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UNCNET

Urban nitrogen cycles: new economy thinking to master the challenges of climate change

D4/1: Development of high-resolution N inputs and irrigation datasets from agricultural soils

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Organisation name of co-chairs for this deliverable: **PKU, CAS**

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Dissemination Level		
PU	Public	☒
PP	Restricted to other programme participants (including funding agencies)	☐
RE	Restricted to a group specified by the consortium (including funding agencies)	☐
CO	Confidential, only for members of the consortium (including funding agencies)	☐

1. Executive Summary

This task, D4/1, aims to develop a high-resolution and real-time N inputs and irrigation datasets from targeted cities or regions (e.g., BTH), which plays an important role for modelling N leaching from agricultural soils and associated negative impacts on groundwater quality. UNCNET compiled a nationwide survey-based reconstruction dataset of N inputs and irrigation at 1-km resolution for different crop types over the period 1961-2014, based on the county- or prefecture-scale statistics and random surveys. The N inputs are defined as the annual quantity of synthetic fertilizers, manure, crop residues, and human excreta applied to croplands and atmospheric depositions over croplands, but it does not include fertilizer used for pasture or industries. Irrigation water inputs, in line with that from FAO AQUASTAT, are defined as the annual quantity of water withdrawn for irrigation including the losses during conveyance and field application. Cropland N input and irrigation rates over the period 1961-2014 were calculated as the ratio of total N inputs and irrigation water use to cropland (irrigated) area, and were resampled into the gridded irrigation maps of HYDE 3.2.1.

2. Objectives:

The task aims to develop a nationwide survey-based reconstruction dataset of N inputs and irrigation at 1-km resolution for different crop types over the period 1961-2014.

3. Activities:

Interaction with the Ministry of Water Resources of China, National Bureau of Statistics of China, and China Agricultural University to collect the sub-national statistics and random surveys and to confirm the separation of N inputs and irrigation amounts applied to croplands.

Ziyin Shang and Qihui Wang wrote codes to generate the gridded dataset of N inputs across China's croplands. Yan Bo took in charge of irrigation dataset.

4. Results:

- National gridded dataset of irrigation water use by crop during 1965-2013 (1-km, annual).
- National gridded dataset of N inputs by crop during 1961-2014 (1-km, annual).

5. Milestones achieved:

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6. Deviations and reasons:

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7. Publications:

- Zhou, F.; Bo, Y.; Ciais, P.; Dumas, P.; Tang, Q.; Wang, X.; et al., Deceleration of China's human water use and its key drivers. ***Proceedings of the National Academy of Sciences*** 2020, 117: 1-10. https://doi.org/10.1073/pnas.1909902117
- Wang Q, Zhou F, Shang Z, Ciais P, Winiwarter W, Jackson RB, et al. Data-driven estimates of global nitrous oxide emissions from croplands. ***National Science Review*** 2020, 7(2): 441-452. https://doi.org/10.1093/nsr/nwz087
- Shang Z, Zhou F, Smith P, Saikawa E, Ciais P, Chang J, et al. Weakened growth of cropland N2O emissions in China associated with nationwide policy interventions. ***Global Change Biology*** 2019, 25(25): 3706-3719. https://doi.org/10.1111/gcb.14741

8. Meetings:

Kickoff meeting at Peking University and many UNCNET teleconferences

9. List of Documents/Annexes:

Annex: Development of high-resolution N inputs and irrigation datasets from agricultural soils

REFERENCES

ANNEX 1

Development of high-resolution N inputs and irrigation datasets from agricultural soils

Development of high-resolution N inputs and irrigation datasets from agricultural soils

1. Irrigation water use

   a) Methodology

Definitions. The definition of irrigation water use in this study is in line with that from FAO AQUASTAT. This definition is consistent with the nationally coordinated surveys of water use in China (2016). Irrigation water use is the annual quantity of water withdrawn from surface or groundwater resources including the losses during conveyance and field application, but it does not include water used for irrigated pasture or aquaculture. Irrigated area is the area of cropland under irrigation. Irrigation WUI is defined as water use per unit of irrigated area for each type of crop. The definition and distribution of prefectures can be found in Figure 1.

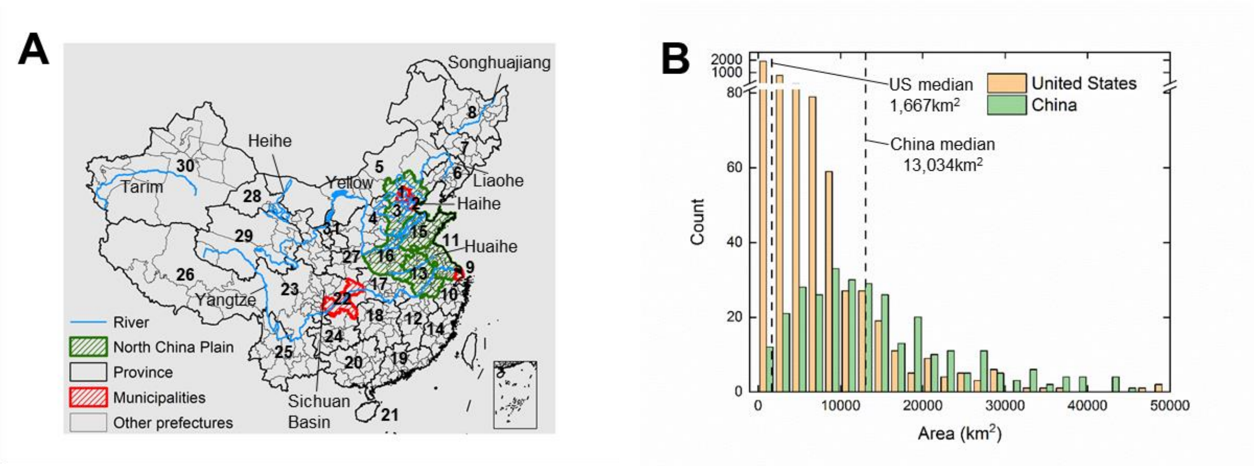

Figure 1. Administrative divisions in China. A. Prefectural-level administrative divisions in 2013. This map includes 286 prefecture-level cities, 14 prefectures, 30 autonomous prefectures, 3 leagues, 4 special districts, and 4 municipalities. Note that the number indicate provinces: 1. Beijing, 2. Tianjin, 3, Hebei, 4, Shanxi, 5, Inner Mongolia, 6. Liaoning, 7. Jilin, 8. Heilongjiang, 9. Shanghai, 10, Zhejiang, 11. Jiangsu, 12, Jiangxi, 13. Anhui, 14. Fujian, 15. Shandong, 16. Henan, 17. Hubei, 18. Hunan, 19. Guangdong, 20. Guangxi, 21. Hainan, 22. Chongqing, 23. Sichuan, 24. Guizhou, 25. Yunnan, 26. Tibet, 27. Shaanxi, 28. Gansu, 29. Qinghai, 30. Xinjiang, 31. Ningxia. **B**. Histogram of prefecture areas in China and comparison with that of the county areas in the USA. Median values of areas are shown for both countries.

Data sources. We reconstructed a new National Long-term Water Use Dataset of China (NLWUD). The NLWUD includes irrigation water use and irrigated area used to calculate WUI for 5 crop types (wheat, maize, rice, vegetables and fruits, and other crops) in 341 prefectures during the period 1965–2013. The data of water use by sub-sector and prefecture were obtained from two nationally-coordinated surveys: the 1st and 2nd National Water Resources Assessment Program for the period 1965–2000 and the Water Resources

Bulletins of 31 provinces for the rest of period 2001–2013. Both of these surveys were led by the Ministry of Water Resources, and had an identical survey methodology including definition, survey unit, sector classification, field survey or measurements, and quality assurance. China experienced an extensive shift of prefectural boundaries during the past five decades, and these changes have resulted in discontinuities in the spatial data. We therefore harmonized the temporal evolution of water use to the 2013 administrative map of China, based on the history of boundary and name changes given by the Ministry of Civil Affairs of China. The prefectural-scale irrigated area by crop were obtained from the statistical yearbooks of China's 31 provinces, given by the provincial statistics registers. It should be noted that the reconstructed data sets contain some uncertainties, but should not affect our findings unduly.

Spatial disaggregation. Crop-specific irrigation rates (mm yr^{-1}) at the prefectural level were then calculated as cropland irrigation amounts divided by irrigated areas, and were resampled into the gridded irrigation maps of HYDE 3.2.1

b) Results

Spatio-temporal patterns. Irrigation water use, accounting for ~70% of total water use in China, shows a clear reversal in trends from a positive value of +8.33 km^3 yr^{-2} in P1 and +3.09 km^3 yr^{-2} in P2 to a negative value of –1.99 km^3 yr^{-2} in P3 (Figs 2A-2C). Reduced irrigation water use firstly occurred during P2 in the Haihe, Liaohe, and Huaihe Rivers and extended to two thirds of the prefectures during P3. More importantly, the decreased irrigation water use dominated the deceleration of water use in China, which occurred in 61% of the prefectures from P1 to P2 and in 45% of them from P2 to P3

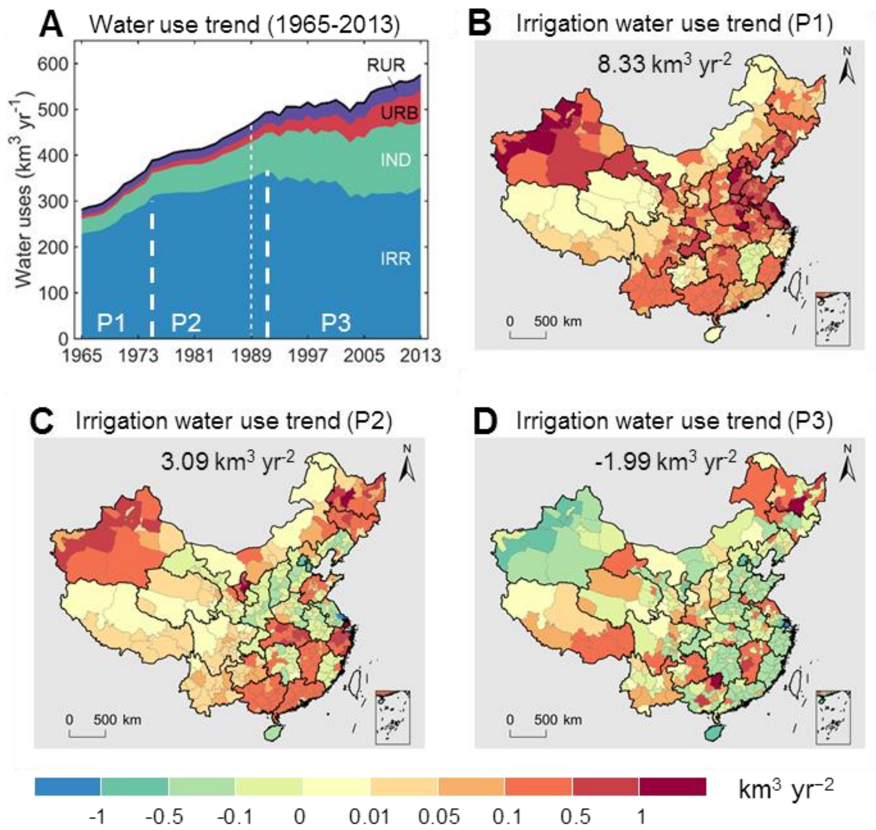

Figure 2. Spatio-temporal patterns of irrigation water use. A. Turning point for irrigation **w**ater use. B-C. Spatial pattern of irrigation water use trends during P1 (1965-1975), P2 (1975-1992) and P3 (1992-2013).

Drivers of irrigation water use change. We then analysed the contributions of irrigated area expansion, shift in crop mix, and change in irrigation water-use intensities (WUI) to irrigation water use trends at the national and prefectural scales, using modelling framework called Logarithmic Mean Divisia Index (LMDI). Before 1975, the expansion of irrigated areas was the main driver of the widespread increase of national water use, amounted to 25.7% (Fig. 3). Decomposition of structural changes in irrigation sector corresponded to increase water use by 2.6%, primarily due to the increased water uses for growing rice in south and wheat in north China, while irrigation WUI kept constant across most of China (Fig. 4). Between 1975 and 1992 in the period P2, the effect of irrigated area expansion in P2 was two thirds smaller than that in the previously analysed period, which dominated the increased water use mainly in northeast China and northern Xinjiang (Fig. 4). Shift in crop mix contributed marginally to the increased total water use. Irrigation WUI began to decrease only in the drier region of north China (Fig. 4). Since 1992 in the period P3, irrigated area expansion alone pushed water use upwards by 18.4%. The shift in crop mix continued to exert as a negligible factor (–0.3%) because the effect of changes in crop types compensated for each other across different regions. For example, the change in rice cultivation drove water use down in south China but up in northeast China. During the period P3, the reduced WUI of irrigation totally offset the positive influence of irrigated area expansion at national scale and in most of the prefectures.

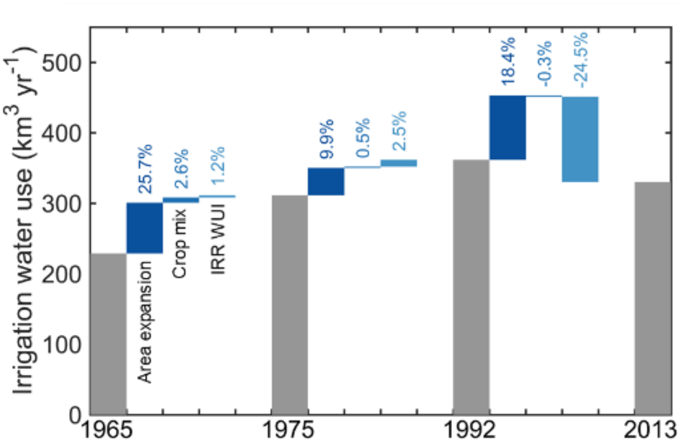

Figure 3. Contribution of different drivers to the change in irrigation water use during P1 (before 1975), P2 (1975-1992), and P3 (after 1992).

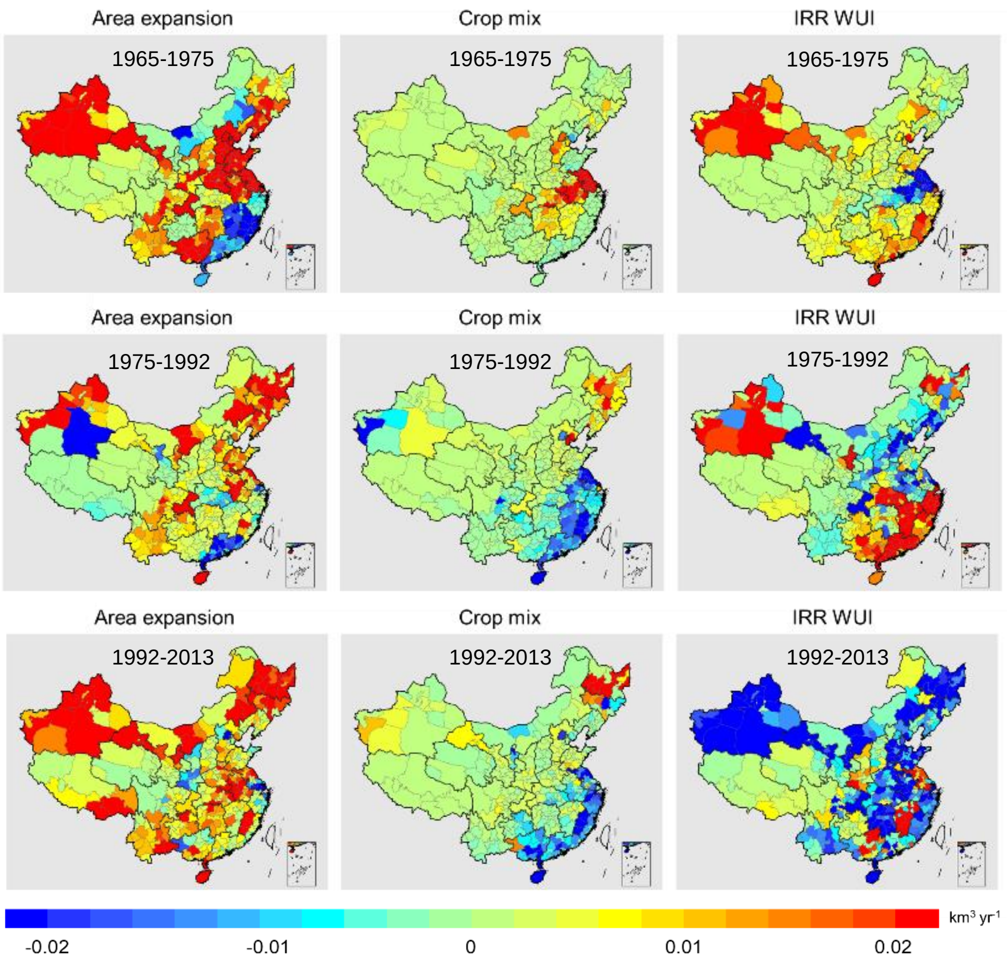

Figure 4. Spatial patterns of the contribution made by 3 drivers to water use changes in different periods

Causes of irrigation efficiency improvement. The reduced irrigation WUI can be linked to the decline in potential irrigation requirement (PIRR) or irrigation water availability (AIRR) (Hanasaki *et al.*, 2008, Pokhrel *et al.*, 2015, Sitch *et al.*, 2003, Tang & Lettenmaier, 2012, Wada *et al.*, 2014), but also to the improvement in irrigation efficiency (Jagermeyr *et al.*, 2015). We first compared the spatial patterns of observed irrigation WUI trends with PIRR trends simulated by GHM models. Our results indicate that, in provinces and times of decreasing WUI, PIRR may be the main factor of a decrease of WUI only in the Sichuan Basin and a part of the North China Plain. We then analysed the relationship between actual irrigation water consumption (IWC = irrigation water × consumption-to-withdrawal ratio) and PIRR at the provincial scale in 1971-2013, each of which was divided by AIRR following a Budyko-type framework of water consumption (Lei *et al.*, 2018). AIRR is defined as renewable freshwater minus flood water and water with higher priority than irrigation. We find that AIRR potentially acted as a limiting factor mainly for the drier northern China, where nearly all available irrigation water was actually used (i.e., IWC/AIRR stabilizing around one) and irrigated agriculture was over-developed (PIRR/AIRR ≥1). Together these results hint that improved irrigation efficiency might be the main driver of nationwide decrease in irrigation WUI, and also that emerging limitations of irrigation water availability could play a role in the push for improved irrigation efficiency.

Unfortunately, there is no observation on irrigation efficiency at prefectural level, or even at provincial level for China. To circumvent this problem, we used information of the irrigated area with adoption of water-conserving technology (WCI) as a proxy for irrigation efficiency. Two elements support this idea, a correlation between irrigation efficiency and WCI in China obtained using diverse sources of data, and one study based on a long-term survey in north China (1995-2007) showed that technological adoption delivered the benefit of reduced irrigation WUI (Huang *et al.*, 2016). To disentangle the contributions of PIRR, AIRR, and WCI, we used diagnostic models that were calibrated well at the provincial scale over the period after 1975. The models explained the decreasing irrigation WUI by technological adoption, which is consistent with Huang et al. (Huang *et al.*, 2016). Studies in other countries, however, suggested an opposite relationship (Grafton *et al.*, 2018, Perry *et al.*, 2017), i.e., water-conserving technological adoption leading to an increase in intensive farming and thereby an increase in irrigation WUI. The first reason for inconsistent results could be that intensive farming such as high planting density and more sequential cropping had already been well developed in many prefectures of China (Liu *et al.*, 2018). The second reason may be found in the nature of land institution in China (Huang *et al.*, 2016, Wu *et al.*, 2018). Indeed, additional intensification requiring a change in irrigation infrastructure has been difficult to be adopted due to the high fixed costs for small fields (~0.14 ha averaged in China) allocated to farmers (Feike *et al.*, 2017, Huang *et al.*, 2016, Meemken & Bellemare, 2019).

According to our diagnostic models, technological adoption could explain most of the reduced irrigation WUI in China and in many provinces during P3, but not during P2 when WCI was too low to have substantial effect on irrigation water use (9.3% of national irrigated area in 1992) (Fig. 5). Other factors that were not explained by the model seem to be non-negligible (Fig. 5), including farmers' behaviour (Knox *et* *al.*, 2012). Farmers were skilled at adjusting their adaptation behaviour in response to the changes in local climate (Wang *et al.*, 2019a), water availability (Hou *et al.*, 2017, Zhang *et al.*, 2019), market condition (Wang *et al.*, 2019b), and irrigation subsidies (Zhong *et al.*, 2017), which eventually influences irrigation. Despite these potential effects in China, how and to what extent can farmers' behaviour determines irrigation WUI changes still remain elusive and require more investigation.

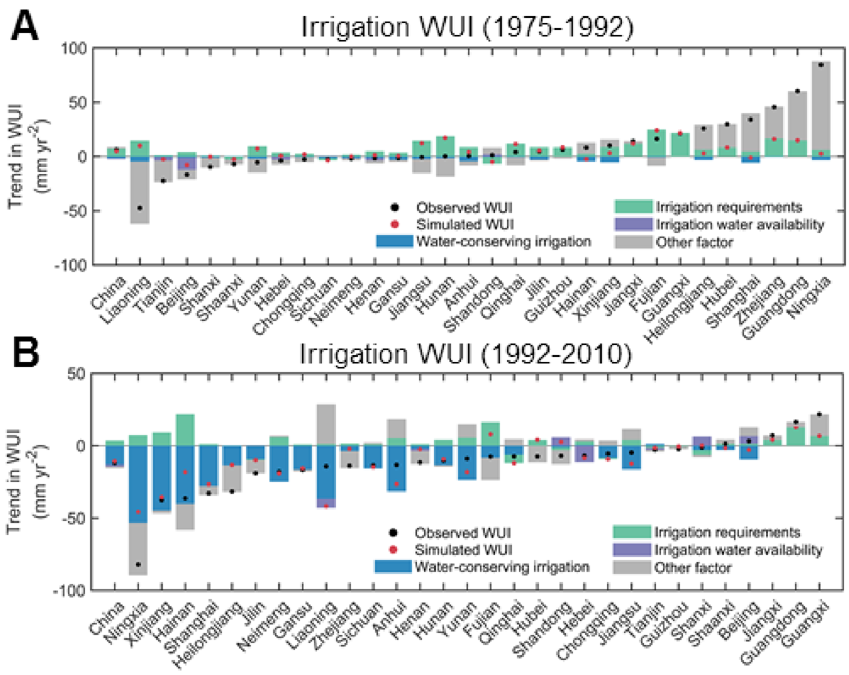

Figure 5. Causes of irrigation WUI trend in different periods. Note different order of provinces in X-axes. The analyses were conducted for the whole country and for 30 provinces in 1975-2010 for irrigation WUI, as the technological adoption data before 1975, irrigation requirement (PIRR) data after 2010, or in Tibet, Hong Kong, Macau, and Taiwan or at the prefectural scale were not accessible.

2. N inputs

a) Methodology

Definitions. N inputs are defined as the annual quantity of synthetic fertilizers, manure, crop residues, and human excreta applied to croplands and atmospheric depositions over croplands, but it does not include fertilizer used for pasture or industries.

Data sources. For N inputs, we first collected nationwide surveys of county-scale (the third-level administrative division) synthetic N fertilizer applied to croplands (F_{SN}, kg N yr^{-1}) for ~ 2900 counties in Mainland China, Taiwan, Hong Kong, and Macau for the period 1990-2014 (http://tongji.cnki.net/kns55/index.aspx, http://eng.coa.gov.tw, http://www.censtatd.gov.hk/hkstat, http://www.dsec.gov.mo). The other data was supplemented by the survey of the Program on Systematic Analysis and Comprehensive Treatment of Agricultural Environment or the Agricultural Information Institute of Chinese Academy of Agricultural Sciences (AII-CAAS; http://aii.caas.net.cn/). These data were further disaggregated by nine types of crop, based on the crop-specific, provincial data of R_{ijt} from the Statistics of Cost and Income of Chinese Farm Produce (http://tongji.cnki.net/overseas). In addition, China has experienced changes of County-scale administrative divisions, such as aggregation, disaggregation, and name changes, so we harmonized the temporal evolution of F_{SN} to fit the latest administrative divisions (http://geodata.pku.edu.cn), based on the historical trajectories summarized by the Ministry of Civil Affairs of China (http://xzqh.mca.gov.cn/). Second, we estimated annual N in livestock manure, human excreta, and crop residues returned to croplands by the *Eubolism* model at county scale (Chen, Chen, & Sun, 2010), based on county-scale activity data, such as the numbers of livestock by animal, rural population, and yields by crop type. The *Eubolism* model has been evaluated against multi-site observations in highly-fertilized cropping areas across China. Third, dry and wet deposition of N species were quantified by the global aerosol chemistry climate model LMDZ-OR-INCA at a horizontal resolution of 1.27° latitude by 2.5° longitude (Wang et al., 2017), in which wet N deposition fluxes have been validated by a recent global dataset (Vet et al., 2014). Finally, crop-specific N application rates (R_{ijt}) were calculated as county-scale N input totals (i.e., synthetic fertilizers, manure, human excreta, crop residues, and N depositions) divided by the associated sowing areas that were obtained from the statistical yearbooks of 31 provinces (http://tongji.cnki.net/overseas).

Spatial disaggregation. This new county-scale dataset of R_{ijt} was then resampled into a 1-km grid map based on the dynamic cropland distributions (Liu et al., 2014). We assumed a maximum N fertilizer application rate of 700 kg N ha^{-1} based on a previous study (Carlson *et al.*, 2017).

b) Results

Validation for synthetic fertilizers. To further verify the N_{syn}, we compare our estimates for upland crops and paddy rice to two in-house surveys of farmers conducted by Chinese Agricultural University around 2001 and 2008[21,22]. Representative farmers were selected for a face-to-face, questionnaire-based household survey to collect information on synthetic fertilizer use in each farmer's household. For the two surveys, a total of 5,827 farmers (19 provinces), 6,668 farmers (20 provinces) and 7,052 farmers (16 provinces) were surveyed for rice, wheat and maize in China, respectively. The N_{syn} averaged in province for both upland crops and paddy rice are comparable to the mean values in farmer's fields (Fig. 6), except for Guizhou, Inner Mongolia, Shanxi, Guangxi in 2007 (R^2=0.70, P<0.01 for upland crops, R^2=0.51, P<0.01 for paddy rice).

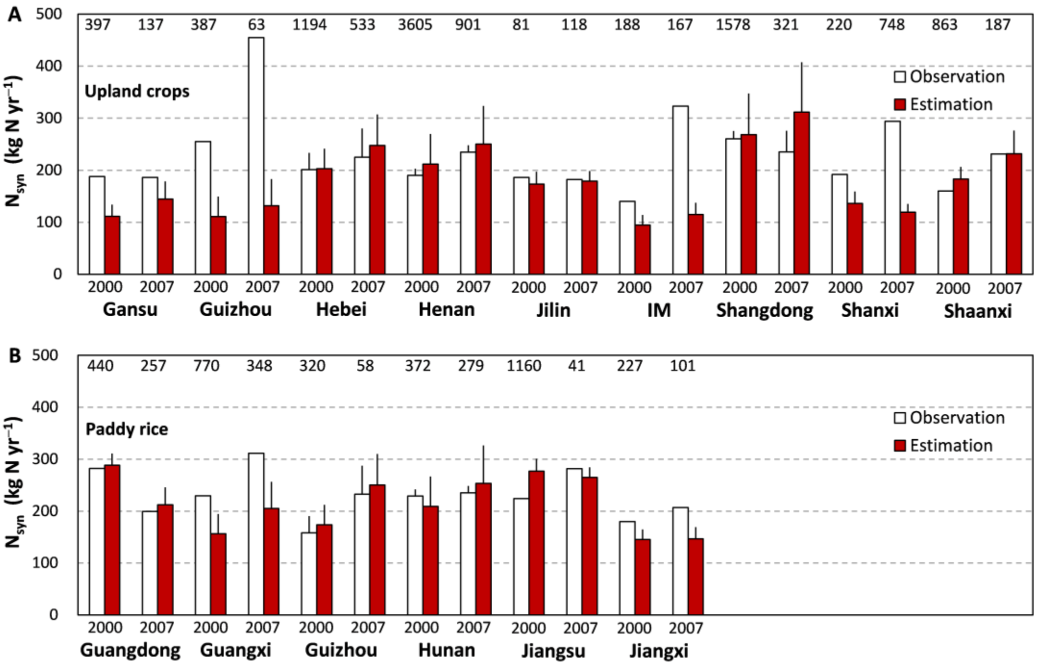

Fig. 6. Validation of nitrogen application rates for upland crops and paddy rice in 2000 and 2007. Observations for each province were determined from two in-house surveys, and our estimates were calculated as the total consumption of synthetic fertilizers within each province divided by sowing area of upland crops or paddy rice. All error bars are one standard deviation. Numbers at the top show the number of farmer's observations available at each province.

In addition, the statistics of annual consumption of synthetic fertilizers by croplands in Mainland China were conducted independently by the National Bureau of Statistics (NBS) and local municipality. NBS provides national and provincial data, while local municipality provides municipal and county-scale data. The two aggregate datasets are accessible by the public through NBS website (http://www.stats.gov.cn/english/) or National Knowledge Infrastructure database (CNKI, http://tongji.cnki.net/kns55/index.aspx). They use the identical survey methodology and quality assurance except sampling size. Specifically, the sampling size is ~800 counties (30% of the total) across all provinces for the national statistical survey but most of counties for local statistical survey (personal communication with the officials of NSB and local governments). Despite such discrepancy, both national and provincial aggregates of local statistics are significantly correlated with those of NBS (Fig. 7), with the difference of 1.4±1.5% and −2.7±13.5% (defined as the difference between the values of local municipality and NBS divided the NBS), respectively.

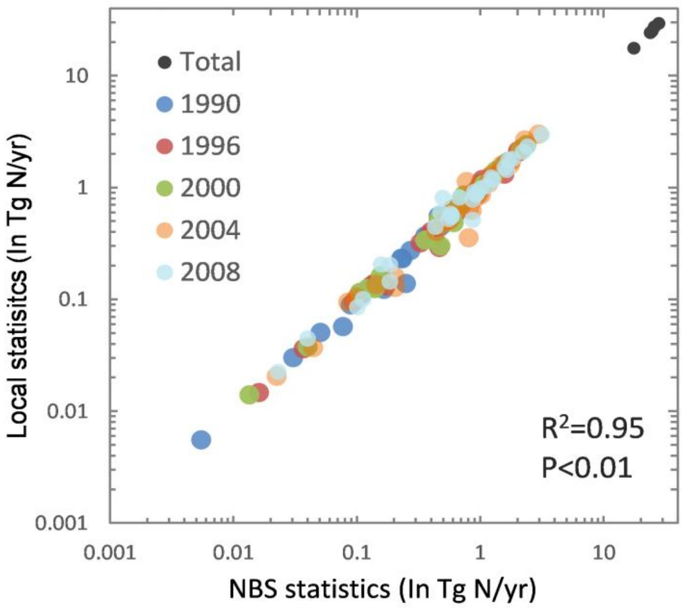

Fig. 7. Comparison of national and provincial aggregates between NBS- and municipality-leading statistics in 1990, 1996, 2000, 2004, and 2008.

Validation for the other fertilizers. Total N applications of manure, crop residues and human excreta in China were estimated as 12.15±1.01 Tg N yr^{-1} over the period from 1990 to 2012, with 6.95±0.81 Tg N yr^{-1}, 2.02±0.28 Tg N yr^{-1}, and 3.18±0.12 Tg N yr^{-1} from animal manure, crop residues, and human excreta, respectively (Table 1). Our estimate for manure and crop residues applied to croplands is close to previous studies[26–29] (5.90-7.40 and 2.00-2.80 Tg N yr^{-1}, respectively), but is double or triple for Human excreta (1.00-1.50 Tg N yr^{-1}).

Table 1. Comparison analysis of manure, crop residues and human excreta applied in in China's croplands

Data source	Period	Manure	Human excreta	Crop residues	Total
Sheldrick et al., 2003	1997	5.20 [g]	1.20 [h]	2.80 [i]	9.20
Ma et al., 2010; Bai et al., 2016	2005	7.5 [d]	1.00 [e]	2.00 [f]	10.5
Gu et al., 2015	2010	5.90 [a]	1.50 [b]	--	7.40 [c]
Cui et al., 2013	2010	8.50 [j]		2.20 [k]	10.7
FAOSTAT	1990-2010	4.57 [l]	--	5.00 [m]	9.56±1.06
This study	1997	6.78	2.92	1.92	11.62
This study	2005	8.09	2.80	2.19	13.09
This study	2010	5.80	1.88	2.34	10.02
This study	1990-2010	6.95±0.81	2.66±0.40	2.02±0.28	11.6±1.1

[a] including cattle (dairy, draft and beef), horses, donkeys/mules, sheep, pigs, layers, chicken, ducks/geese, rabbits, camels and buffaloes.

[b] including urban and rural human excreta

[c] The value does not include the application of crop residues;

[d] including cattle (dairy, draft and beef), horses, donkeys/mules, sheep/goats, pigs, layers, chicken, rabbits

[e] including urban and rural human excreta

[f] including rice, wheat, maize, sorghum, millet, other cereals, beans, potatoes, peanuts, rape, cotton, flax, sugarcane, sugar beet, tobaccoes.

[g] including cattle and buffaloes, pigs, sheep, goats, horses, mules, poultry

[h] including urban and rural human excreta

[i] the type of crop was not explicitly mentioned in the study

[j] The value includes human and livestock excreta. The animals contain cattle, sheep, horses, pigs and poultry, and human represents urban and rural populations.

[k] including wheat, rice paddy, maize, rape, sorghum, potatoes, beet, soybeans, peanut, sesame, tobacco, cotton

[l] including buffaloes, cattle(dairy, non-dairy), sheep/goats, swine (market, breeding), chicken (layers. broilers), ducks, turkeys, horses, asses/mules, camels

[m] including wheat, rice paddy, barley, maize, rye, oats, millet, sorghum, potatoes, beans, soybeans.

Spatio-temporal patterns. Our county-scale estimation of synthetic N fertilizer application was almost identical to the national statistics and FAOSTAT data (Fig. 8), whereas the other N inputs were substantially larger because the inclusion of human excretion and atmospheric deposition over croplands. According to nationwide statistics, China's N_{rate} showed a clear reversal in trend around 2003, from an increasing rate of +5.1 kg N ha^{-1} yr^{-2} in P1 to a decrease of –0.7 kg N ha^{-1} yr^{-2} in P2, although it varied across different cropping regions (Fig. 5a). Similar decreases in crop-specific N_{rate} were found for wheat, maize, and paddy rice, but not for vegetables and fruits, all with Pettitt's test (Fig. 8, $p < 0.001$). Interestingly, these change points were, in general, coincident with changes in cropland-N_2O emissions in China. The reductions of N_{rate} were mainly due to declines in synthetic fertilizer uses, particularly in the eastern and central China, the Yunnan-Guizhou Plateau, and the North China Plain (Fig. 9).

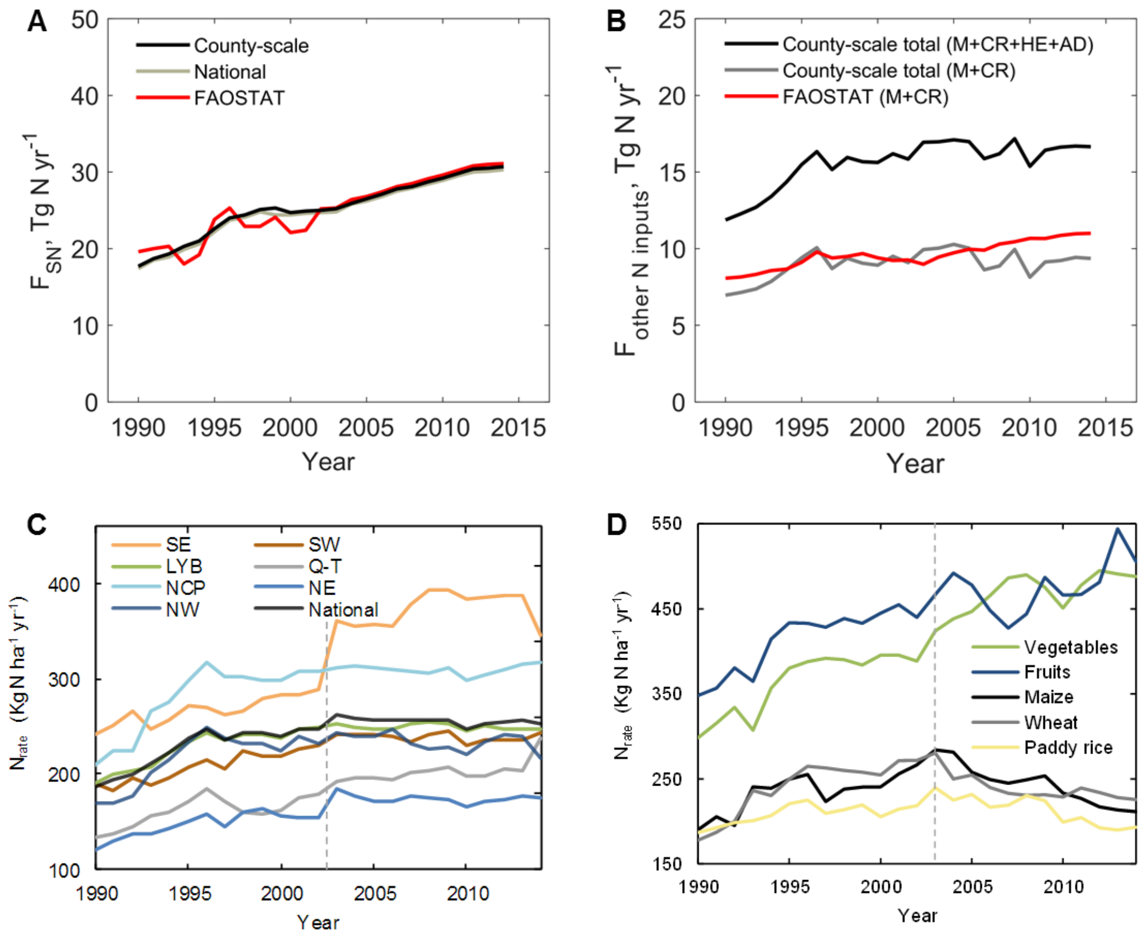

Figure 8. Temporal changes of different N inputs. A. Synthetic fertilizers applied to croplands. B. Other N inputs, including manure (M), crop residues (CR), human excreta (HE) returned to croplands, and atmospheric deposition (AD) over croplands. C. N_{rate} in 7 major cropping regions. D. N_{rate} by crops.

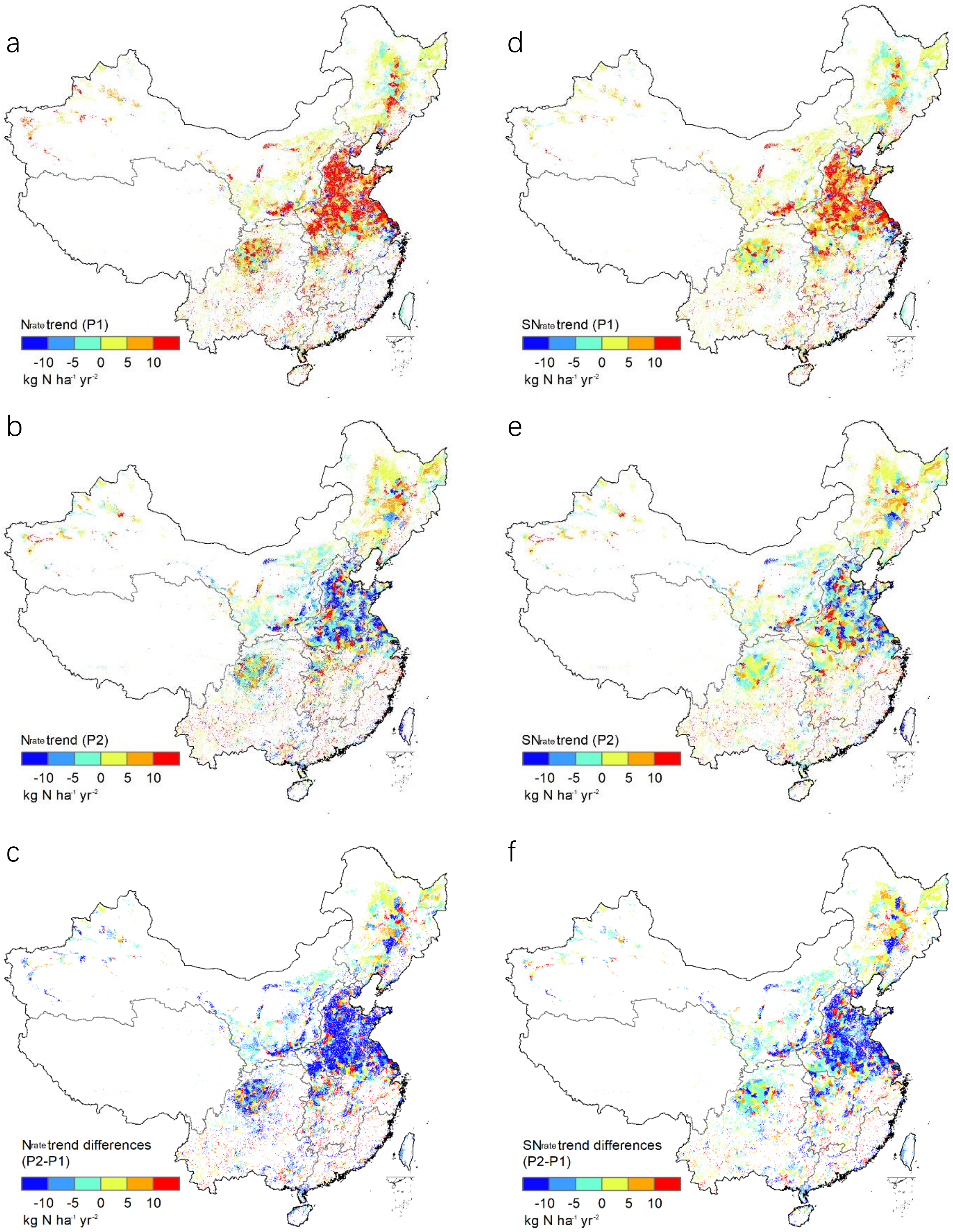

Fig. 9. Spatial patterns of application rates to Chinese croplands during P1 (1990-2003) and P2 (2003-2014), and their differences between P1 and P2 for of total (a, b, and c) and synthetic fertilizers (d, e and f).

Potential association with policy interventions. The reduced N_{rate} suggests that national N use efficiency of fertilizers has improved over recent decades, given that there was no reduction in per-area crop yields according to the national statistics (Sun & Huang, 2012). One of the most effective methods of making fertilizer use more efficient is to match the supply of nutrients with demand during field application (Richards et al., 2015). Such an approach was one of targets of the Nationwide Soil Testing and Formulation Fertilization Program, launched in the early 2000s. This program started with staple crops, which account for ~50% of national N inputs on average, but after 2010 it extended to a number of cash crops. These improved N use efficiencies for staple crops were also found in the most recent study (Liu et al, 2016; Zuo et al., 2018). According to national statistics (Sun & Huang, 2012), such technologies increased in prevalence on croplands from 3.3 million ha in 200 counties, to ~93 million ha in 2,498 counties. In addition, spatial re-allocation of crops has extensively happened in China over recent decades, and is characterized by an emerging shift from peri-urban areas in the South and Central China (high N rate) to rural areas in the North (low N rate) because of urbanization (Zuo et al., 2018). Besides, smallholder communities have been aware of the benefits from the adoption of enhanced management practices for greater production with less N inputs (Cui et al., 2018), possibly due to the outreach activities from this program, other national campaign (e.g., national 'high yield high efficiency' umbrella project), or strict pollution protection and control laws (Liu et al, 2016). Although the effectiveness of the Nationwide Soil Testing and Formulation Fertilization Program on the N_{rate} is difficult to quantify at the regional scale, these measures contributed to the decline in N_{rate} across China (Chen et al., 2014).

3. Public distribution.

Irrigation dataset was publicly available online at https://figshare.com/articles/Zhou_et_al_2020_PNAS_dataset_xlsx/11545176. N inputs data will be available when the dataset manuscript is accepted.

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