

RESEARCH ARTICLE

ENVIRONMENTAL SCIENCES

Addressing China's grand challenge of achieving food security while ensuring environmental sustainability

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China's increasingly urbanized and wealthy population is driving a growing and changing demand for food, which might not be met without significant increase in agricultural productivity and sustainable use of natural resources. Given the past relationship between lack of access to affordable food and political instability, food security has to be given a high priority on national political agendas in the context of globalization. The drive for increased food production has had a significant impact on the environment, and the deterioration in ecosystem quality due to historic and current levels of pollution will potentially compromise the food production system in China. We discuss the grand challenges of not only producing more food but also producing it sustainably and without environmental degradation. In addressing these challenges, food production should be considered as part of an environmental system (soil, air, water, and biodiversity) and not independent from it. It is imperative that new ways of meeting the demand for food are developed while safeguarding the natural resources upon which food production is based. We present a holistic approach to both science and policy to ensure future food security while embracing the ambition of achieving environmental sustainability in China. It is a unique opportunity for China to be a role model as a new global player, especially for other emerging economies.

FOOD SECURITY IN CHINA WITHIN A GLOBAL CONTEXT

China is entering a new era of rapid urbanization (fig. S1), which is considered to be the biggest driver of economic growth by the Chinese leadership (1). Although the annual population growth rate in China (fig. S2) has slowed to 0.49% in 2013 (2), the population is still expected to grow by an additional 60 million in the next 15 years (3). Although per capita consumption of many foods and feeds in China is still lower than those in developed countries (4, 5), urbanization and increasing wealth (fig. S3), together with a large population and changing dietary preferences, are expected to be the main drivers of food demand in the coming two decades (5). Growing demand in China will place increased pressure on the global markets, which, together with increased transport and storage costs, may potentially result in escalating food and feed prices. The necessity of significantly increasing domestic agricultural production is a priority if food security is to be achieved. Given the past relationship between lack of access to affordable food and political instability (6), food security has to be given a high priority on national political agendas in the context of globalization.

Within China, changing dietary preferences are already reflected in a shift in the structure of production from one dominated by staple grains toward increased production of higher-value horticultural and animal products (livestock and aquaculture) (fig. S4). In

addition, China increasingly imports oilseeds, soybeans, edible oils, and dairy products, which may also bring uncertainty in global markets. The pressure on food production has also stimulated heated debates on whether genetically modified organisms should be widely grown in China, because there are popular concerns on uncertainties around the potential human and environmental health risks (7, 8).

As a result, rural development has been placed firmly at the top of the policy agenda in China, highlighted by agriculture, the countryside and farmers being central to every "National 1st policy document," which has been issued since 2004 (9). In addition to the need to address future food security issues, the Chinese leadership has recently proposed an ambition of achieving environmental sustainability as part of an "ecological civilization" as presented at the 18th Plenary Congress of the Communist Party of China (10). This implies the need to adopt appropriate environmental management measures and interventions and to undertake restoration of currently degraded environments. This will undoubtedly mark a move away from purely economic-driven growth to a more balanced and sustainable development that supports broader environmental and social contexts.

ENVIRONMENTAL CHALLENGES FOR ACHIEVING FOOD SECURITY

Food security in China is undoubtedly under threat as limited arable land availability, deteriorated soil quality, water scarcity and pollution, climate change, and intensive reliance on fertilizers and pesticides have become widespread issues, which will all begin to limit or reduce agricultural production (11, 12). The drive for increased food production has had a significant impact on the environment as manifested

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through deterioration in the quality of air, soil, and water, and reduction in the availability of water. In turn, the deterioration in ecosystem quality due to historic and current levels of pollution will potentially compromise the food production system in China. Evidence of food quality issues resulting from environmental contamination is now widespread, and the frequent reports of food contamination have caused great public concern over food safety in China (13).

Looming water shortages in China represent a serious threat to food security (fig. S5) because of the highly uneven distribution of surface water resources nationally and the rising demands from irrigation, population increase, and rapid urbanization (12). Furthermore, the use of water for irrigation has significantly compromised the availability of water resources for ecology and other purposes (14). The decline in groundwater tables over the last few decades is well documented (15) and has significant implications for the ecological quality of wetlands, rivers, and lake ecosystems. Moreover, serious surface water pollution caused by rapid urbanization, industrialization, and formation of city clusters in China aggravates water resource allocation problems because poor water quality is unsuitable for some purposes. Surface water pollution in some basins has reached the point where much of the resource is unsuitable for drinking and even for irrigation (fig. S6). Gray water irrigation is an effective method to alleviate the shortage of water resources, but it is one of the main sources of heavy metal pollution in farmland soils and river water. The main sources of heavy metals in farmland soil also include mining and smelting, sludge reuse, and fertilizer application (16).

In an effort to increase productivity, nitrogen and phosphorus fertilizers, supplied at low cost and with subsidies in China, have been widely applied to soils. The overuse of mineral fertilizer has resulted in serious impacts in the aquatic environment as phosphorus and nitrate are leached from soils. In 2007, the area of eutrophic lakes in China was estimated to be 8700 km² from only 135 km² in 1967 (17), and the number of “red tides” reported in coastal seas has risen from 4 in the 1980s to 80 in the 2000s (18).

Agriculture is a major contributor of reactive nitrogen emission to the atmosphere (fig. S7). Ammonia emission, which is mainly emitted from nitrogen fertilizer and animal production systems, is estimated to have risen from about 5.8 Tg NH₃-N for all of China in 1980 to 14.7 Tg NH₃-N in 2010 (19). The overapplication of mineral fertilizers to crops has also contributed to the significant increase in nitrogen oxide emission, along with more rapidly increased vehicle, power plant, and industrial emissions from about 1.5 Tg NO_x-N in 1980 to about 6.4 Tg NO_x-N in 2010 (19). These gases are climate forcers and contribute to global climate change and to hemispheric air pollution issues. It is also clear that agricultural reactive nitrogen sources may play an important role in the air pol-

lution (for example, secondary aerosol or PM_{2.5} pollution) in China’s major cities (19, 20). Air pollution has a significant but negative impact on crop productivity (table S1), for example, future projections of O₃ concentrations indicate a potential 18% loss of winter wheat production across China (21).

Efforts to increase food production through the control of crop pests and diseases (22) have led to the widespread use of herbicides and pesticides. On average, usage of pesticides per unit area in China is twice the world average level, and as a result, organic chemicals derived from pesticides and herbicides are widely found in rivers and soils (23). Soil erosion promoted by poor tillage and soil management provides large fluxes of sediment to river systems and also represents a significant loss of the soil resource itself. China is among the most affected countries in the world in terms of the extent, intensity, and economic impact of land degradation. Current estimates suggest that greater than 40% of the land area (3 million to 4 million km²) is adversely affected by wind and water erosion, overgrazing, deforestation, and salinization (24).

The challenge, therefore, is not only to produce more food but also to produce it sustainably and without environmental degradation (Fig. 1). This requires food production to be considered as part of an environmental system (soil, air, water, and biodiversity) and not independent from it. Future food production must also consider the direct and indirect impacts of climate change (25). It is imperative that new ways of meeting the demand for food are developed, such as integrated nutrient management (7), while, at the same time, safeguarding the natural resources upon which food production is based (Fig. 2). There is a need to develop a sustainable agricultural system that advances multiple goals—crop productivity, resource

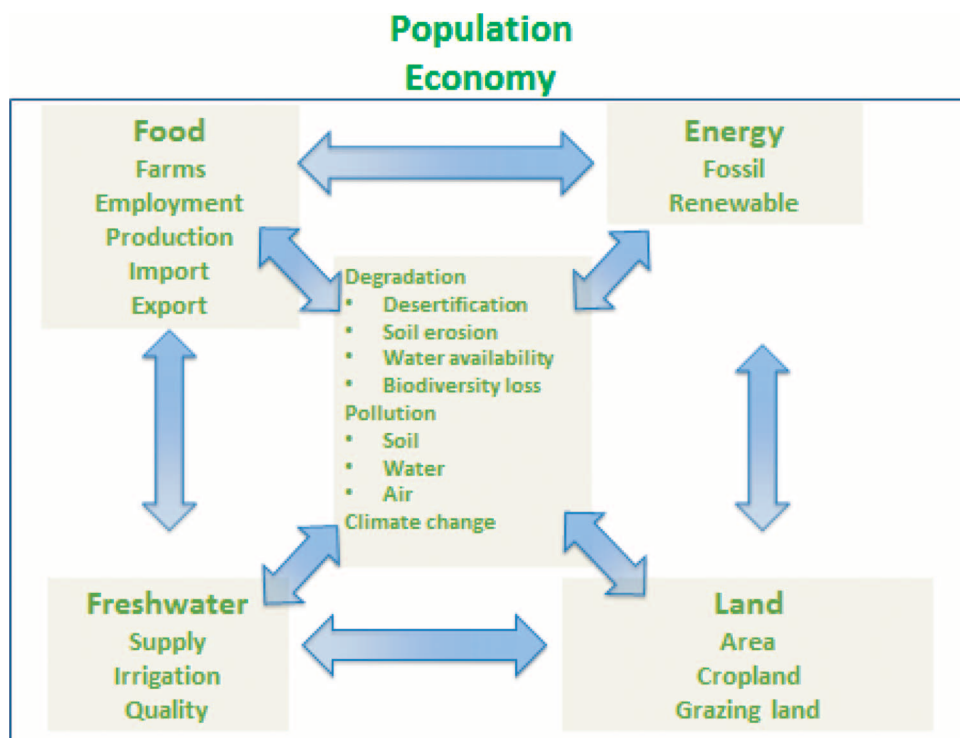


Fig. 1. Global challenges and interrelations within the water-food-energy nexus.

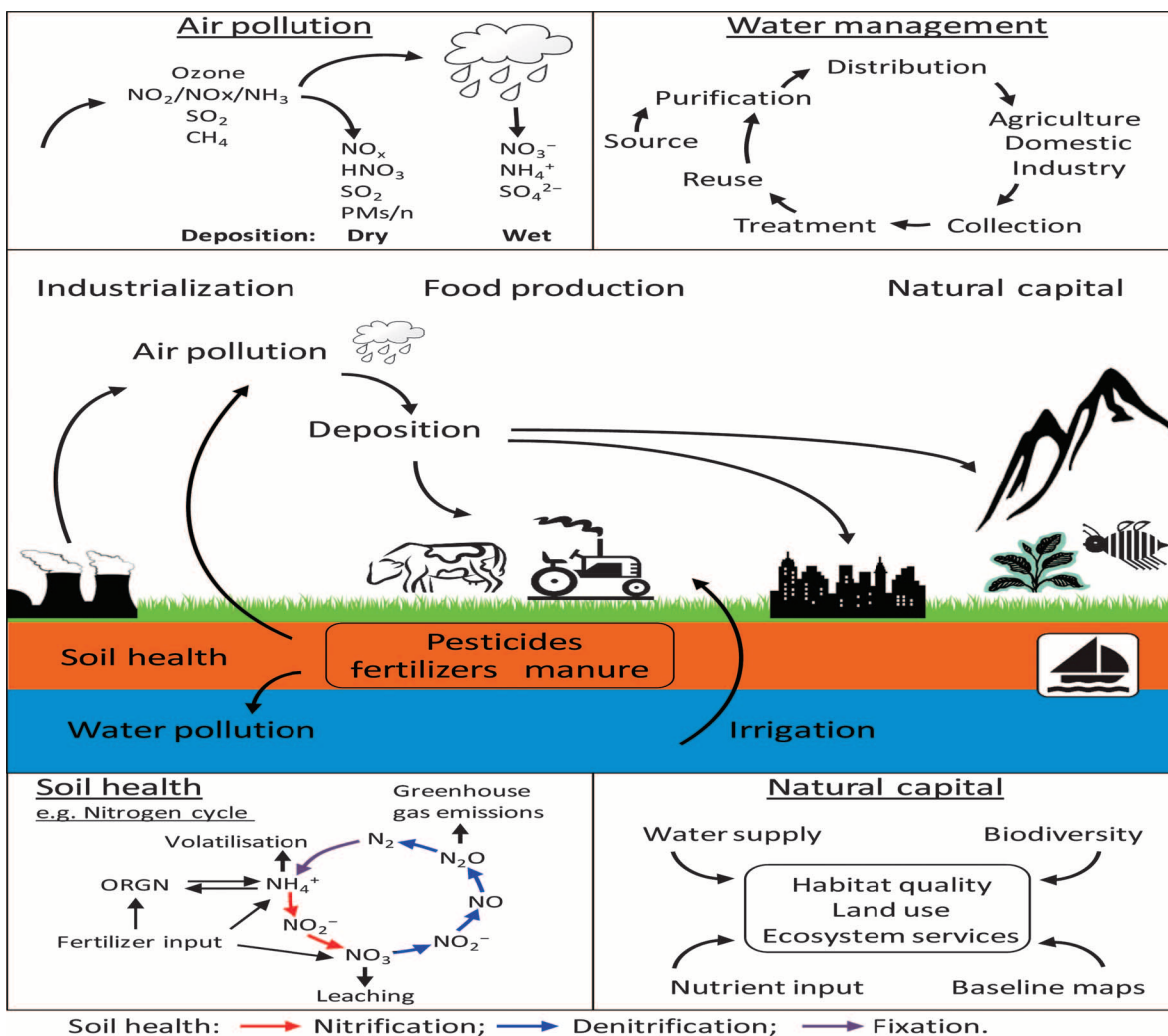


Fig. 2. Interaction between food production and environmental systems. Courtesy of Ian Toth.

stewardship, health, social well-being, farm income, and rural development (26).

POLICIES FOR ENSURING FOOD SECURITY WHILE ACHIEVING ENVIRONMENTAL SUSTAINABILITY

Science-based “ecological red line” must be defined to guarantee arable land for food production

The concept of an ecological red line was proposed to achieve the ambitious strategy of an ecological civilization by the current Chinese leadership at the 18th Plenary Congress of the Communist Party of China (10). The Third Plenum of the 18th Party Congress report highlighted that changes “unprecedented in both scale and degree” are necessary to address the growing environmental problems facing the country. There is an urgent need to define a methodology to support the Chinese government’s ecological red line, which embraces the principle of environmental protection informed by a wider evaluation of ecosystem services and focused on safeguarding natural capital. A key feature of this will be the need to collate available information on the state of ecosystems and the ecosystem

services they provide at different spatial scales across China, and to link this with the wider mapping of drivers of change, including future climate scenarios. This “natural capital” assessment and accounting will provide the necessary holistic approach to balance increased food production and environmental sustainability (Fig. 2). Such an assessment will enable the identification of areas where environmental restoration/ remediation is required and appropriate.

Environmental policy and agricultural policy must be coordinated and balanced to maintain natural capital for sustainable food supply and food safety

The understanding that environmental systems and food production are inherently linked, whereby air, water, and soil provide the natural capital that is essential for food production, must form the basis of both agricultural and environmental policy development and reform. Environmental policy and agricultural policy must support a resource-efficient economy, advocate support for ecological and organic farming systems in future food security (26), protect people’s health, and ensure that the underpinning natural capital is maintained. For example, in recent years, the Ministry of Water Resources of China has established

“the strictest system of water resource management,” operationalized through the “Three Red Lines” policy, which sets targets for total water use, the establishment of water use efficiency indicators, and the need for water quality standards to be achieved up to 2030. These challenging targets reflect the government’s concern for developing a more sustainable approach to water resources management, but it is unclear how meeting this challenge can be achieved without the development of concomitant policies relating to agricultural production and land use.

Food safety issues relating to environmental pollution have prompted the creation of alternative food networks, such as community agriculture and garden production. A system of progressively stringent food quality production standards, such as “hazard free,” “green food,” and “organic food,” has been introduced (27). The governmental supports to establish ecolabeling for various food quality standards are encouraging. Although the recent rise of farmers’ markets and community-supported agriculture represents only a small segment of the food system, it may provide a new avenue to improve China’s food safety in the future (28).

Fundamentally, environmental and agricultural policy should attempt to integrate natural science understanding within a socioeconomic framework, which encourages and supports change and addresses issues of governance, equity, empowerment, and resilience. In practice, this requires an appropriate science to policy interface at the highest levels of governance and interaction between environmental scientists and farmers on the ground.

Integrated research programs on environmental sustainability and food security should be implemented

Past and current studies on food security and environmental sustainability in China are discipline-based, and data describing the issues in space and time are often collected using different methods with little or no coordinated management of data. As a result, data transfer and access are limited, hampering rigorous scientific evaluation of the magnitude and spatial extent of environmental issues. In China, integrated collaborative research programs and projects are needed to address the complex questions around food production, environmental remediation, and future management. The integration of social and natural science research on these themes is extremely important and challenging. These would aim to cross current sectoral, institutional, and regional boundaries. In addition, such an approach would provide the basis for long-term interdisciplinary studies on processes, mechanisms, patterns, and key drivers of interactions between environmental system and food security, and for identifying systems solutions to preventing and reducing ecological deterioration and environmental pollution.

Capacity building must be considerably strengthened for delivering sustainable options for food security

In China, basic agricultural infrastructure has been neglected for a long time, and priority must focus on construction and maintenance of water conservation facilities, such as reservoir, river, lake, canal and irrigation networks, precision farming systems and agricultural technologies, and improved natural vegetation and wetland conservation. Networks for technology transfer and support centers should be expanded and better connected at different levels to strengthen science communication and knowledge exchange with local stakeholders, managers, and farmers, through which to provide real-time agronomic assistance and technical support.

Governance structures must be changed for better coordination and consistency of policy-making in food security and ecological preservation

The responsibility for achieving food security and environmental sustainability in China falls between various governmental agencies (fig. S8), which potentially weakens both the efficiency and efficacy of policy delivery. The ambiguity, duplication, and lack of coordination of responsibility of many governmental departments increase transactions costs and delays in developing and implementing policy. In many instances, it is difficult for institutions to collaborate on identifying issues and possible solutions, for example, in tracing sources of water and soil pollution in food production regions and in the development of mitigation strategies. In this regard, China may learn some successful experiences from Europe. In the European Union, there has been a growing realization that further integration is necessary to respond to the interlinkages and cross-dependencies between sectoral policies. For example, the focus of environmental stewardship measures within Common Agricultural Policy is closely entwined with European water policy such as the Nitrates and Water Framework Directives because of the need to link diffuse pollution source control with environmental impacts and consequences (29, 30). It would be prudent, therefore, to revise how the governance of environmental protection in China is delivered and to better identify individual and collective responsibilities. Increasing transparency in the decision-making process would shorten the time to response and ensure that policies were equitably and consistently implemented. Sharing of all available environmental data between agencies and with scientists is fundamentally required to enable appropriate legislation to be developed and implemented at national, provincial, and local scales.

China has set itself a challenging goal of reducing the environmental footprint of meeting the growing food demands of a more affluent population. This challenge will only be met if the scientific community engages with policy-makers and land managers to ensure robust evidence used to assess the systems consequences of land use decisions cross all levels of society.

SUPPLEMENTARY MATERIALS

Supplementary material for this article is available at <http://advances.sciencemag.org/cgi/content/full/1/1/e1400039/DC1>

Fig. S1. The change in China’s urban and rural population (in millions) in 1980 to 2012.

Fig. S2. The change in China’s annual population growth rate (percentage) in 1970 to 2030.

Fig. S3. The increase in China’s real GDP since 1950 and the predicted continued increase to 2020.

Fig. S4. Per capita food consumption (kilogram per person) in China since 1980.

Fig. S5. Water availability index for China.

Fig. S6. Surface water pollution and grain yield in 2010.

Fig. S7. The increase in anthropogenic reactive nitrogen emissions in China since 1980.

Fig. S8. Governmental departments influencing food security.

Table S1. Aggregate wheat production loss (WPL) in the years 2000 and 2020 estimated by O₃ dose metrics [AOT40 (ppb.h), accumulated hourly ozone concentration over 40 ppb] for the top five wheat-producing provinces in China as well as for all of China.

REFERENCES AND NOTES

1. X. J. Yang, China’s rapid urbanization. *Science* **342**, 310 (2013).
2. Annual Statistics Data from National Bureau of Statistics of China (2013); <http://data.stats.gov.cn/workspace/index?m=hgnd>.
3. *World Population Prospects: The 2010 Revision* (UN DESA, New York, 2010); <http://esa.un.org/wpp/documentation/WPP%202010%20publications.htm>; *World Urbanization Prospects: The 2011 Revision* (UN DESA, New York, 2011); http://esa.un.org/wpp/ppt/CSIS/WUP_2011_CSIS_4.pdf.

4. J. M. Li, Z. H. Li, Physical limitations and challenges to grain security in China. *Food Sec.* **6**, 159–167 (2014).
5. K. John, Food consumption trends and drivers. *Philos. Trans. R. Soc. Lond. B Biol. Sci.* **365**, 2793–2807 (2010).
6. H. J. Brinkman, C. S. Hendrix, *Food Insecurity and Violent Conflict: Causes, Consequences, and Addressing the Challenges. Occasional Paper 24* (World Food Programme, Rome, 2011).
7. F. Zhang, X. Chen, P. Vitousek, Chinese agriculture: An experiment for the world. *Nature* **497**, 33–35 (2013).
8. R. Stone, Activists go on warpath against transgenic crops—And scientists. *Science* **331**, 1000–1001 (2011).
9. *Environmental Protection Report to the 11th National People's Congress of China* (Ministry of Environmental Protection of China, Beijing, 2011).
10. G. He, L. Zhang, A. P. J. Mol, Y. Lu, J. Liu, Revising China's environmental law. *Science* **341**, 133 (2013).
11. Y. L. Liu, C. Wen, X. J. Liu, China's food security soiled by contamination. *Science* **339**, 1382–1383 (2013).
12. J. Li, Food security water shortages loom as northern China's aquifers are sucked dry. *Science* **328**, 1462–1463 (2010).
13. H. F. Gale, D. H. Hu, Food safety pressure push integration in China's agricultural sector. *Am. J. Agri. Econ.* **94**, 483–488 (2012).
14. J. Li, C. Zang, S. Tian, J. Liu, H. Yang, S. Jia, L. You, B. Liu, M. Zhang, Water conservancy projects in China: Achievements, challenges and way forward. *Global Environ. Chang.* **23**, 633–643 (2013).
15. S. Khan, M. A. Hanjra, J. Mu, Water management and crop production for food security in China: A review. *Agri. Water Manage.* **96**, 349–360 (2009).
16. H. M. Chen, C. R. Zheng, C. Tu, Y. G. Zhu, Heavy metal pollution in soils in China: Status and countermeasures. *Ambio* **28**, 130–134 (1999).
17. X. C. Jin, *Oral Report About Concepts and Tactic of Aquatic Runoff Generation Mechanism Restoration in Lake Watershed in the International Lake Environment Committee from Xinhua News* (2009); http://news.xinhuanet.com/politics/2009-11/05/content_12391302.htm.
18. China Marine Environment Bulletin (China State Oceanic Administration, Beijing, 2013); <http://www.mem.gov.cn/gjgb/index.htm>.
19. X. J. Liu, Y. Zhang, W. X. Han, A. H. Tang, J. L. Shen, Z. L. Cui, P. Vitousek, J. W. Erisman, K. Goulding, P. Christie, A. Fangmeier, F. S. Zhang, Enhanced nitrogen deposition over China. *Nature* **494**, 459–462 (2013).
20. X. J. Liu, L. Duan, J. M. Mo, E. Z. Du, J. L. Shen, X. K. Lu, Y. Zhang, X. B. Zhou, C. E. He, F. S. Zhang, Nitrogen deposition and its ecological impact in China: An overview. *Environ. Pollut.* **159**, 2251–2264 (2011).
21. H. Tang, M. Takigawa, G. Liu, J. Zhu, K. Kobayashi, A projection of ozone-induced wheat production loss in China and India for the years 2000 and 2020 with exposure-based and flux-based approaches. *Glob. Chang. Biol.* **19**, 2739–2752 (2013).
22. L. Zhang, Z. Huo, W. Li, Y. Jiang, Effects of climate change on the occurrence of crop insect pests in China. *Chin. J. Ecol.* **31**, 1499–1507 (2012).
23. S. H. Yang, T. Q. Song, Problems about usage of pesticide in China. *Manage. Agric. Sci. Tech.* **26**, 42–45 (2007).
24. L. Berry, *Land Degradation in China: It's Extent and Impact* (2003); http://rportal.net/library/content/frame/land-degradation-case-studies-02-china/at_download/file.
25. P. Eriksen, What is the vulnerability of a food system to global environmental change? *Ecol. Soc.* **13**, 14 (2008); <http://ecologyandsociety.org/vol13/iss2/art14/>.
26. B. D. McIntyre, H. R. Herren, J. Wakhungu, R. T. Watson, *Agriculture at a Crossroad: Global Report* (International Assessment of Agricultural Knowledge, Science & Technology for Development, IAASTD, Island Press, Washington, 2008); <http://www.unep.org/dewa/assessments/ecosystems/iaastd/tabid/105853/default.aspx>.
27. S. Zhenzhong, T. Schumilas, S. Scott, Characterising alternative food networks in China. *Agric. Hum. Values* 10.1007/s10460-014-9530-6 (2015).
28. S. Scott, Z. Si, T. Schumilas, A. Chen, Contradictions in state- and civil society-driven developments in China's ecological agriculture sector. *Food Policy* **45**, 158–166 (2014).
29. I. Heinz, Co-operative agreements and the EU Water Framework Directive in conjunction with the Common Agricultural Policy, *Hydrol. Earth Syst. Sci.* **12**, 715–726 (2008).
30. European Commission, *Impact Assessment: Common Agricultural Policy Towards 2020* (European Commission, Brussels, 2011); http://ec.europa.eu/agriculture/policy-perspectives/impact-assessment/cap-towards-2020/report/annex2e_en.pdf

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