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The long-term soil phosphorus balance across Chinese arable land

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Abstract

Quantifying temporal and spatial variation of soil phosphorus (P) input, output and balance across Chinese arable land is necessary for better P management strategies. Here, we address this challenge using a soil P budget to analyse the soil P balance in arable land across the whole of China, for the period 1980–2012. Results indicated that the total P input to soil increased from 22.5 kg P/ha in 1980 to 79.1 kg P/ha in 2012. However, the total P output from soil only increased from 17.9 kg P/ha in 1980 to 36.9 kg P/ha in 2012. Therefore, the average net soil P surplus in China increased from 4.6 kg P/ha in 1980 to 42.1 kg P/ha in 2012. Our research found great variation in soil P balances across different regions. Soil P balance varied between regions with the order of southeast (SE) > north central (NC) and the middle and lower reaches of Yangtze River (MLYR) > southwest (SW) > northwest (NW) > northeast (NE). Phosphorus that has accumulated in agricultural soil across China could theoretically meet crop P demands for approximately 4.8–12.0 yrs, depending on the bioavailability of P stored in soils. Increasing the return rates of manure and straw could substantially reduce the demand for fertilizer-P. This paper represents a basis for more targeted, regionally informed P fertilizer recommendations in Chinese soils.

Keywords: Soil P balance, long-term soil P accumulation, sustainable P management, P use efficiency

Introduction

Meeting the societal demand for food is a global challenge as recent estimates predict that global food demand will double within 30 yrs (Fixen *et al.*, 2015). Continued use of phosphorus (P) in agriculture is essential to meet future demand for food production (Oelkers & Valsami-Jones, 2008). Key challenges surrounding the stewardship of P have emerged over the last century, from the fundamentally finite nature of reserves of this mineral (Reijnders, 2014), through to the unequal global distribution of these reserves (Cooper *et al.*, 2011). Particular concern surrounds access to P resources to underpin future supplies of chemical P fertilizer, particularly given the need to ensure an adequate food supply for an increasing global population (Smil and Bennett, 2000; Elser & Bennett, 2011; Food and Agriculture Organization of the United Nations, 2015). However, the poor management of fertilizer-P, especially excessive application of P to soils, can result in a low level of P use efficiency (Ma *et al.*, 2011; Dhillon *et al.*, 2017) and contribute to environmental problems with water quality (Chen *et al.*, 2006; Carpenter, 2008; Childers *et al.*, 2011; Ni *et al.*, 2015; Steffen *et al.*, 2015). For example, in the United States, nearly half of the eutrophication in 2000 was believed to be caused by agricultural diffuse pollution (United States Environmental Protection Agency, 2000). In China, the transfer of P from arable soils to surface water has been described as one of the main factors resulting in eutrophication of receiving waters (Chen *et al.*, 2010). For example, lake eutrophication has developed rapidly during recent decades in China, with data showing that approximately 58% of 40 surveyed lakes were eutrophic or hypertrophic (Jin *et al.*, 2005). The First National Census of Pollution Sources of China indicated that the P load from agricultural sources contributed 67.4% of total P emission. Therefore, increasing the efficiency of fertilizer-P use is crucial for protecting the environment and sustaining the development of agriculture.

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Better quantifying P inputs and assessing the temporal and spatial variation of the soil P balance for the arable land of China would provide a stronger basis for future P management strategies and the control of eutrophication, thereby establishing more sustainable agricultural production systems (Sharpley, 2016). However, most previous studies of soil P balances in China have focused only on one specific year (Chen *et al*., 2008; Li & Jin, 2011; Wang *et al*., 2014), providing snapshot, static assessments and limited information regarding temporal changes in the soil P balance. Although there have been some temporal studies conducted on the soil P balance (Sheldrick *et al*., 2003; Liu *et al*., 2016; Wu *et al*., 2016; Bellarby *et al*., 2018), these were either performed at a national scale, or focused only on one province, therefore being unable to provide sufficient spatial disaggregation of the soil P balance across the whole of China.

In this paper, a soil P budget was used to quantify temporal and spatial changes in the soil P balance for China from 1980 to 2012. The objectives of this research were (i) to analyse P inputs and outputs; (ii) to analyse the temporal and spatial changes in the soil P balance; (iii) to evaluate the temporal changes in P use efficiency (PUE); and (iv) to explore the potential opportunities to substitute chemical fertilizers with organic resources for arable land across China.

Materials and methods

Study area

This study covers the majority of China's arable land at a provincial scale, incorporating 45 different crops. To support a spatially disaggregated assessment, six regions were defined, based on China's administrative divisions and geographical locations, and specific parameters related to our research were used for each region. The six regions comprised the northeast (NE), north central (NC), the middle and lower reaches of Yangtze River (MLRY), northwest (NW), southeast (SE) and southwest (SW) (Figure 1). Details of the characteristics of these six regions are summarised in Table 1.

The data used to estimate soil P balances originated from the China Agriculture Statistical Report from 1981 to 2013 (Ministry of Agriculture People's Republic of China, 1981–2013), an official and representative statistical report on China's yearly provincial agriculture and rural economy. More than fifty input variables were collated from this source, including crop yield, planting area, fertilizer consumption, as well as livestock types and numbers. Missing data were sourced from statistical yearbooks (e.g. China Statistical Yearbook) and published literature, or by averaging between adjacent years.

Soil phosphorus budget calculations

A soil P budget was calculated as the difference between P input and P output as follows:

$$P_{\text{balance}} = P_{\text{input}} - P_{\text{output}}, \qquad (1)$$

where P_{input} included total P input to the soil from chemical fertilizers, manure, atmospheric deposition, irrigation water, seeds, straw returned to field and cake fertilizers (the waste from oil crops). P_{output} included the total P output from the soil, including crop P removal and P loss through leaching, erosion and runoff during an annual cycle. Further details regarding these calculations are given in the Appendix S1.

Phosphorus use efficiency

The phosphorus use efficiency (PUE) used in this study is the simplest form of nutrient recovery efficiency, calculated as:

$$\text{Phosporous use efficiency (PUE)} = \frac{\text{Crop } P_{\text{removal}}}{P_{\text{input}}} \times 100\%, \qquad (2)$$

where crop removal in equation (2) refers to the crop P removal by aboveground biomass only (see supplementary information).

Scenario analyses for substitution of chemical fertilizer-P with organic resources

To maximize the opportunity for reducing chemical fertilizer-P application, organic resources of P including crop straw and manure were considered as potential substitutes for chemical fertilizer-P. We hypothesized that the return rates of straw and manure to a field could be improved by four grades (first, 10 and 5%; second, 20 and 10%; third, 30 and 15%; and fourth, 40 and 20%, respectively) based on the current situation (straw return rates varying from 15 to 60% across individual provinces, manure return rate 36%, except in Tibet and Qinghai which have a return rate of 5%). The residual demand for chemical fertilizer-P, calculated by crop P demand minus P provided by organic resources, was evaluated in each province based on these four scenarios.

Results

Phosphorus input and output

The main P inputs and outputs associated with the arable land of China from 1980 to 2012 show that total P input increased from 22.5 kg P/ha in 1980 to 79.1 kg P/ha in 2012 (Figure 2). Fertilizer-P, the main contributor to P inputs,

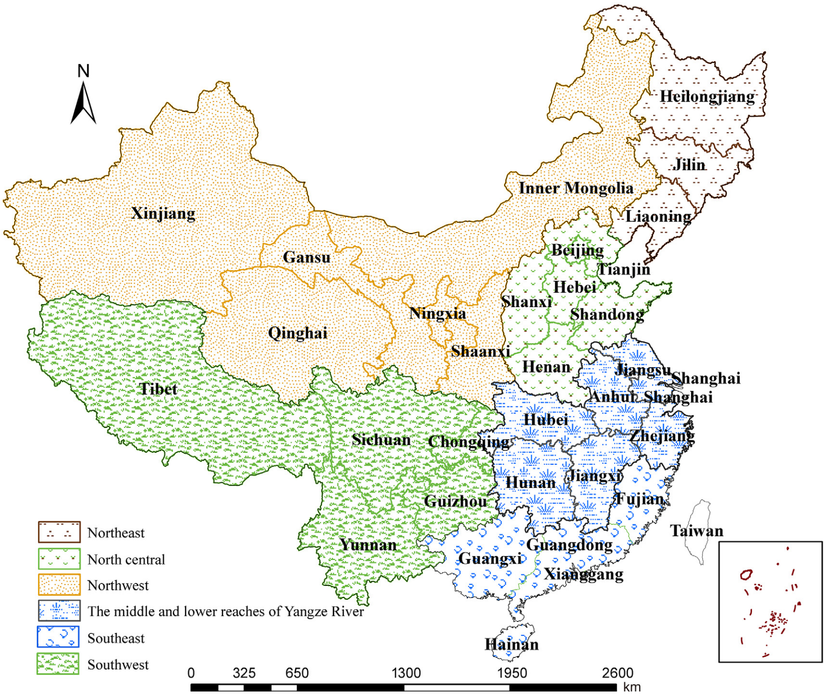

Figure 1 Geographical distribution of China's major agricultural production regions. [Colour figure can be viewed at wileyonlinelibrary.com]

showed a trend similar to the increase in total P input, with total fertilizer-P input increasing from 12.6 kg P/ha in 1980 to 60.1 kg P/ha in 2012. Although animal stocks and the yield of crop straw in China have grown substantially since the early 1950s (Li *et al.*, 2016a), at the national level, the average input of P to arable land from organic resources only increased slightly and the ratio of manure P to total P input showed a downward trend from 1980 to 2012. At the regional level, the total P input across all six regions considered in this research increased over time, although there was substantial variation in P input between regions (Table 2). The total P input in the SE region exceeded that in all other regions across the 1980s, 1990s and 2000s with the full order being SE > MLYR > NC > SW > NW > NE.

Crop removal was the main component of P output. However, the total P output only increased from 17.9 kg P/ha in 1980 to 36.9 kg P/ha in 2012. There were substantial variations in P output at the regional level (Table 2). Output of P was particularly high in MLYR, with the SE, SW and NC having larger P outputs in comparison with the NW and NE regions, with the latter being characterised by a relatively low P output.

Soil phosphorus surplus

From 1980 to 2012, the average soil P surplus in China showed an upward trend, increasing by 1.1 kg P/ha/yr. On average, the soil P surplus increased from 4.6 kg P/ha in 1980 to 42.1 kg P/ha in 2012 (Figure 2).

The temporal and spatial variations in net soil P balances in Chinese arable land were established for the six geographical regions, over the course of three decades from 1980. To evaluate changes in the net soil P balance in different regions of China between 1980 and 2012, the net soil P balance was compared across different time periods: the 1980s, 1990s and 2000s. Results showed that there were substantial variations in the net soil P balances across regions with the order of soil P surplus: SE > NC > MLYR > SW > NW > NE (Table 2).

Phosphorus use efficiency

The average PUE in arable land was 72% (ranging between 32 and 163%) in the 1980s; 55% (ranging between 28 and 134%) in the 1990s; and 45% (ranging between 20 and 83%) in the 2000s, meaning that approximately 28, 45 and 55% of total P input initially accumulated in the soil or was lost through leaching and runoff (Figure 3a–c). Between the 1980s and 2000s, PUE declined across China, as evidenced by consistent reductions in the gradient of the regression lines in Figure 3.

Accumulation of soil phosphorus

The accumulation of soil P between 1980 and 2012 averaged 841 kg P/ha across the whole of China, ranging from 224 kg P/ha in Heilongjiang to 2009 kg P/ha in Hainan (Table 3). Results also indicated that, on average, P retained in the soil in 2012 accounted for approximately 56.6% of total P input, ranging from 23.4% in Shanghai to 71.5% in Hainan. Compared to the crop demand for P in 2012, the accumulation of soil P between 1980 and 2012 could

Table 1 Characteristics of six agricultural regions in China (agricultural regions were grouped based on geographical locations and China's administrative division: NE, northeast; NC, north central; NW, northwest; MLYR, the middle and lower reaches of the Yangtze River; SE, southeast; SW, southwest)

Regions	Provinces	Proportion of farms (cultivated land > 0.67 ha)[a]	Proportion of arable land (slope > 15 degree)[a]	Proportion of grain crop planted area to total planted area[a]	Main crops[b]	Cropping systems[a]	Main soil types[b]	Main climatic types
NE	Heilongjiang	83%	1%	90%	Maize, rice, soybean, cabbage, cucumber, flax	Mono-cropping system, predominant with rice and maize	Black soil, cinnamon soil, meadow soil	Temperate continental monsoon climate
	Jilin	73%	3%	88%				
	Liaoning	32%	2%	85%				
SE	Fujian	6%	18%	55%	Maize, wheat, rice, rape, tomato, sugarcane, rapeseed, banana, cassava, pepper, pineapple, tea	Double or Triple cropping systems, predominant with rice and maize	Yellow brown soil, red soil, purple soil, paddy soil	Tropical and subtropical monsoon climate
	Guangdong	3%	4%	56%				
	Guangxi	11%	9%	56%				
	Hainan	8%	2%	54%				
NC	Beijing	8%	3%	69%	Wheat, maize, cotton, cabbage, cucumber, peanuts, pumpkin, eggplants, tomato, cauliflower	Double cropping systems, predominant with wheat and maize	Cinnamon soil, fluvo-aquic soil, brown soil, saline alkali soil	Temperate continental monsoon climate, subtropical monsoon climate, temperate monsoon climate
	Hebei	13%	2%	72%				
	Henan	10%	1%	68%				
	Shandong	7%	2%	65%				
	Shanxi	27%	16%	82%				
	Tianjin	11%	0	66%				
NW	Gansu	41%	31%	71%	Maize, wheat, potato, cotton, cabbage, spinach, onion, carrot, cucumber, pepper, tomato, rapeseed	Mono or double cropping systems, predominant with wheat and maize	Loess soil, irrigation-silting soil, chestnut soil, grey calcareous soil, fluvo-aquic soil, desert soil	Temperate monsoon climate, plateau mountain climate
	Inner Mongolia	73%	1%	75%				
	Ningxia	51%	9%	72%				
	Qinghai	31%	20%	58%				
	Shaanxi	15%	34%	77%				
	Xinjiang	50%	1%	36%				
SW	Guizhou	4%	47%	64%	Maize, wheat, rice, rape, tomato, sugarcane, rapeseed, banana, cassava, pepper, pineapple, tea	Mono or Double cropping systems, predominant with rice and maize	Yellow brown soil, red soil, purple soil, paddy soil	Plateau mountain climate, tropical and subtropical monsoon climate
	Sichuan	5%	31%	69%				
	Tibet	33%	13%	74%				
	Yunnan	14%	48%	70%				
	Chongqing	3%	43%	70%				
MLYR	Anhui	12%	3%	73%	Wheat, maize, rice, cotton, cabbage, beans, sugarcane, citrus, banana, rapeseed, sesame	Double or Triple cropping systems, predominant with rice and maize	Yellow brown soil, fluvo-aquic soil, red soil, paddy soil	Subtropical monsoon climate
	Hubei	12%	17%	57%				
	Hunan	6%	10%	62%				
	Jiangsu	5%	0	69%				
	Jiangxi	11%	15%	67%				
	Shanghai	1%	0	41%				
	Zhejiang	2%	13%	50%				

[a]National Bureau of Statistics of China (2006). [b]Liu *et al.* (2017).

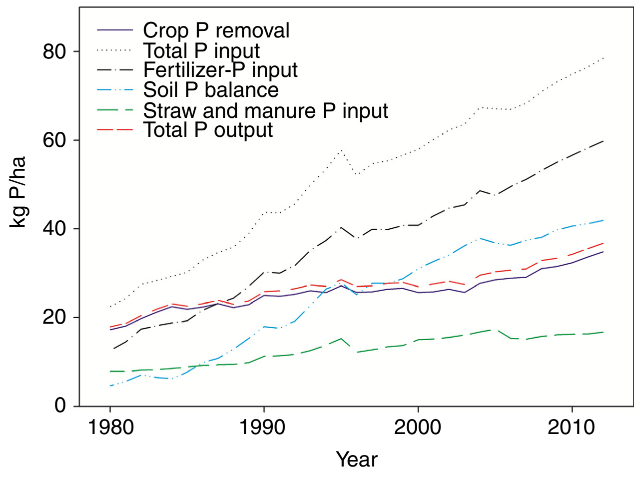

Figure 2 Historical trends of phosphorus input, output and balance in Chinese arable soils for the period 1980–2012. [Colour figure can be viewed at wileyonlinelibrary.com]

Table 2 Temporal and spatial changes in soil P input, output and balance in arable land across China

		Region (kg P/ha)					
Categories	Time	NE	NC	MLYR	NW	SE	SW
P input	1980s	21.6	28.5	43.1	16.6	50.4	30.6
	1990s	25.7	52.9	70.1	29.1	86.5	49.1
	2000s	35.1	80.8	89.3	40.6	114.9	63.2
P output	1980s	15.4	21.4	36.1	9.8	28.2	23.3
	1990s	19.0	28.9	42.9	13.3	34.8	31.3
	2000s	21.6	31.9	44.9	16.7	37.4	35.8
P balance	1980s	6.2	7.0	7.0	6.8	22.2	7.2
	1990s	6.7	24.1	27.2	15.8	51.7	17.8
	2000s	13.5	48.9	44.5	23.9	77.5	27.4

Northeast (NE), north central (NC), the middle and lower reaches of Yangtze River (MLYR), northwest (NW), southeast (SE), and southwest (SW).

theoretically support crop P demands for approximately 4.8–12.0 yrs, assuming that 20 or 50% of the accumulated soil P was ultimately plant available.

Opportunities to reduce chemical fertilizers with organic resources

Taking crop production in China in 2012 as an example, if the PUE was improved to 72%, as it was in the 1980s, the amount of P required to support the yields in 2012 was 5.3 Mt P. Under these circumstances, total external fertilizer-P demands were 3.2, 2.9, 2.6 and 2.3 Mt P across the four scenarios for straw and manure return to land, meaning that external P demands would be much lower than the actual

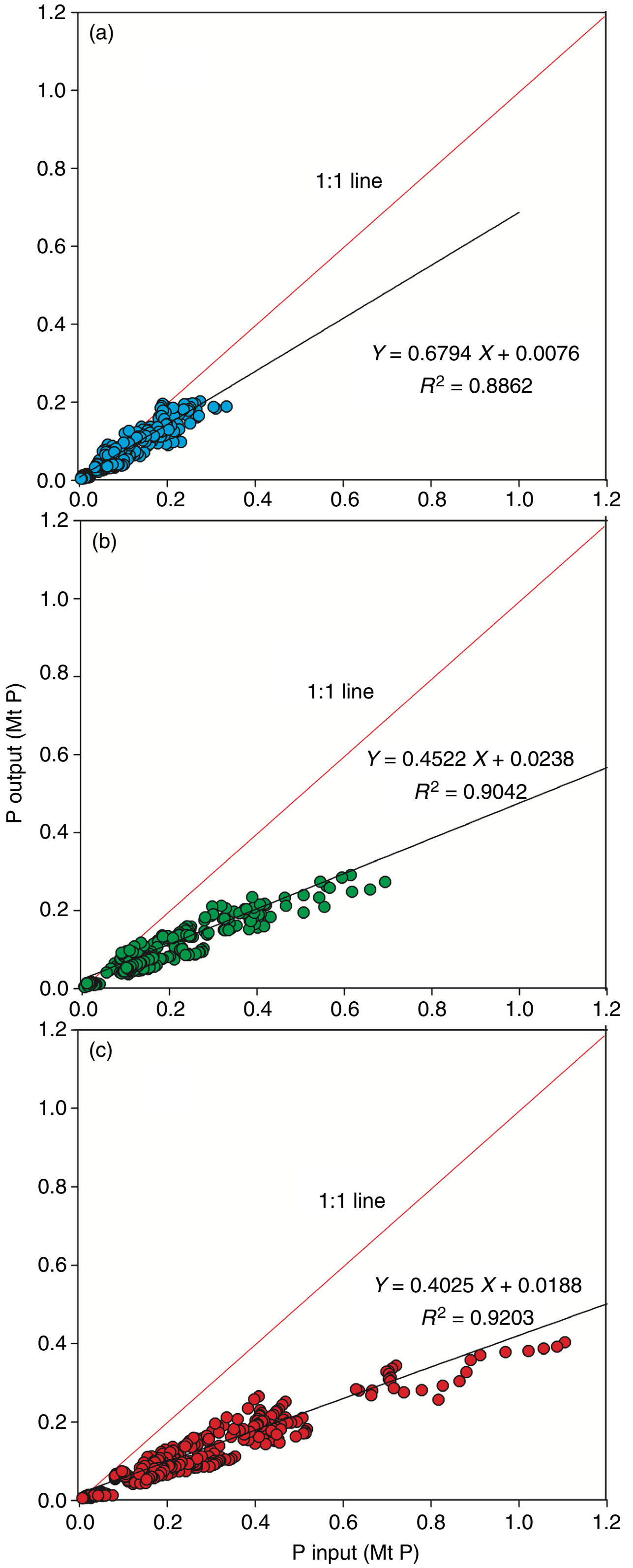

Figure 3 Phosphorus use efficiency, calculated as crop phosphorus removal divided by total phosphorus input to a system (a) in the 1980s, (b) in the 1990s and (c) in the 2000s. [Colour figure can be viewed at wileyonlinelibrary.com]

Table 3 Estimates of long-term accumulated soil phosphorus in arable land across China and the potential for soils to meet crop phosphorus demand according to two scenarios of soil phosphorus availability

			2012[b]				
Regions	Provinces	Legacy soil P 1980–2012 (kg P/ha)[a]	Total input (kg P/ha/yr)	Crop uptake (kg P/ha/yr)	Ratio of P retained in soil to total P input (%)	Years of crop P supply (20%)[c]	Years of crop P supply (50%)[c]
NE	Heilongjiang	223.5	34.6	22.4	35.3	2.0	5.0
	Jilin	226.5	48.2	28.5	40.9	1.6	4.0
	Liaoning	461.6	52.6	31.0	40.9	3.0	7.4
SE	Fujian	1577.4	111.9	35.8	68.0	8.8	22.1
	Guangdong	1622.3	103.1	34.8	66.3	9.3	23.3
	Guangxi	1776.8	127.0	39.2	69.1	9.1	22.6
	Hainan	2009.4	141.2	40.2	71.5	10.0	25.0
NC	Beijing	1096.0	93.8	39.3	58.2	5.6	14.0
	Hebei	812.4	74.8	39.5	47.2	4.1	10.3
	Henan	1443.6	140.0	50.5	63.9	5.7	14.3
	Shandong	1157.9	96.5	45.3	53.0	5.1	12.8
	Shanxi	595.9	47.7	18.1	62.0	6.6	16.4
	Tianjin	574.9	86.0	27.5	68.0	4.2	10.4
NW	Gansu	451.9	32.1	14.6	54.7	6.2	15.5
	Inner Mongolia	444.1	44.6	19.1	57.2	4.7	11.6
	Ningxia	425.0	44.4	20.2	54.5	4.2	10.5
	Qinghai	363.8	25.3	14.8	41.4	4.9	12.2
	Shaanxi	715.3	88.4	32.1	63.7	4.5	11.1
	Xinjiang	818.2	78.1	26.4	66.2	6.2	15.5
SW	Guizhou	233.1	47.5	35.4	25.4	1.3	3.3
	Sichuan	916.7	106.5	50.6	52.5	3.6	9.1
	Tibet	331.2	46.1	26.3	42.9	2.5	6.3
	Yunnan	875.4	97.1	38.3	60.5	4.6	11.4
	Chongqing	480.5	65.8	26.8	59.3	3.6	9.0
MLYR	Anhui	1337.5	122.2	49.8	59.3	5.4	13.4
	Hubei	1737.0	153.5	53.1	65.4	6.5	16.4
	Hunan	729.8	79.9	45.6	43.0	3.2	8.0
	Jiangsu	918.4	88.3	48.5	45.1	3.8	9.5
	Jiangxi	812.9	82.1	40.6	50.5	4.0	10.0
	Shanghai	591.4	68.4	52.3	23.4	2.3	5.7
	Zhejiang	312.4	58.0	30.8	46.8	2.0	5.1
China	Average	841.1	80.2	34.8	56.6	4.8	12.0

Northeast (NE), north central (NC), the middle and lower reaches of Yangtze River (MLYR), northwest (NW), southeast (SE) and southwest (SW). [a]The accumulation of soil P between 1980 and 2012. [b]The total P input, crop uptake and ratio of P retained in the soil to total P input in 2012. [c]The number of years the accumulated soil P (1980–2012) could theoretically support crop P demand, if 20 or 50% of that accumulated soil P was plant available. The ratios (20 and 50%) used in this calculation refer to Rowe *et al.* (2016).

fertilizer-P input that was determined from the agricultural statistics. If this strategy had been adopted in 2012, approximately 3.3, 3.6, 3.8 and 4.1 Mt P would have been saved across the four assumed scenarios of straw and manure return to land. Based on this assumption, we evaluated the external fertilizer-P demand in each province based on the different return ratios of straw and manure to fields (Figure 4a–d). The results confirmed that external fertilizer-P demand decreased with increasing return rates of straw and manure, especially in Hainan and Beijing where the return rates of straw and manure increased by 40 and 20% and the P input through organic materials met the demand of crops.

Discussion

Phosphorus input, output and balance

Soil P balances are affected by organic and inorganic fertilizer-P application, crop P removal and P losses, which correlated according to differences in crop types, cropping systems and soil fertility. In this study, substantial temporal

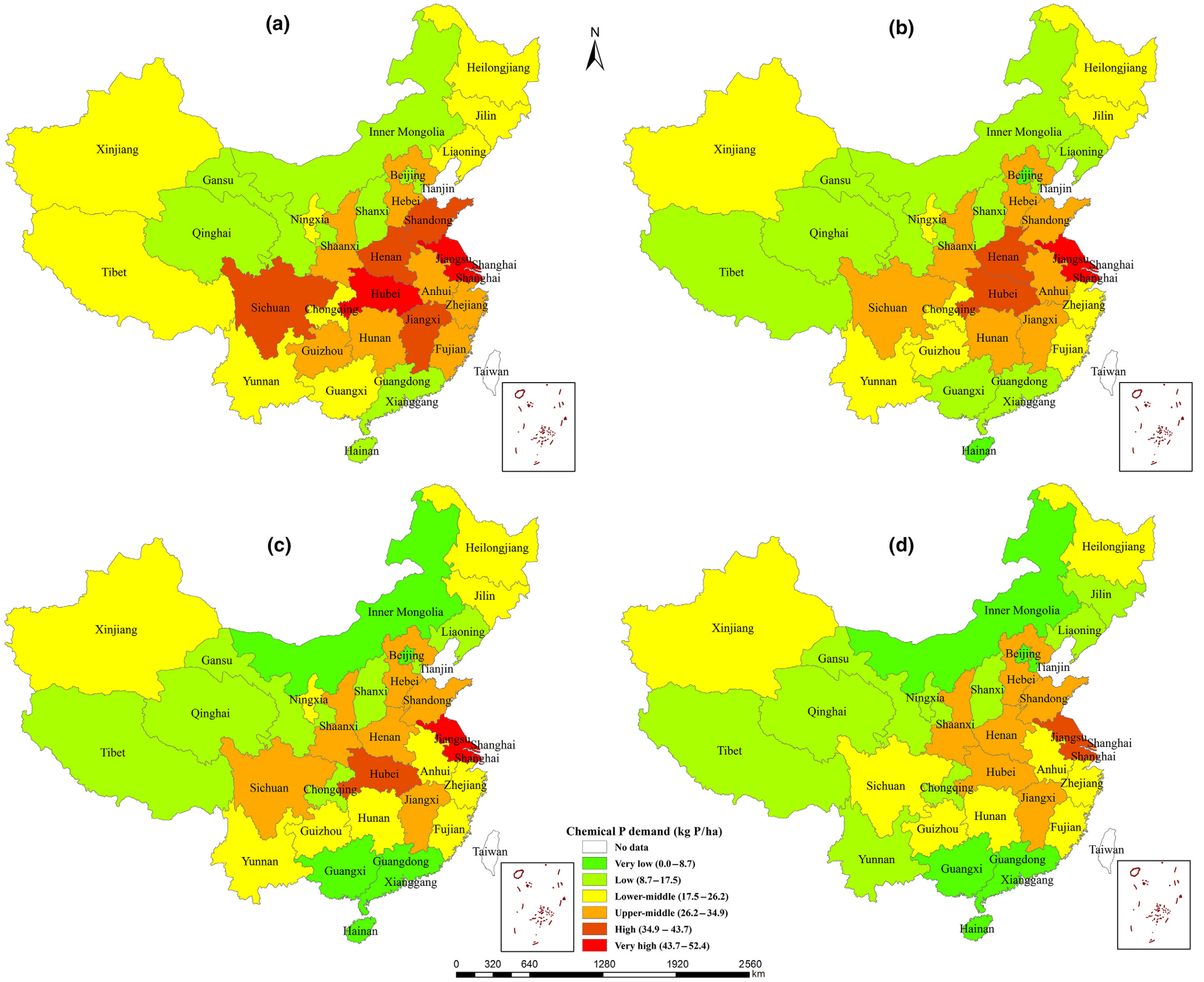

Figure 4 Fertilizer phosphorus demand for each province with varying return rates of straw and manure: (a) with 10 and 5% increase of return rates of straw and manure, (b) with 20 and 10% increase of return rates of straw and manure, (c) with 30 and 15% increase of return rates of straw and manure and (d) with 40 and 20% increase of return rates of straw and manure. [Colour figure can be viewed at wileyonlinelibrary.com]

and spatial variation in P input, output and balance was observed. China started to develop a fertilizer industry in the 1960s, which developed very rapidly after the 1980s. During this process, to pursue larger crop yields, Chinese farmers tended to over apply fertilizers, especially in the absence of scientific knowledge about balanced fertilizer application (Yang & Fang, 2015). In comparison with 1980, soil P input, output and balance increased by 252, 107 and 815% respectively in 2012. Previous studies have shown that the average P surplus in arable land across the whole country to be 4.8, 7.1, 13.3, 26.3, 37.9 and 52.7 kg P/ha in 1980, 1985, 1990, 1995, 1999 and 2010, respectively (Lu, 2003; Wang *et al.*, 2014), consistent with the results of our research. This increase in soil P balance has also been supported by our previous report on the increase of soil available P with time from 1990 to 2012 in China (Ma *et al.*, 2016).

Our research also indicates that there were substantial variations in soil P input, output and balances across different regions in China, due to the differences in P management practices, cropping systems and soil fertility. The minimum P input and relatively large P output resulted in the smallest net soil P balance in the NE. The SE had a larger P input than other regions because of the level of P fertilizer being applied to cash crops but a relatively small P removal in these crops, which resulted in a large P balance. The order of soil P balance in other regions was NC > MLYR > SW > NW. The NC and MLYR areas are China's main grain producing regions and intensification of production since 1980 has accelerated their P surplus across the period 1980–2012. Farming in the NW and SW regions is mixed, producing both crops and livestock, resulting in the slower upward trend of P soil balance when compared with other regions dominated by crop production (except for the NE).

Solutions to reduce the use of chemical fertilizer phosphorus in agricultural production

Fertilizer-P added to soils can be easily fixed and retained in soils. Reports showed that over 50% of P input since 1952 to a grazed pasture soil in New Zealand and over 80% of fertilizer-P applied to continuous barley over 51 yrs in the United Kingdom was retained in soils as legacy P (Blake *et al*., 2003; Macdonald *et al*., 2012). In China, fertilizer-P added to soils was observed to have accumulated in soils according to our study and other reports since 1980 (Lu, 2003; Li & Jin, 2011; Wang *et al*., 2014). The accumulated soil P is a large potential source of P that may be available to crops. Rowe *et al*. (2016) indicated that legacy soil P could theoretically substitute for a large fraction of P fertilizer use globally, meeting crop P demands for approximately 9–22 yrs depending on the scenarios for its availability. Results in our research also indicated that the accumulated soil P (1980–2012) could theoretically support crop demand for approximately 4.8–12.0 yrs, if 20 or 50% of the accumulated soil P was ultimately plant available. However, considering the spatial variation of accumulated soil P in China, more careful consideration needs to be given to the potential for legacy P within agricultural soils to support future production.

Tremendous increases in Chinese crop production and livestock farming have resulted in large amounts of animal wastes and crop residues, which are regarded as important potential sources of nutrients that can be used as substitutes for chemical fertilizers. In 2015, the Chinese Ministry of Agriculture released the action of Zero Growth of Chemical Fertilizer Use by 2020, in which substitution of chemical fertilizer with organic resources is one of the key methods (http://jiuban.moa.gov.cn/zwllm/tzgg/tz/201503/t20150318_4444765.htm). It was estimated that the total amount of organic resources in China contained 6.3 Mt P (Li *et al*., 2016b). Results from our research show that approximately 3.3, 3.6, 3.8 and 4.1 Mt P could be saved across the four assumed scenarios of straw and manure return to land. Thus, this study has shown a great potential for substitution of chemical fertilizer-P with the current available organic resources in China to increase P efficiency and maintain sustainable development of agriculture.

Conclusions

It has proved useful to determine the long-term soil P balance across Chinese arable land, to provide a basis for designing P management strategies for sustainable agricultural production and the control of eutrophication. There was a large soil P surplus and great spatial variation in the soil P balance among regions in China, highlighting that P fertilizer application and management practices need to be adjusted to suit local conditions. Evaluating the external P demand based on different manure and straw management scenarios provides promising strategies to substitute chemical fertilizer-P with available organic resources, a realistic solution to and reference to the Action to achieve Zero Growth of Chemical Fertilizers by 2020 in China.

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References

Bellarby, J., Surridge, B., Haygarth, P.M., Liu, K., Siciliano, G. & Smith, L. 2018. The stocks and flows of nitrogen, phosphorus and potassium across a 30-year time series for agriculture in huantai county, china. *Science of the Total Environment*, **619–620**, 606–620.

Blake, L., Johnston, A.E., Poulton, P.R. & Goulding, K.W.T. 2003. Changes in soil phosphorus fractions following positive and negative phosphorus balances for long periods. *Plant and Soil*, **254**, 245–261.

Carpenter, S.R. 2008. Phosphorus control is critical to mitigating eutrophication. *Proceedings of the National Academy of Sciences of the United States of America*, **105**, 11039–11040.

Chen, M., Chen, J. & Du, P. 2006. An inventory analysis of rural pollution loads in China. *Water Science and Technology*, **54**, 65–74.

Chen, M., Chen, J. & Sun, F. 2008. Agricultural phosphorus flow and its environmental impacts in China. *Science of the Total Environment*, **405**, 140–152.

Chen, W., Liu, D.L., Liu, J.J., Wang, M.Z. & Wu, Z.H. 2009. Study on livestock carrying capacity based on manure nutrients. *Chinese Journal of Animal Science*, **45**, 46–50. (in Chinese with English abstract).

Chen, M., Chen, J. & Sun, F. 2010. Estimating nutrient releases from agriculture in China: an extended substance flow analysis framework and a modelling tool. *Science of the Total Environment*, **408**, 5123–5136.

Childers, D.L., Corman, J., Edwards, M. & Elser, J.J. 2011. Sustainability challenges of phosphorus and food: solutions from closing the human phosphorus cycle. *BioScience*, **61**, 117–124.

China National Agricultural Technology Extension Service 1999. *Data collection for organic fertilizer nutrients in China*. China Agriculture Press, Beijing. (in Chinese).

Cooper, J., Lombardi, R., Boardman, D. & Carliell-Marquet, C. 2011. The future distribution and production of global phosphate rock reserves. *Resources Conservation and Recycling*, **57**, 78–86.

Dhillon, J., Torres, G., Driver, E., Figueiredo, B. & Raun, W.R. 2017. World phosphorus use efficiency in cereal crops. *Agronomy Journal*, **109**, 1–8.

Elser, J. & Bennett, E. 2011. Phosphorus cycle: a broken biogeochemical cycle. *Nature*, **478**, 29–31.

Fixen, P., Brentrup, F., Bruulsema, T., Garcia, F., Norton, R. & Zingore, S. 2015. Nutrient/fertilizer use efficiency: measurement, current situation and trends. Managing Water and Fertilizer for Sustainable Agricultural Intensification.

Food and Agriculture Organization of the United Nations. 2015. World fertilizer trends and outlook to 2018. Available at: www.fao.org/3/a-i4324e.pdf (accessed 15.02.2017)

Haygarth, P.M., Condron, L.M., Heathwaite, A.L., Turner, B.L. & Harris, G.P. 2005. The phosphorus transfer continuum: linking source to impact with an interdisciplinary and multi-scaled approach. *Science of the Total Environment*, **344**, 5–14.

Jin, X., Xu, Q. & Huang, C. 2005. Current status and future tendency of lake eutrophication in China. *Science in China Series C: Life Sciences*, **48**, 948–954.

Kellogg, R.L., Lander, C.H., Moffitt, D.C. & Gollehon, N. 2000. Manure nutrients relative to the capacity of cropland and pastureland to assimilate nutrients: spatial and temporal trends for the United States. *Proceedings of Water Environment Federation*, **140**, 18–157.

Krueger, T., Quinton, J.N., Freer, J., Macleod, C.J., Bilotta, G.S., Brazier, R.E., Butler, P. & Haygarth, P.M. 2009. Uncertainties in data and models to describe event dynamics of agricultural sediment and phosphorus transfer. *Journal of Environmental Quality*, **38**, 1137–1148.

Li, S.T. & Jin, J.Y. 2011. Characteristics of nutrient input/output and nutrient balance in different regions of China. *Scientia Agricultura Sinica*, **44**, 4207–4229. (in Chinese with English abstract).

Li, H., Huang, G., Meng, Q., Ma, L., Yuan, L., Wang, F., Zhang, W., Cui, Z., Shen, J., Chen, X., Jiang, R., &Zhang, F. 2011. Integrated soil and plant phosphorus management for crop and environment in china: a review. *Plant and Soil*, **349**, 157–167.

Li, H.G., Huang, G., Li, H., Van Ittersum, M.K., Leffelaar, P.A. & Zhang, F. 2016a. Identifying potential strategies in the key sectors of China's food chain to implement sustainable phosphorus management: a review. *Nutrient Cycling in Agroecosystems*, **104**, 341–359.

Li, S.T., Liu, X.Y. & Ding, W.C. 2016b. Estimation of organic nutrient sources and availability for land application. *Better Crops with Plant Food*, **3**, 4–6.

Lin, B. & Li, J.K. 2001. Phosphate fertilizer consumption and NP ratios in China. Proceedings of the international symposium on phosphorus fertilizer use in China. Nanning Guangxi China (in Chinese with English abstract).

Liu, Q. 2014. Distribution of fertilizer application and its environmental risk in different provinces of China. *Scientia Agricultura Sinica*, **47**, 3596–3605. (in Chinese with English abstract).

Liu, X., Sheng, H., Jiang, S., Yuan, Z., Zhang, C. & Elser, J.J. 2016. Intensification of phosphorus cycling in China since the 1600s. *Proceedings of the National Academy of Sciences of the United States of America*, **113**, 2609–2614.

Liu, Y., Yang, J., He, W., Ma, J., Gao, Q., Lei, Q. & Yang, F. 2017. Provincial potassium balance of farmland in China between 1980 and 2010. *Nutrient Cycling in Agroecosystems*, **107**, 247–264.

Lu, R.K. 2003. The phosphorus level of soil and environmental protection of water body. *Phosphate and Compound Fertilizer*, **18**, 1–8. (in Chinese with English abstract).

Ma, J. 2018. Temporal and spatial variation of phosphorus balance and solutions to improve phosphorus use efficiency in Chinese arable land. China Academy of Agricultural Science.

Ma, W., Ma, L., Li, J., Wang, F. & Zhang, F. 2011. Phosphorus flows and use efficiencies in production and consumption of wheat, rice, and maize in China. *Chemosphere*, **86**, 814–821.

Ma, L., Velthof, G.L., Wang, F.H., Qin, W., Zhang, W.F., Liu, Z. & Zhang, F. 2012. Nitrogen and phosphorus use efficiencies and losses in the food chain in China at regional scales in 1980 and 2005. *Science of the Total Environment*, **434**, 51–61.

Ma, J., He, P., Xu, X., He, W., Liu, Y., Yang, F. & Johnston, A.M. 2016. Temporal and spatial changes in soil available phosphorus in China (1990–2012). *Field Crops Research*, **192**, 13–20.

Macdonald, G.K., Bennett, E.M. & Taranu, Z.E. 2012. The influence of time, soil characteristics, and land-use history on soil phosphorus legacies: a global meta-analysis. *Global Change Biology*, **18**, 1904–1917.

Ministry of Agriculture People's Republic of China, 1981-2013. *China agriculture statistical report*. China Agricultural Press, Beijing.

National Bureau of Statistics of China 2006. *China's second national agricultural census data assembly [in Chinese]*. China Statistic Press, Beijing.

Ni, Z., Wang, S., Chu, Z. & Jin, X. 2015. Historical accumulation of N and P and sources of organic matter and N in sediment in an agricultural reservoir in northern China. *Environmental Science and Pollution Research*, **22**, 9951–9964.

Oelkers, E.H. & Valsami-Jones, E. 2008. Phosphate mineral reactivity and global sustainability. *Elements*, **4**, 83–87.

Reijnders, L. 2014. Phosphorus resources, their depletion and conservation, a review. *Resources Conservation and Recycling*, **93**, 32–49.

Rowe, H., Withers, P.J., Baas, P., Chan, N.I., Doody, D., Holiman, J. & Sharpley, A.N. 2016. Integrating legacy soil phosphorus into sustainable nutrient management strategies for future food, bioenergy and water security. *Nutrient Cycling in. Agroecosystems*, **104**, 393–412.

Sharpley, A. 2016. Managing agricultural phosphorus to minimize water quality impacts. *Scientia Agricola*, **73**, 1–8.

Sheldrick, W.F., Syers, J.K. & Lingard, J. 2003. Soil nutrient audits for China to estimate nutrient balances and output/input relationships. *Agriculture, Ecosystems and Environment*, **4**, 41–354.

Smil, V. 2000. Phosphorus in the environment: natural flows and human interferences. *Annual Review of Energy and the Environment*, **25**, 53–88.

Steffen, W., Richardson, K., Rockström, J., Cornell, S.E., Fetzer, I., Bennett, E.M. & Folke, C. 2015. Planetary boundaries: guiding human development on a changing planet. *Science*, **347**, 1–10.

United States Environmental Protection Agency, 2000. Best management practices to reduce Non-Point pollution in the town of plain field. Connecticut Boston: 157–163.

Wang, X., Feng, A., Wang, Q., Wu, C., Liu, Z., Ma, Z. & Wei, X. 2014. Spatial variability of the nutrient balance and related NPSP risk analysis for agro-ecosystems in China in 2010. *Agriculture, Ecosystems and Environment*, **193**, 42–52.

Wu, H., Zhang, Y., Yuan, Z. & Gao, L. 2016. Phosphorus flow management of cropping system in Huainan, China, 1990–2012. *Journal of Cleaner Production*, **112**, 39–48.

Yan, X. 2008. The status of chemical fertilizers use and the efficiency utilization of nutrient resources in China. China Academy of Agricultural Science.

Yang, X. & Fang, S. 2015. Practices, perceptions, and implications of fertilizer use in east-central china. *Ambio*, **44**, 647–652.

Supporting Information

Additional Supporting Information may be found online in the Supporting Information section at the end of the article:

Appendix S1. Details of soil phosphorus budget calculation.