et al. Environmental impacts of dietary quality improvement in China. *J. Environ. Manag.* **240**, 518–526 (2019).
24. Tukker, A. et al. Environmental and resource footprints in a global context: Europe's structural deficit in resource endowments. *Glob. Environ. Chang.* **40**, 171–181 (2016).
25. FAO. Food-based dietary guidelines 2022. *FAO* https://www.fao.org/nutrition/education/food-dietary-guidelines/en/ (2022).
26. Lassaletta, L. et al. Future global pig production systems according to the Shared Socioeconomic Pathways. *Sci. Total Environ.* **665**, 739–751 (2019).
27. FAO. The future of food and agriculture—alternative pathways to 2050. *FAO* https://www.fao.org/global-perspectives-studies/resources (2018).
28. Chaudhary, A. & Krishna, V. Country-specific sustainable diets using optimization algorithm. *Environ. Sci. Technol.* **53**, 7694–7703 (2019).
29. Komarek, A. M. et al. Income, consumer preferences, and the future of livestock-derived food demand. *Glob. Environ. Chang.* **70**, 102343 (2021).
30. Zhang, S. et al. Pork production systems in China: a review of their development, challenges and prospects in green production. *Front. Agr. Sci. Eng.* **8**, 15–24 (2021).
31. National Bureau of Statistics of the People's Republic of China. *China Statistical Yearbook* (China Statistics Press, 2018).
32. Wei, S. et al. Environmental, economic and social analysis of peri-urban pig production. *J. Clean. Prod.* **129**, 596–607 (2016).
33. Tan, M. X. et al. Operational costs and neglect of end-users are the main barriers to improving manure treatment in intensive livestock farms. *J. Clean. Prod.* **289**, 125149 (2021).
34. Chadwick, D. et al. Improving manure nutrient management towards sustainable agricultural intensification in China. *Agr. Ecosyst. Environ.* **209**, 34–46 (2015).
35. Zhu, Z. et al. Integrated livestock sector nitrogen pollution abatement measures could generate net benefits for human and ecosystem health in China. *Nat. Food* **3**, 161–168 (2022).
36. Zhang, X. et al. Societal benefits of halving agricultural ammonia emissions in China far exceed the abatement costs. *Nat. Commun.* **11**, 4357 (2020).
37. Lacoste, M. et al. On-farm experimentation to transform global agriculture. *Nat. Food* **3**, 11–18 (2022).
38. Zhang, N. et al. Reducing ammonia emissions from dairy cattle production via cost-effective manure management techniques in China. *Environ. Sci. Technol.* **53**, 11840–11848 (2019).
39. Fan, L. et al. Decreasing farm number benefits the mitigation of agricultural non-point source pollution in China. *Environ. Sci. Pollut.* **26**, 464–472 (2018).
40. Herrero, M. et al. Livestock, livelihoods and the environment: understanding the trade-offs. *Curr. Opin. Environ. Sustain.* **1**, 111–120 (2009).
41. Mottet, A. et al. Livestock: on our plates or eating at our table? A new analysis of the feed/food debate. *Glob. Food Secur.* **14**, 1–8 (2017).
42. Jin, X. et al. Nitrogen budgets of contrasting crop-livestock systems in China. *Environ.Pollut.* **288**, 117633 (2021).
43. Zhang, X. et al. Benefits and trade-offs of replacing synthetic fertilizers by animal manures in crop production in China: a meta-analysis. *Glob. Change Biol.* **26**, 888–900 (2019).
44. Xue, L. et al. China's food loss and waste embodies increasing environmental impacts. *Nat. Food* **2**, 519–528 (2021).
45. Willett, W. et al. Food in the Anthropocene: the EAT–Lancet Commission on healthy diets from sustainable food systems. *Lancet* **393**, 447–492 (2019).
46. Gan, M. et al. High altitude adaptability and meat quality in Tibetan pigs: a reference for local pork processing and genetic improvement. *Animals* **9**, 1080 (2019).
47. Allen, T. et al. Global hotspots and correlates of emerging zoonotic diseases. *Nat. Commun.* **8**, 1124 (2017).
48. IPCC. IPCC Guidelines for National Greenhouse Gas Inventories. In *Agriculture, Forestry and Other Land Use* Vol. 4 (2006).
49. Lei, A. et al. The nitrogen footprint of food products in the European Union. *J. Agr. Sci.* **152**, 20–33 (2014).
50. Günther, J. et al. Carbon and phosphorus footprint of the cotton production in Xinjiang, China, in comparison to an alternative fibre (Apocynum) from Central Asia. *J. Clean. Prod.* **148**, 490–497 (2017).
51. National Development and Reform Commission of the People's Republic of China. *National Cost–Benefit Compilation of Agricultural Products* (China Statistics Press, 2018).
52. Mason-D'Croz, D. et al. Modelling the global economic consequences of a major African swine fever outbreak in China. *Nat. Food* **1**, 221–228 (2020).
53. Herrero, M. & Thornton, P. K. Livestock and global change: emerging issues for sustainable food systems. *Proc. Natl Acad. Sci. USA* **110**, 20878–20881 (2013).
54. Chen, X. P. et al. Integrated soil-crop system management for food security. *Proc. Natl Acad. Sci. USA* **108**, 6399–6404 (2011).
55. Chen, X. P. et al. Producing more grain with lower environmental costs. *Nature* **514**, 486–489 (2014).
56. Xia, L. et al. Can knowledge-based N management produce more staple grain with lower greenhouse gas emission and reactive nitrogen pollution? A meta-analysis. *Glob. Change Biol.* **23**, 1917–1925 (2017).
57. Chen, D. Nutrition and feed strategies for sustainable swine production in China. *Fron. Agric. China* **3**, 471–477 (2009).
58. Reckmann, K., Traulsen, I. & Krieter, J. Life cycle assessment of pork production: a data inventory for the case of Germany. *Livest. Sci.* **157**, 586–596 (2013).
59. Hou, Y., Velthof, G. L. & Oenema, O. Mitigation of ammonia, nitrous oxide and methane emissions from manure management chains: a meta-analysis and integrated assessment. *Glob. Change Biol.* **21**, 1293–1312 (2015).
60. Hou, Y. et al. Nutrient recovery and emissions of ammonia, nitrous oxide, and methane from animal manure in Europe: effects of manure treatment technologies. *Environ. Sci. Technol.* **51**, 375–383 (2017).
61. Wang, Y. et al. Mitigating greenhouse gas and ammonia emissions from swine manure management: a system analysis. *Environ. Sci. Technol.* **51**, 4503–4511 (2017).
62. Ma, L. et al. Modeling nutrient flows in the food chain of China. *J. Environ. Qual.* **39**, 1279–1289 (2010).

Acknowledgements

This work was supported by the National Natural Science Foundation of China (NSFC, grant no. 31772393 to Y.H.), the National Key R&D Program of China funded by the Ministry of Science and Technology of the People's Republic of China (MOST, grant no. 2016YFE0103100 to Y.H.), the Program of Advanced Discipline Construction in Beijing (Agriculture Green Development to Y.H. and B.T.), the High-level Team Project of China Agricultural University (CAU to Y.H.) and Agriculture Green Development Program sponsored by China Scholarship Council and Hainan University (no. 201913043 to L.Z. and W.L.).

Author contributions

B.T., L.Z., Y.H. and O.O. designed the research; B.T., L.Z. and W.L. developed the model; B.T., L.Z., Y.H. and O.O. analysed data; B.T., L.Z., Y.H., O.O., G.V., W.M. and F.Z. wrote the paper. All authors contributed to analysis of the results. All authors read and commented on various drafts of the paper.

Competing interests

The authors declare no competing interests.

Additional information

Supplementary information The online version contains supplementary material available at https://doi.org/10.1038/s43016-022-00640-6.

Correspondence and requests for materials should be addressed to Yong Hou.

Peer review information *Nature Food* thanks Hongmin Dong, Aimable Uwizeye and the other, anonymous, reviewer(s) for their contribution to the peer review of this work.

Reprints and permissions information is available at www.nature.com/reprints.

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

nature portfolio

Corresponding author(s): Yong Hou

Last updated by author(s): Oct 16, 2022

Reporting Summary

Nature Portfolio wishes to improve the reproducibility of the work that we publish. This form provides structure for consistency and transparency in reporting. For further information on Nature Portfolio policies, see our Editorial Policies and the Editorial Policy Checklist.

Statistics

For all statistical analyses, confirm that the following items are present in the figure legend, table legend, main text, or Methods section.

n/a	Confirmed	
☒	☐	The exact sample size (n) for each experimental group/condition, given as a discrete number and unit of measurement
☒	☐	A statement on whether measurements were taken from distinct samples or whether the same sample was measured repeatedly
☒	☐	The statistical test(s) used AND whether they are one- or two-sided *Only common tests should be described solely by name; describe more complex techniques in the Methods section.*
☒	☐	A description of all covariates tested
☐	☒	A description of any assumptions or corrections, such as tests of normality and adjustment for multiple comparisons
☐	☒	A full description of the statistical parameters including central tendency (e.g. means) or other basic estimates (e.g. regression coefficient) AND variation (e.g. standard deviation) or associated estimates of uncertainty (e.g. confidence intervals)
☒	☐	For null hypothesis testing, the test statistic (e.g. F, t, r) with confidence intervals, effect sizes, degrees of freedom and P value noted *Give P values as exact values whenever suitable.*
☒	☐	For Bayesian analysis, information on the choice of priors and Markov chain Monte Carlo settings
☒	☐	For hierarchical and complex designs, identification of the appropriate level for tests and full reporting of outcomes
☒	☐	Estimates of effect sizes (e.g. Cohen's d, Pearson's r), indicating how they were calculated

Our web collection on statistics for biologists contains articles on many of the points above.

Software and code

Policy information about availability of computer code

Data collection	No software was used for data collection.
Data analysis	We used R4.1.0 to visualize the results.

For manuscripts utilizing custom algorithms or software that are central to the research but not yet described in published literature, software must be made available to editors and reviewers. We strongly encourage code deposition in a community repository (e.g. GitHub). See the Nature Portfolio guidelines for submitting code & software for further information.

Data

Policy information about availability of data

All manuscripts must include a data availability statement. This statement should provide the following information, where applicable:

- Accession codes, unique identifiers, or web links for publicly available datasets
- A description of any restrictions on data availability
- For clinical datasets or third party data, please ensure that the statement adheres to our policy

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Human research participants

Policy information about studies involving human research participants and Sex and Gender in Research.

Reporting on sex and gender	n/a
Population characteristics	n/a
Recruitment	n/a
Ethics oversight	n/a

Note that full information on the approval of the study protocol must also be provided in the manuscript.

Field-specific reporting

Please select the one below that is the best fit for your research. If you are not sure, read the appropriate sections before making your selection.

☐ Life sciences ☐ Behavioural & social sciences ☒ Ecological, evolutionary & environmental sciences

For a reference copy of the document with all sections, see nature.com/documents/nr-reporting-summary-flat.pdf

Ecological, evolutionary & environmental sciences study design

All studies must disclose on these points even when the disclosure is negative.

Study description	Nearly half of global pork production and consumption occurs in China, but the transition towards intensification is associated with worsening environmental impacts. Here, we explore scenarios for implementing structural and technological changes across the pork supply chain to improve environmental sustainability and meet future demand. Following the middle-of-the-road socioeconomic pathway (SSP2), we estimate the environmental footprints from the pork supply chain will increase by ~50% from 2017 to 2050. Reducing pork consumption and utilizing technologies that improve feed crop production could reduce phosphorus and nitrogen losses by three quarters and a third, respectively, with modest reductions in greenhouse gas emissions and cropland area. Increased feed and pork imports would decrease domestic environmental footprints and meet demand, but increase footprints elsewhere. We conclude that farm-specific technologies and structural adjustments can support the development of rural, small-scale pig farms near cropland and promote circular economy principles.
Research sample	n/a
Sampling strategy	n/a
Data collection	The data was collected from existing database, statistics and published literature.
Timing and spatial scale	n/a
Data exclusions	n/a
Reproducibility	n/a
Randomization	n/a
Blinding	n/a

Did the study involve field work? ☐ Yes ☒ No

Reporting for specific materials, systems and methods

We require information from authors about some types of materials, experimental systems and methods used in many studies. Here, indicate whether each material, system or method listed is relevant to your study. If you are not sure if a list item applies to your research, read the appropriate section before selecting a response.

Materials & experimental systems

n/a	Involved in the study
☒	☐ Antibodies
☒	☐ Eukaryotic cell lines
☒	☐ Palaeontology and archaeology
☒	☐ Animals and other organisms
☒	☐ Clinical data
☒	☐ Dual use research of concern

Methods

n/a	Involved in the study
☒	☐ ChIP-seq
☒	☐ Flow cytometry
☒	☐ MRI-based neuroimaging