communications earth & environment

ARTICLE

https://doi.org/10.1038/s43247-022-00481-y OPEN

Manure amendment can reduce rice yield loss under extreme temperatures

Xiangcheng Zhu[1,2,11], Jin Chen[3,11], Shan Huang[4], Weiwei Li[1], Josep Penuelas[5,6], Ji Chen[7], Feng Zhou[8], Weijian Zhang[9], Ganghua Li[1], Zhenghui Liu[1], Yanfeng Ding[1✉], Songhan Wang[1✉], Kees Jan van Groenigen[10] & Yu Jiang[1✉]

Extreme temperatures are predicted to become increasingly common due to climate change, threatening the sustainability and profitability of global rice production. Manure amendment is a common agricultural practice to improve soil fertility and increase crop yields, but whether this practice modulates the effect of extreme temperatures on crop yield is unclear. Here we show through a series of experiments and meta-analysis that long-term manure amendment reduces losses of rice yield due to extreme temperatures. We propose that by increasing soil fertility, manure amendment increased net photosynthetic rate and plant physiological resistance to extreme temperatures. Without considering the impact of other global change factors, we estimate that manure amendment could potentially reduce global losses of rice yield due to extreme temperatures from 33.6 to 25.1%. Thus, our findings indicate that manure amendment may play a key role in improving food security in a changing climate.

[1] Jiangsu Collaborative Innovation Center for Modern Crop Production/Key Laboratory of Crop Physiology and Ecology in Southern China, Nanjing Agricultural University, Nanjing 210095, China. [2] Department of Agronomy, College of Life Sciences and Resource Environment, Yichun University, Yichun 336000, China. [3] Soil and Fertilizer & Resources and Environmental Institute, Jiangxi Academy of Agricultural Science, Nanchang 330200, China. [4] Jiangxi Key Laboratory of Crop Physiology, Ecology, and Genetic Breeding, Jiangxi Agricultural University, Nanchang, China. [5] CSIC, Global Ecology Unit CREAF-CSIC-UAB, Bellaterra, 08193 Barcelona, Catalonia, Spain. [6] CREAF, Cerdanyola del Vallès, 08193 Barcelona, Catalonia, Spain. [7] Aarhus University Centre for Circular Bioeconomy, Department of Agroecology, Aarhus University, Blichers Allé 20, 8830 Tjele, Denmark. [8] Sino-French Institute of Earth System Sciences, Peking University, 100871 Beijing, China. [9] Institute of Crop Sciences, Chinese Academy of Agricultural Sciences, Beijing, China. [10] Department of Geography, College of Life and Environmental Sciences, University of Exeter, Exeter, UK. [11] These authors contributed equally: Xiangcheng Zhu, Jin Chen. ✉email: dingyf@njau.edu.cn; wangsonghan@njau.edu.cn; yujiang@njau.edu.cn

Rice is the most important staple food in the world, with ~50% of the world's population depending on it as their main source of caloric intake[1]. To meet a growing global food demand, rice yields need to increase by ~28% in the next three decades[2]. However, the frequency and intensity of temperature extremes are predicted to increase due to global climate change, threatening the sustainability of crop production in many countries, including China, India, the United States, Thailand, and others[3–5]. Indeed, field experiments, statistical analyses of yield records, and crop models suggest that rice yields are already being negatively affected by recent increases in temperature extremes[6–9]. Moreover, rice yields have stagnated in 35% of the rice-growing regions worldwide, mostly due to a decline in soil quality (e.g., decrease in SOC contents and nutrient availability, and soil acidification due to high N fertilizer rates[10–12]). Increasing rice yields in a changing climate is therefore a key challenge of the 21st century.

Fertilizer application is a key management practice to improve soil fertility and increase crop yields[12,13]. Inorganic fertilizers are intensively applied to cropland in many areas around the world to reach high crop yields[13,14]. Yet, excessive inorganic fertilizer use is associated with a broad range of environmental impacts such as soil acidification, surface water eutrophication, and groundwater contamination[15,16]. To reduce inorganic fertilizer use and create more sustainable cropping systems, recycling manures to cropland is widely recommended[17,18]. Long-term experiments have found that substituting 30–70% of inorganic fertilizers with manure maintained or even increased rice yields in subtropical China[19]. A recent meta-analysis further indicates that manure amendment increases rice yield, SOC concentration, soil availability of nitrogen (N), phosphorus (P), and potassium (K)[20]. Nutrient availability affects the responses of plants to abiotic stress, especially under extreme temperature stress[21–23]. Together, these results suggest that manure amendment may modulate the effect of extreme temperatures on crop yield.

To the best of our knowledge, no experiments have yet quantified the effect of the interaction between climate change and manure amendment on crop yield. We thus conducted a comprehensive study to investigate whether manure application affected the impact of extreme temperatures on rice yield. First, we assessed the effect of manure amendment on yield losses due to extreme temperatures in a long-term field experiment. We then conducted a pot experiment to determine the effect of manure amendment on the mechanisms underlying temperature stress resistance. Finally, we tested the generality of our findings through a meta-analysis of long-term field experiments.

Results and discussion

Reduced rice yield losses under extreme temperatures with manure amendment. We compared rice yields with inorganic fertilizer (NPK) to yields with 30% of the fertilizer substituted by manure (NPKM) in a 35-year old field experiment established in a double rice-cropping system (see "Methods"). NPKM increased the mean yield in both early seasons (+5.0%) and late seasons (+7.2%) compared to NPK alone (Supplementary Table 1). Rice yields were not correlated with average daily minimum, mean, or maximum temperatures during the growing season (Supplementary Table 2) but decreased significantly with the averaged intensity of the temperature extremes over the growing period (see "Methods") (Supplementary Fig. 1 and Supplementary Table 1). However, NPKM reduced rice yield losses due to extreme temperatures by 19.3% in the early season and by 16.2% in the late season relative to NPK (Fig. 1a).

We also conducted a pot experiment with controlled temperature treatments using soils from the field experiment. This experimental design allowed us to study the effect of extreme temperatures in isolation, because all other environmental conditions were the same between treatments (see Methods). We planted rice under open field conditions and then exposed the plants to optimum and extreme temperatures in growth chambers for 10 days after flowering. The average daily temperatures in three growth chambers were: 25 °C in the treatment with optimum temperature, 19 °C in the treatment with extreme low temperature, and 31 °C in the treatment with extreme high temperature. Extreme low and high temperatures significantly reduced rice yield, but these reductions were smaller with NPKM than NPK (Fig. 1b and Supplementary Fig. 2a); high temperatures decreased yield by 33.2% in NPK and by 24.1% in NPKM, whereas low temperatures decreased yield by 19.4% in NPK and by 7.7% in NPKM.

We tested the generality of our findings by conducting a meta-analysis to quantify the effect of manure amendment on rice yield, using 45 paired long-term (>10 years) studies with 1177 site-year observations (Supplementary Data 1). Manure amendment increased rice yields by an average of 7.0% across the studies in our dataset (Fig. 2a). Rice yields decreased with the intensity of temperature extremes in all studies (Supplementary Data 2), but long-term manure amendment reduced rice yield losses due to extreme temperatures (Fig. 2a, b). The impact of manure amendment on yield loss was not affected by cropping system, soil texture, concentration of soil organic carbon (SOC), the ratio of manure N to total N input, and whether or not manure replaced inorganic fertilizers (Supplementary Table 3). However, animal manure and high manure N input reduced rice yield losses under extreme temperatures more strongly than did green manure and low manure N inputs. Our field experiment, pot experiment, and meta-analysis thus consistently indicated that manure amendment alleviated the negative effects of extreme temperatures on rice yield.

Mechanisms underlying manure effects on rice yield losses. Extreme temperatures affect plant growth and development at the leaf level, tissue and cell level and even at a sub-cellular level. First, extreme temperatures may suppress the activity of metabolic enzymes, thereby decreasing the rate of biochemical processes (e.g., photosynthesis) of plants[24,25]. Second, extreme temperature stresses can induce the accumulation of reactive oxygen that causes damage to proteins and cell membranes and endangers the chloroplasts, which ultimately weakens photosynthetic capacity[26]. Third, high temperatures can directly lead to thylakoid grana disintegration, thereby reducing chlorophyll content and photosynthetic rates[27]. Finally, extreme temperatures can increase spikelet sterility, thereby reducing rice yield[7,19]. However, extreme temperature stress also activates genes involved in stress resistance[28–30]. Examples include OsHSFA2d, CBF, and OsAPXa, which encode proteins such as transcription factors and antioxidative enzymes to increase stress tolerance in rice plants. Also, temperature stress may stimulate the synthesis of osmotic substances (e.g., proline) to maintain osmotic potential[31].

Our results show that extreme high and low temperatures significantly reduced net foliar photosynthetic rates, but these reductions were smaller with NPKM than NPK (Fig. 3a and Supplementary Fig. 2b). Extreme high and low temperatures, however, significantly increased foliar proline concentrations, and these increases were larger with NPKM than NPK (Fig. 3b and Supplementary Fig. 2c). These results can be explained by the key role of plant nutrition in alleviating extreme temperature stress. First, plant nutrition regulates the expression of genes involving stress resistance. For instance, increased N availability promotes

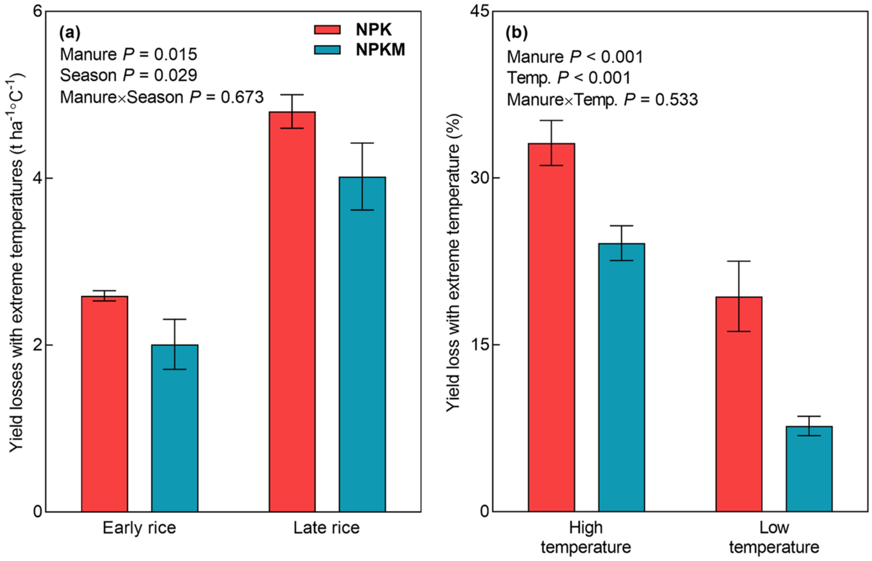

Fig. 1 Rice yield losses due to extreme temperatures as affected by manure amendment. a Yield losses due to extreme temperatures in a long-term field experiment in a double rice cropping system. Results are shown for both early and late rice ($n = 3$). **b** Effect of temperature stress on rice yield as affected by manure amendment in a pot experiment ($n = 5$). NPK, inorganic fertilizer; NPKM, a combination of manure and inorganic fertilizer. Error bars represent standard errors.

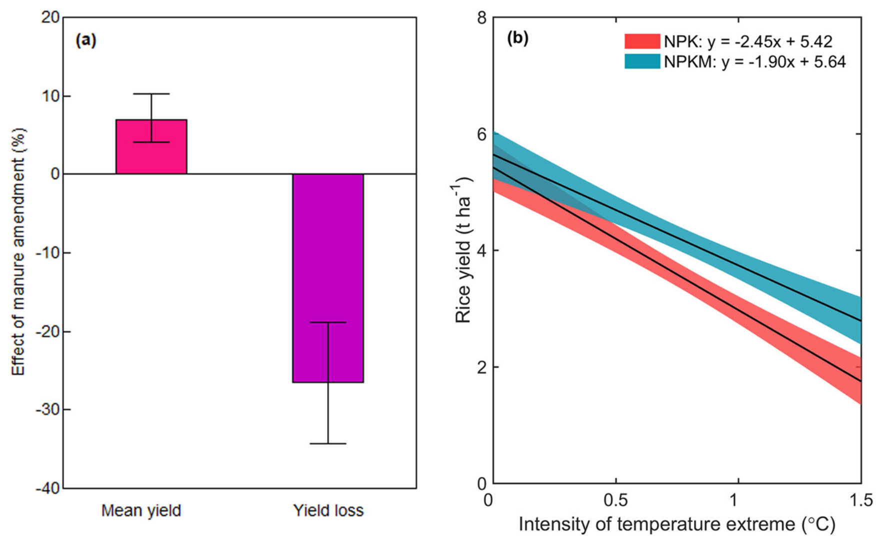

Fig. 2 Results from a meta-analysis investigating the effect of long-term manure amendment on rice yield. a Effect of long-term manure amendment on rice yield ($n = 45$) and rice yield losses with extreme temperatures ($n = 45$). **b** Relationship between the intensity of temperature extremes and rice yield for inorganic fertilizer (NPK) and a combination of manure and inorganic fertilizer (NPKM). Error bars and shaded areas represent 95% confidence intervals.

nitric oxide content in plant material, which acts as a signal to activate the expression of heat stress-responsive genes such as ROS scavenging enzymes genes and heat shock proteins genes[31–33]. Second, adequate nutrition is essential for key physiological processes. For example, N is an important component of chlorophyll and primary enzymes of the Calvin cycle involving in photosynthesis[34,35], phosphorus is a structural part of nucleic acids[36], and K helps to stimulate various enzymatic reactions and increase the translocation and accumulation of photosynthates[37,38]. Indeed, several studies indicate that increased N availability alleviates the negative effects of stress caused by extreme temperatures on photosynthesis and rice yield[39,40], whereas increased P availability can increase the proline concentrations of rice foliar[41]. High N and P availability often enhance the photosynthetic and antioxidant capacity, which are beneficial for plants to circumvent the negative effects of temperature stress[21–23].

Our field experiment and meta-analysis both indicate that manure amendments strongly enhance soil nutrient availability. Manure amendment increased SOC concentration by 23.6%, total N concentration by 24.0%, total P concentration by 50.0%, available N concentration by 26.1%, and available P concentration by 52.1% in our field experiment (Table 1). Similarly, manure amendment also significantly increased SOC concentration (+13.8%), available N concentration (+16.0%), P concentration (+36.6%), and K concentration (+5.9%) across the studies in our data set (Fig. 4). Our meta-analysis further showed that high manure N input and animal manure lead to the strongest reductions in yield losses (Supplementary Table 3). These manure treatments result in relatively strong increases

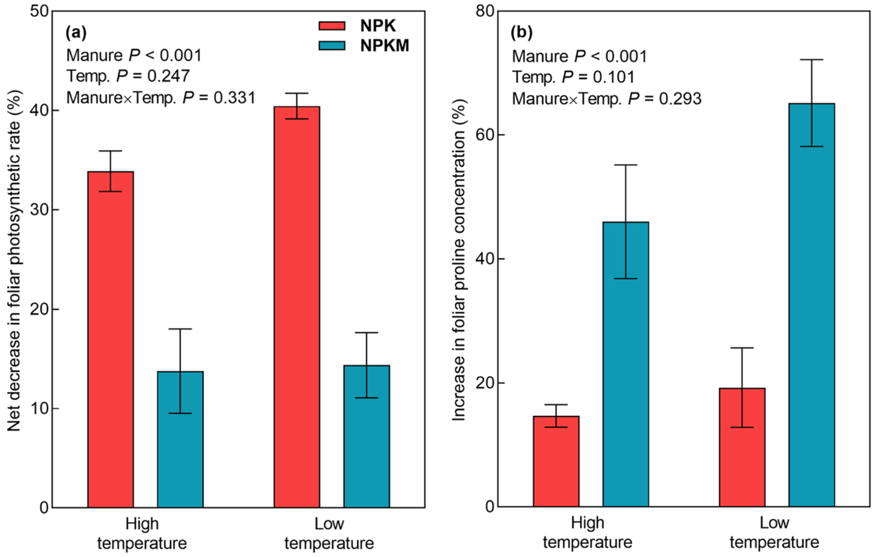

Fig. 3 Effect of temperature stress with and without manure amendment on net foliar photosynthetic rate and foliar proline concentration in a pot experiment. **a** Effect of temperature stress net foliar photosynthetic rate ($n = 4$). **b** Effect of temperature stress on foliar proline concentration ($n = 4$). NPK, inorganic fertilizer; NPKM, a combination of manure and inorganic fertilizer. Error bars represent standard errors (SE).

Table 1 Effect of manure amendment on soil properties in a long-term field experiment.

	SOC ($g\ kg^{-1}$)	Total N ($g\ kg^{-1}$)	Total P ($g\ kg^{-1}$)	Total K ($g\ kg^{-1}$)	Available N ($mg\ kg^{-1}$)	Available P ($mg\ kg^{-1}$)	Available K ($mg\ kg^{-1}$)	Bulk density ($g\ cm^{-3}$)
NPK	24.6 ± 0.6*	2.5 ± 0.1*	0.6 ± 0.0*	10.0 ± 0.3	225.9 ± 5.8*	51.8 ± 3.4*	44.1 ± 3.0	1.2 ± 0.0
NPKM	30.4 ± 0.6	3.1 ± 0.1	0.9 ± 0.0	9.6 ± 0.2	284.9 ± 7.2	78.8 ± 2.3	43.2 ± 1.1	1.1 ± 0.0*

SOC soil organic carbon concentration. Means ± standard errors ($n = 3$). $^*P < 0.05$.

in nutrient availability[20,42], supporting our interpretation that manure amendment reduces yield losses by improving soil fertility. Our supplementary experiment indicated that relative to the NPK treatment, additional N fertilizer also reduced yield losses with extreme temperatures (Supplementary Fig. 3). However, higher rates of inorganic fertilizer are rates are not desirable, as this would increase nutrient losses to the environment, and its production requires burning of fossil fuel[13]. Taken together, these results provide strong evidence that manure amendment reduces rice yield losses due to extreme temperature, and that this effect can be explained by its effect on nutrient availability.

Manure amendment also improves aspects of soil fertility other than nutrient availability, which may reduce yield losses under extreme temperatures. For instance, long-term manure amendment increased SOC stocks and improved soil structure, indicated by the lower bulk density in NPKM in our field experiment (Table 1) and many others[20]. Low bulk density can stimulate root growth and increase the uptake of nutrients and water by roots[43], which may ultimately reduce losses in rice yield. Soils with high SOC concentrations often contain more rhizospheric microbiota that promotes stress tolerance in plants[44], and manure amendment often suppresses nematodes[45], suggesting that long-term manure amendment may improve the tolerance of rice to stress by altering the composition of the soil microbial community. Finally, manure often includes humic substances[46], which can increase crop yield and proline concentrations under extreme temperatures[46,47].

Extrapolation and wider implications. Our results have important implications for efforts to protect rice cropping systems from the effects of a warming climate. Models included in the Coupled Model Intercomparison Project Phase 6 (CMIP6) predict that the intensities of temperature extremes in rice-growing regions will increase from the current decade (2021–2030) to the end of this century (Supplementary Fig. 4). Global rice yield under these circumstances may be greatly reduced, but this reduction could be alleviated by manure amendment. Assuming that the impacts of extreme temperatures on rice yield followed the same formula in Fig. 2b and without considering other effects (see "Methods"), We estimate that extreme temperatures will reduce global rice yields by 10.6% in the current decade and by 33.6% in the last decade of this century (Fig. 5a, c). If manure is applied in all rice paddies, extreme temperature will reduce global rice yields by 7.9% in the current decade and by 25.1% in the last decade of this century (Fig. 5b, d). Predicted yield losses will be highest where the intensity of extreme temperatures are the highest, i.e., in northern rice growing regions such as northern India and the Yangtze River Basin (Fig. 5).

Several caveats must be noted regarding our estimate that manure amendment could potentially reduce global rice yield losses due to extreme temperatures from 33.6 to 25.1%. First, this estimate does not consider the effects from other environmental factors; future climatic changes are not restricted to increased instances of temperature extremes, but also include changes in atmospheric CO_2, humidity etc. Global change factors are known to interact in their effects on plants[48], and may also affect the effect of manure additions. Second, the nature and production procedures of manures are highly diverse, which may affect the effectiveness of manure amendment. For instance, our meta-analysis found stronger effects for animal manure than plant manure, and also found stronger effects for manures with high N content. This variation needs to be accounted for in future projections of yield losses due to climate change. Finally, the relative importance of the various specific effects of each nutrient, root development and physiological activity, and microbes to enhance plant tolerance to temperature stress are still unclear. These knowledge gaps need to be addressed to better understand the effect of manure on rice yields under future climatic conditions.

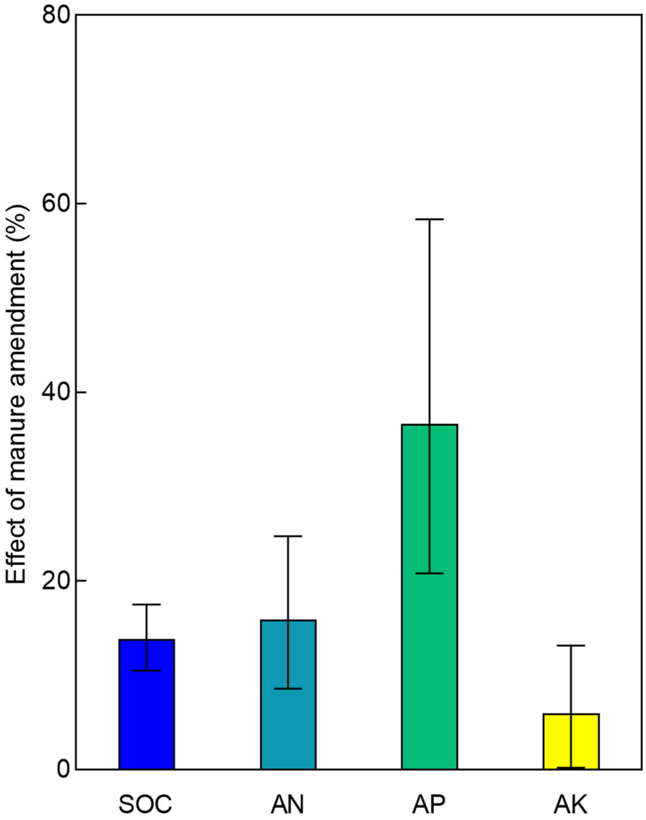

Fig. 4 Results from a meta-analysis investigating the effect of long-term manure amendment on soil fertility. SOC soil organic carbon concentration ($n = 39$); AN available N concentration ($n = 30$), AP available P concentration ($n = 37$); AK available K concentration ($n = 31$). Error bars represent 95% confidence intervals.

Both our experiments and meta-analysis indicated that long-term manure amendment increased average rice yield by 6–8% by improving soil fertility, supporting numerous field studies[19,49]. However, recent meta-analyses have suggested that manure amendment reduced rice yield by 2.8%[20] and that partial substitution of inorganic fertilizers with manure increased rice yields in China only by 3.3%[50]. This apparent contradiction is likely due to the inclusion in previous analyses of short-term studies and studies where inorganic fertilizers were completely substituted by manure[20,50]. Indeed, complete substitution often reduced crop yield because manure could not ensure an adequate supply of nutrients for rice growth[20]. Numerous long-term experiments have similarly indicated that the positive effects of manure amendment on soil fertility and crop yield increased over time[19,49].

Our study focused solely on the effects of manure amendment on rice yield. Long-term manure amendment, however, also improves the yields of maize, wheat, and soybean and soil fertility of upland cropping systems[20,51], suggesting that it may increase the resistance of maize and wheat yields to extreme temperatures. Amendment with other types of organic matter such as straw and sludge also gradually increase rice yield and soil fertility[52,53], suggesting that these amendments may also increase the resistance of rice to extreme temperatures. Finally, improving soil fertility may also increase the resilience of agronomic systems to other impacts of climate change. For instance, global warming is expected to increases the frequency of heavy cloud cover and rainfall in much of East Asia[54], thereby reducing photosynthetically active radiation (PAR) and potentially reducing rice productivity[55]. However, long-term straw incorporation increases rice yield most strongly at low PAR levels[53].

Recent estimates suggest substantial potential to expand manure application in cropland, including rice paddies. Croplands worldwide receive ~42.2 Tg N yr^{-1} of fertilizer N and 7.4–24 Tg N yr^{-1} of manure N[56,57]. In comparison, global livestock produces 80–140 Tg N yr^{-1} in manure, and this number continues to increase[58,59]. Nonetheless, manure is applied in only 42% of the rice paddies in southern Asia, and the use of manure is decreasing over time[60]. In China, the country with the largest rice production, only 4.6% of the N input for rice is derived from

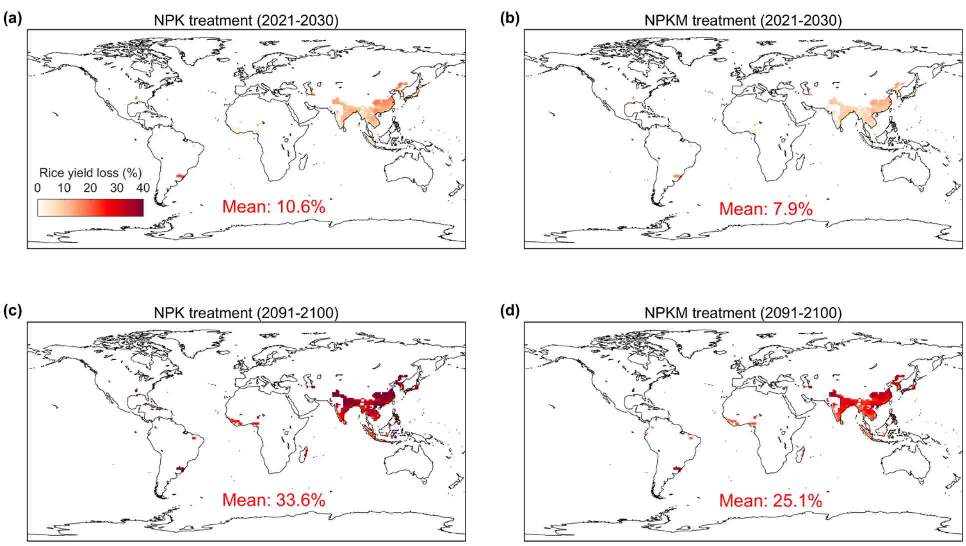

Fig. 5 Projected global losses of rice yield due to extreme temperatures. a Global losses of rice yield due to extreme temperatures under NPK in 2021–2030, **b** global losses of rice yield due to extreme temperatures under NPKM in 2021–2030, **c** global losses of rice yield due to extreme temperatures under NPK in 2091–2100, **d** global losses of rice yield due to extreme temperatures under NPKM in 2091–2100.

manure[61]. Much of the N in livestock excretion is currently lost to the environment through ammonia volatilization and nitrate leaching, causing various environmental issues[62]. Thus, applying a larger fraction of manure N to cropland may not only increase yields, but also reduce environmental pollution. The increased use of manure may also reduce the dependence on inorganic fertilizers, which could increase the income of farmers[13,14] and reduce ancillary CO_2 emissions associated with fertilizer production[63].

However, several hurdles have to be overcome for manure application to be expanded more widely. Firstly, most manure is produced at livestock farms far away from crop farms. As a result, manure amendment is currently concentrated in areas with intensive cropping systems and high livestock densities[64]. Second, low quality manure may cause weed, pests, and disease infestations and increase heavy metals and antibiotic resistance genes in soils[18,65], which may dissuade farmers from using manure. Finally, lack of labor force, high labor costs, and a lack of manure application machines present socio-economic barriers[18]. Addressing these issues requires coordinated planning to recouple livestock and cropping systems at the regional level[66,67]. Through policy incentives and outreach, governments may stimulate the creation of infrastructure needed to collect, store, treat, distribute and recycle manure. Access to accurate information regarding the price and composition of manure products, manure subsidies, middle men to transfer manure from livestock farms to crop farms, and contractors with manure application equipment may further promote manure use by farmers[18]. In summary, our study indicates that long-term manure amendment could improve global food security and agriculture sustainability, and highlights the need for incorporating manure amendment into management practices as our climate continues to change.

Methods

Field experiment. The field experiment was established in a double rice-cropping system in Nanchang (28°06′N, 115°09′E), China, in 1984. The experimental site has a subtropical monsoonal humid climate, with a mean annual temperature of 17.5 °C and a mean annual precipitation of 1600 mm. The soil is a ferralic Cambisol, or red paddy soil of the Chinese system of soil classification. The early rice crop was transplanted in early April and harvested in mid-July, and the late crop was transplanted in late July and harvested in mid-October. *Astragalus sinicus* L., a species of milkvetch, was planted in late October and harvested in mid-March of the following year. Plots in the experiment received either chemical fertilizers (NPK) or chemical fertilizers plus manure (NPKM). The experiment had a completely randomized block design with three replicates for each treatment. The plots (10 m long and 3.33 m wide) were separated by concrete walls. In the NPK treatment, N as urea, P as superphosphate, and K as potassium chloride were applied at rates of 150 kg N ha^{-1}, 60 kg P_2O_5 ha^{-1}, and 150 kg K_2O ha^{-1} in the early season and 180 kg N ha^{-1}, 60 kg ha^{-1} P_2O_5, and 150 kg ha^{-1} K_2O in the late season, respectively. The P fertilizer was applied at transplanting. Half of the N fertilizer was applied at transplanting, 25% of N fertilizer and 50% of K fertilizer were applied at the tillering stage, and the remaining N and K fertilizers were applied at the young panicle differentiation stage. In the NPKM treatment, 30% of the inorganic fertilizers were replaced by *A. sinicus* in the early season and by fermented swine manure in the late season at transplanting. All other management practices followed local recommendations. Detailed information of the long-term experiment is provided by Chen et al. (2017)[68]. We measured rice yield from 1984 to 2018.

Pot experiment. We further tested whether long-term manure amendment affected the resistance of rice to extreme temperatures by conducting a pot experiment at the Jiangxi Academy of Agricultural Science, Nanchang. Soil was collected from the long-term field experiment described above in late July 2020 after the early rice crop was harvested. We collected the soil using a shovel to a depth of 15 cm from each of the six plots. We combined and mixed the soils per treatment. Plastic pots (diameter, 22 cm; height, 20 cm) were filled with 4.5 kg of air-dried soil. The diameter and height of the pots allowed us to approximate the common transplant density (25 × 15 cm per plant) and depth of the plow layer (0–15 cm) in paddy fields. The application rates of the inorganic fertilizer and swine manure were the same as in the field experiment. We transplanted two healthy rice seedlings (*Oryza sativa L. cv. Gan 929*) into each pot when the late rice was transplanted at our experimental site. The pots were placed on a rice paddy field up to the heading stage.

At the heading stage, we set minimum and maximum temperatures at 15 and 25 °C in the first chamber (extreme low temperature), at 21 and 31 °C in the second chamber (optimum temperature), and 27 and 37 °C in the third chamber (extreme high temperature)[69]. We placed pots with healthy plants into the chambers at the heading stage for 10 d., during which the daily average temperature was 25.3 °C in the optimum-temperature treatment, 19.2 °C in the extreme low-temperature treatment, and 31.5 °C in the extreme high-temperature treatment. Details for the daily temperature dynamics, light, relative humidity, and CO_2 concentrations have been described in ref. [69]. The pots were again placed on a rice paddy field after 10 days. Five pots for each treatment were used to measure grain yield, and the other four pots were used to measure net foliar photosynthetic rate and foliar proline concentration, indicating plant resistance[25,33]. We measured the photosynthetic rate of flag leaves using an LI-6400 Portable Photosynthesis System (LI-COR Inc., Lincoln, USA) at day 10 during the temperature treatments. We also collected the flag leaves to measure the proline concentrations using ninhydrin colorimetry[70]. Grain yield was measured at maturity. Soil organic C was determined by the oxidation method using vitriol acid potassium dichromate oxidation[71]. Soil total N, P, and K were measured following ref. [72], ref. [73], and ref. [74], respectively. Soil available N, P, and K were determined in accordance with ref. [72], ref. [75], and ref. [71], respectively. Soil bulk density was measured by a metal corer method.

Statistical analysis. For the Nanchang site, we collected data for daily air–surface temperature from the nearest meteorological station. To calculate the intensity of temperature extremes at the Nanchang site and other sites, we used the daily temperature records and conducted the following steps.

(1) We first detrended the temperature data by applying linear fitting to remove the long-term trend in the temperature record.
(2) For each day, the mean value and one standard deviation (mean ± SD) of multi-year observations were used as the baseline, i.e., we used [mean-SD, mean+SD] as a reasonable range of temperature variations. We used a threshold of one SD by assuming that the variations in temperature under normal conditions were generally within the range of one SD either side of the multi-year mean[76].
(3) For each day in a growing season, if the observed daily temperature exceeded the reasonable range, the absolute difference between the temperature and this range was termed the intensity of the temperature extreme (Supplementary Fig. 5). If the observed daily temperature was within the reasonable range, the intensity was defined as 0.
(4) Finally, we calculated the average extreme temperature intensity (ETI) throughout the growing season. Thus, our approach yields one data point per growing season; a value of 0 indicates that a growing season had no extreme temperatures.

We correlated air temperature with the intensity of a temperature extreme and rice yield in the field experiment. Rice yield loss due to extreme temperatures (t ha^{-1} °C^{-1}) was calculated as the absolute value of the slope of linear regression between rice yield and intensity of temperature extremes. A three-way ANOVA was used to analyze mean rice yields and rice yield losses to extreme temperatures, with manure and season as fixed factors and block as a random factor. Paired-sample *t*-tests were used to analyze the effect of manure on soil fertility in the field experiment. We used two-way ANOVAs (manure and temperature) to analyze the data for grain yield, net foliar photosynthetic rate, and foliar proline concentration in the pot experiment. We performed all analyses using the software of SPSS Statistics 19.0 (SPSS, Chicago, USA). Differences between treatments were considered significant at $P < 0.05$.

Meta-analysis. We conducted a meta-analysis to assess the effects of long-term manure amendment on rice yield. We used the Web of Science and the China National Knowledge Infrastructure to search journal articles published before June 2020 using search terms “long term” and “rice OR paddy”, and “yield”. The studies had to meet the following criteria to be included in our data set: (i) the experiment was conducted under field conditions with replicates, (ii) experimental duration was at least 10 years, (iii) control treatments only received inorganic fertilizer, and the manure treatment received both manure and inorganic fertilizer, and (iv) all management practices needed to be the same between the manure treatment (NPKM) and the control treatment. We included studies where both the control and manure plots received the same amount of inorganic fertilizer and studies where manure partly replaced the inorganic fertilizer. We collected a total of 45 studies and 1177 site-year observations (Supplementary Data 1 and Supplementary Fig. 6). We collected transplanting and harvesting dates for each study in our data set. If this information was not provided, we collected it from other studies conducted near to the experimental site. We extracted daily air-surface temperatures at the experimental site based on the ERA-5 data set using Google Earth Engine. For each study, we calculated mean rice yield and rice yield losses under extreme temperatures using linear regression between the yield and intensity of the temperature extreme (Supplementary Data 2). We also collected data for soil fertility (i.e., concentrations of SOC, available N, available P, and available K) (Supplementary Data 3).

We quantified the effects of manure amendment on rice yield, rice yield losses under extreme temperatures, and soil fertility by calculating the natural logarithm of the response ratio (R),

$$LnR = Ln(X^{\mathrm{NPKM}}/X^{\mathrm{NPK}}) \quad (1)$$

where X^{NPKM} and X^{NPK} are the rice yield, rice yield losses under extreme temperatures, and soil fertility for NPKM and NPK, respectively[77]. Most of the studies did not report standard deviation of rice yield or related information (i.e., standard errors or confidence intervals), so we conducted a meta-analysis using unweighted data[78]. We tested whether environmental factors affected the impact of long-term manure addition on rice yield losses under extreme temperatures by categorizing each study based on cropping system (upland rice and double cropping), manure type (animal and green manure), soil texture (light vs heavy), SOC concentration (<10 g kg^{-1} and ≥10 g kg^{-1}), rate of manure N input (<70 kg ha^{-1} vs ≥70 kg ha^{-1}), ratio of manure N to total N input (<0.5 and ≥0.5), and whether inorganic fertilizers were replaced by manures (no vs yes). We used MetaWin 2.1 to calculate the average effects and 95% bootstrapped confidence intervals. To ease interpretation, we back-transformed the ln$R$ results and reported them as percent change [(R−1) × 100] with manure amendment.

Extrapolation. We estimated the effects of manure amendment on future rice yields by first calculating the intensities of temperature extremes during the current decade (2021–2030) and the last decade of this century (2091–2100). Future air-surface temperatures were simulated as multi-mean temperatures based on four CMIP6 models (CanESM5, CNRM-CM6-1, INM-CM5-0, and HadGEM3-GC31-LL). CMIP6 datasets were obtained from https://esgf-node.llnl.gov/projects/cmip6/. The spatial resolutions of these four models were 128 × 64, 256 × 128, 180 × 120, and 192 × 144, respectively. The global rice growing areas were extracted from the widely-used global cropland maps with a high-spatial resolution (5 min by 5 min)[79]. The transplanting and harvesting dates for each pixel were extracted from a global data set of rice calendars[80] by selecting the nearest estimate from the center of the pixel. The intensities of temperature extremes for each pixel were calculated following the same procedure described in the previous section. Using the predicted intensities of temperature extremes and the two fitted equations shown in Fig. 2b, we calculated for each pixel the potential loss of rice yield due to extreme temperatures under NPK and NPKM treatments during 2015–2024 and 2091–2100:

$$\begin{cases} X_0^{\mathrm{NPK}} = -2.45{*}0 + 5.42 \\ X_t^{\mathrm{NPK}} = -2.45{*}ETI_t + 5.42 \\ Loss_t^{\mathrm{NPK}} = [(X_t^{NPK}/X_0^{\mathrm{NPK}}) - 1] \times 100\% \end{cases} \quad (2)$$

$$\begin{cases} X_0^{\mathrm{NPKM}} = -1.90{*}0 + 5.64 \\ X_t^{\mathrm{NPKM}} = -1.90{*}ETI_t + 5.64 \\ Loss_t^{\mathrm{NPKM}} = [(X_t^{\mathrm{NPKM}}/X_0^{\mathrm{NPKM}}) - 1] \times 100\% \end{cases} \quad (3)$$

where $X_0{}^{\mathrm{NPKM}}$ and $X_0{}^{\mathrm{NPK}}$ represent rice yield with $ETI = 0$ for NPK and NPKM, respectively; $X_t{}^{\mathrm{NPKM}}$ and $X_t{}^{\mathrm{NPK}}$ represent the predicted rice yield for NPK and NPKM; $Loss_t{}^{\mathrm{NPKM}}$ and $Loss_t{}^{\mathrm{NPK}}$ represent the potential loss of rice yield (%) due to extreme temperatures for NPK and NPKM; ETI_t represents the intensity of a temperature extreme, and t denotes the time period (2015–2024 and 2091–2100). Global average rice yield losses were then estimated as the average across all pixels representing rice growing regions.

Data availability

The datasets generated during the current study are available at https://doi.org/10.5281/zenodo.6644987. Coupled Model Intercomparison Project Phase 6 datasets were available at https://esgf-node.llnl.gov/projects/cmip6/.

Received: 3 December 2021; Accepted: 16 June 2022;
Published online: 27 June 2022

References

1. Zhu, C. et al. Carbon dioxide (CO_2) levels this century will alter the protein, micronutrients, and vitamin content of rice grains with potential health consequences for the poorest rice-dependent countries. *Sci. Adv.* **4**, eaaq1012 (2018).
2. Alexandratos, N. & Bruinsma, J. *World Agriculture Towards 2030/2050: The 2012 Revision* (FAO Agricultural Development Economics Division, 2012).
3. Arunrat, N., Pumijumnong, N., Sereenonchai, S., Chareonwong, U. & Wang, C. Assessment of climate change impact on rice yield and water footprint of large-scale and individual farming in Thailand. *Sci. Total Environ.* **726**, 137864 (2020).
4. Lafferty, D. C. et al. Statistically bias-corrected and downscaled climate models underestimate the adverse effects of extreme heat on U.S. maize yields. *Commun. Earth Environ.* **2**, 196 (2021).
5. Davis, K. F., Downs, S. & Gephart, J. A. Towards food supply chain resilience to environmental shocks. *Nat. Food.* **2**, 54–65 (2021).
6. Wang, X. et al. Emergent constraint on crop yield response to warmer temperature from field experiments. *Nat. Sustain.* **3**, 908–916 (2020).
7. Sun, T. et al. Current rice models underestimate yield losses from short-term heat stresses. *Glob. Chang. Biol.* **27**, 402–416 (2020).
8. Challinor, A. J. et al. A meta-analysis of crop yield under climate change and adaptation. *Nat. Clim. Chang.* **4**, 287–291 (2014).
9. Iizumi, T. & Ramankutty, N. Changes in yield variability of major crops for 1981–2010 explained by climate change. *Environ. Res. Lett.* **11**, 034003 (2016).
10. Ray, D. K., Ramankutty, N., Mueller, N. D., West, P. C. & Foley, J. A. Recent patterns of crop yield growth and stagnation. *Nat. Commun.* **3**, 1293 (2012).
11. Amelung, W. et al. Towards a global-scale soil climate mitigation strategy. *Nat. Commun.* **11**, 1–10 (2020).
12. Mueller, N. D. et al. Closing yield gaps through nutrient and water management. *Nature* **494**, 390 (2013).
13. Chen, X. et al. Producing more grain with lower environmental costs. *Nature* **514**, 486–489 (2014).
14. Zhang, X. et al. Managing nitrogen for sustainable development. *Nature* **528**, 51–59 (2015).
15. Guo, J. et al. Significant acidification in major Chinese croplands. *Science* **327**, 1008–1010 (2010).
16. Galloway, J. et al. Transformation of the nitrogen cycle: Recent trends, questions, and potential solutions. *Science* **320**, 889–892 (2008).
17. Xia, L., Lam, S. K., Yan, X. & Chen, D. How does recycling of livestock manure in agroecosystems affect crop productivity, reactive nitrogen losses, and soil carbon balance? *Environ. Sci. Technol.* **51**, 7450–7457 (2017).
18. Zhang, T. et al. Replacing synthetic fertilizer by manure requires adjusted technology and incentives: A farm survey across China. *Resour. Conserv. Recycl.* **168**, 105301 (2021).
19. Bi, L. et al. Long-term effects of organic amendments on the rice yields for double rice cropping systems in subtropical China. *Agric. Ecosyst. Environ.* **129**, 534–541 (2009).
20. Du, Y. et al. Effects of manure fertilizer on crop yield and soil properties in China: A meta-analysis. *Catena* **193**, 104617 (2020).
21. Wang, K., Zhang, X. & Ervin, E. Antioxidative responses in roots and shoots of creeping bentgrass under high temperature: Effects of nitrogen and cytokinin. *J. Plant Physiol.* **169**, 492–500 (2012).
22. Jespersen, D. & Huang, B. Proteins associated with heat-induced leaf senescence in creeping bentgrass as affected by foliar application of nitrogen, cytokinins, and an ethylene inhibitor. *Proteomics.* **15**, 798–812 (2015).
23. Xi, Y. et al. Exogenous phosphite application alleviates the adverse effects of heat stress and improves thermotolerance of potato (Solanum tuberosum L.) seedlings. *Ecotoxicol. Environ. Saf.* **190**, 110048 (2020).
24. Waraich, E. A., Ahmad, R., Halim, A. & Aziz, T. Alleviation of temperature stress by nutrient management in crop plants: a review. *J. Soil Sci. Plant Nut.* **12**, 221–244 (2012).
25. Yamori, W., Noguchi, K., Hikosaka, K. & Terashima, I. Phenotypic plasticity in photosynthetic temperature acclimation among crop species with different cold tolerances. *Plant Physiol.* **152**, 388–399 (2010).
26. Mittler, R. Oxidative stress, antioxidants and stress tolerance. *Trends. Plant Sci.* **7**, 405–410 (2002).
27. Wang, Q., Chen, J., He, N. & Guo, F. Metabolic reprogramming in chloroplasts under heat stress in plants. *Int. J. Mol. Sci.* **19**, 849 (2018).
28. Cheng, Q. et al. An alternatively spliced heat shock transcription factor, OsHSFA2dI, functions in the heat stress-induced unfolded protein response in rice. *Plant Biol.* **17**, 419–429 (2015).
29. Miura, K. et al. SIZ1-mediated sumoylation of ICE1 controls CBF3/DREB1A expression and freezing tolerance in Arabidopsis. *Plant Cell* **19**, 1403–1414 (2007).
30. Xie, G., Kato, H., Sasaki, K. & Imai, R. A cold-induced thioredoxin h of rice, OsTrx23, negatively regulates kinase activities of OsMPK3 and OsMPK6 in vitro. *FEBS Lett.* **583**, 2734–2738 (2009).
31. Hasanuzzaman, M., Hossain, M. A. & Fujita, M. Nitric oxide modulates antioxidant defense and the methylglyoxal detoxification system and reduces salinity-induced damage of wheat seedlings. *Plant Biotechnol. Rep.* **5**, 353 (2011).
32. Uchida, A., Jagendorf, A. T., Hibino, T., Takabe, T. & Takabe, T. Effects of hydrogen peroxide and nitric oxide on both salt and heat stress tolerance in rice. *Plant Sci.* **163**, 515–523 (2002).
33. Khan, S. et al. Plants mechanisms and adaptation strategies to improve heat tolerance in rice. A review. *Plants* **8**, 508 (2019).
34. Li, Y., Gao, Y., Xu, X., Shen, Q. & Guo, S. Light-saturated photosynthetic rate in high-nitrogen rice (*Oryza sativa* L.) leaves is related to chloroplastic CO_2 concentration. *J. Exp. Bot.* **60**, 2351–2360 (2009).

35. Xiong, D. et al. Rapid responses of mesophyll conductance to changes of CO_2 concentration, temperature, and irradiance are affected by N supplements in rice. *Plant. Cell Environ.* **38**, 2541–2550 (2015).
36. Waraich, E. A., Ahmad, R., Ashraf, M. Y., Saifullah & Ahmad, M. Improving agricultural water use effciency by nutrient management in crop plants. *Acta Agric. Scand. Sect.-B Soil. Plant Sci.* **61**, 291–304 (2011).
37. Dias, A. S. & Lidon, F. C. Bread and durum wheat tolerance under heat stress: A synoptical overview. *Emir. J. Food Agric.* **22**, 412–436 (2010).
38. Meshah, E. A. E. Effect of irrigation regimes and foliar spraying of potassium on yield, yield components and water use efficiency of wheat in sandy soils. *World J. Agric. Sci.* **5**, 662–669 (2009).
39. Huang, G., Zhang, Q., Wei, X., Peng, S. & Li, Y. Nitrogen can alleviate the inhibition of photosynthesis caused by high temperature stress under both steady-state and flecked irradiance. *Front. Plant Sci.* **8**, 945 (2017).
40. Zhou, Y. et al. High nitrogen input reduces yield loss from low temperature during the seedling stage in early-season rice. *Field Crop. Res.* **228**, 68–75 (2018).
41. Hou, L. et al. Effects of different phosphate fertilizer application on permeability of membrane and antioxidative enzymes in rice under low temperature stress. *Acta Agriculturae. Boreali-Sinica* **27**, 118–123 (2012).
42. Dong, W. et al. Effect of different fertilizer application on the soil fertility of paddy soils in red soil region of southern China. *PLoS One* **7**, e44504 (2012).
43. Bertollo, A. M. et al. Precrops alleviate soil physical limitations for soybean root growth in an Oxisol from southern Brazil. *Soil Till. Res.* **206**, 104820 (2021).
44. Ren, Y. et al. Functional compensation dominates plant rhizosphere microbiota assembly of plant rhizospheric bacterial community. *Soil Biol. Biochem.* **150**, 107968 (2020).
45. Oka, Y. Mechanisms of nematode suppression by organic soil amendments—a review. *Appl. Soil Ecol.* **44**, 101–115 (2010).
46. Rose, M. T. et al. A meta-analysis and review of plant-growth response to humic substances: Practical implications for agriculture. *Adv. Agron* **124**, 37–89 (2014).
47. García, A. C. et al. Vermicompost humic acids modulate the accumulation and metabolism of ROS in rice plants. *J. Plant Physiol.* **192**, 56–63 (2016).
48. Dieleman, W. I. et al. Simple additive effects are rare: A quantitative review of plant biomass and soil process responses to combined manipulations of CO_2 and temperature. *Glob. Chang. Biol.* **18**, 2681–2693 (2012).
49. Muhammad, Q. et al. Yield sustainability, soil organic carbon sequestration, and nutrients balance under long-term combined application of manure and inorganic fertilizers in acidic paddy soil. *Soil Till. Res.* **198**, 104509 (2020).
50. Zhang, X. et al. Benefits and trade-offs of replacing synthetic fertilizers by animal manures in crop production in China: A meta-analysis. *Glob. Chang. Biol.* **26**, 888–900 (2020).
51. Zhang, X. et al. Significant residual effects of wheat fertilization on greenhouse gas emissions in succeeding soybean growing season. *Soil Till. Res.* **169**, 7–15 (2017).
52. Latare, A. M., Kumar, O., Singh, S. K. & Gupta, A. Direct and residual effect of sewage sludge on yield, heavy metals content and soil fertility under rice–wheat system. *Ecol. Eng.* **69**, 17–24 (2014).
53. Zhang, J. et al. Long-term straw incorporation increases rice yield stability under high fertilization level conditions in the rice–wheat system. *Crop J.* **9**, 1191–1197 (2021).
54. Pachauri, R. K. et al. *Climate change 2014: Synthesis Report. Contribution of Working Groups I, II, and III to the fifth assessment report of the Intergovernmental Panel on Climate Change* (IPCC, 2014).
55. Choi, W. J., Lee, M. S., Choi, J. E., Yoon, S. & Kim, H. Y. How do weather extremes affect rice productivity in a changing climate? An answer to episodic lack of sunshine. *Glob. Chang. Biol.* **19**, 1300–1310 (2013).
56. FAO. FAOSTAT Online Statistical Service. https://www.fao.org/faostat/en/#data/RFN, (FAO, 2016).
57. Carlson, K. M. et al. Greenhouse gas emissions intensity of global croplands. *Nat. Clim. Chang.* **7**, 63–68 (2017).
58. Sheldrick, W., Syers, J. K. & Lingard, J. Contribution of livestock excreta to nutrient balances. *Nutr. Cycling Agroecosyst.* **66**, 119–131 (2003).
59. Thangarajan, R., Bolan, N. S., Tian, G., Naidu, R. & Kunhikrishnan, A. Role of organic amendment application on greenhouse gas emission from soil. *Sci. Total Environ.* **465**, 72–96 (2013).
60. Aryal, J. P. et al. Factors affecting farmers' use of organic and inorganic fertilizers in South Asia. *Environ. Sci. Pollut. Res.* **28**, 51480–51496 (2021).
61. Zhang, Q. et al. Targeting hotspots to achieve sustainable nitrogen management in China's smallholder-dominated cereal production. *Agronomy* **11**, 557 (2021).
62. Tyagi, V. K. et al. Anaerobic co-digestion of organic fraction of municipal solid waste (OFMSW): Progress and challenges. *Renewable Sustain. Energy Rev.* **93**, 380–399 (2018).
63. Schlesinger, W. H. Carbon sequestration in soils: Some cautions amidst optimism. *Agric. Ecosyst. Environ.* **82**, 121–127 (2000).
64. Potter, P., Ramankutty, N., Bennett, E. M. & Donner, S. D. Characterizing the spatial patterns of global fertilizer application and manure production. *Earth Interact.* **14**, 1–22 (2010).
65. Zhao, F., Yang, L., Chen, L., Li, S. & Sun, L. Bioaccumulation of antibiotics in crops under long-term manure application: Occurrence, biomass response, and human exposure. *Chemosphere* **219**, 882–895 (2019).
66. Chadwick, D. R. et al. Strategies to reduce nutrient pollution from manure management in China. *Front. Agr. Sci. Eng.* **7**, 45–55 (2020).
67. Jin, S. et al. Decoupling livestock and crop production at the household level in China. *Nat. Sustain* **4**, 48–55 (2021).
68. Chen, D., Yuan, L., Liu, Y., Ji, J. & Hou, H. Long-term application of manures plus chemical fertilizers sustained high rice yield and improved soil chemical and bacterial properties. *Eur. J. Agron.* **90**, 34–42 (2017).
69. Siddik, M. A. et al. Responses of indica rice yield and quality to extreme high and low temperatures during the reproductive period. *Eur. J. Agron.* **106**, 30–38 (2019).
70. Bates, L. S., Waldren, R. P. & Teare, I. D. Rapid determination of free proline for water stress studies. *Plant Soil* **39**, 205–207 (1973).
71. Page, A. L., Miller, R. H. & Dennis, R. K. *Methods of Soil Analysis. Part 2 Chemical Methods* (ed Page, A. L.) (Soil Science Society of America, 1982).
72. Black, C. A. *Methods of Soil Analysis Part II. Chemical and Microbiological Properties* (ed Norman, A. G.) (American Society of Agriculture, 1965).
73. Murphy, J. & Riley, J. P. A modified single solution method for the determination of phosphate in natural waters. *Anal. Chim. Acta* **27**, 31–36 (1962).
74. Knudsen, D., Peterson, G. A. & Pratt, P. F. *Methods of Soil Analysis. Part 2. Chemical and Microbiological Properties* (ed Page, A. L.) (American Society of Agriculture, 1982).
75. Olsen, S. R. *Estimation of Available Phosphorus in Soils by Extraction with Sodium Bicarbonate* (United States Department of Agriculture Circular, 1954).
76. Lewis, S. L., Brando, P. M., Phillips, O. L., Van Der Heijden, G. M. F. & Nepstad, D. The 2010 amazon drought. *Science* **331**, 554–554 (2011).
77. Hedges, L. V., Gurevitch, J. & Curtis, P. S. The meta-analysis of response ratios in experimental ecology. *Ecology* **80**, 1150–1156 (1999).
78. van Groenigen, K. J., Van Kessel, C. & Hungate, B. A. Increased greenhouse-gas intensity of rice production under future atmospheric conditions. *Nat. Clim. Chang.* **3**, 288–291 (2013).
79. Monfreda, C., Ramankutty, N. & Foley, J. A. Farming the planet: 2. Geographic distribution of crop areas, yields, physiological types, and net primary production in the year 2000. *Global Biogeochem. Cycles* **22**, GB1022 (2008).
80. Laborte, A. G. et al. RiceAtlas, a spatial database of global rice calendars and production. *Sci. Data* **4**, 170074 (2017).

Acknowledgements

This work was supported by the National Natural Science Foundation of China (32022061), the National Key R&D Program of China (2017YFD0300100), Modern Agro-industry Technology Research System-Green manure (CARS-22), Fundación Ramón Areces project ELEMENTAL-CLIMATE, the Spanish Government project (CGL2016-79835-P), and the Catalan Government projects (SGR 2017-1005 and AGAUR-2020PANDE00117).

Author contributions

Y.J. designed the research. X.C.Z., Jin Chen, W.W.L., and S.H.W. conducted the experiments and data collection. Y.J., X.C.Z., Ji Chen, Y.F.D., S.H., J.P., Jin Chen, F.Z., W.J.Z., G.H.L., Z.H.L., S.H.W., and K.J.v.G. contributed to data analysis and interpretation. Y.J., X.C.Z., and S.H.W. wrote the draft manuscript. All authors commented on and approved the final manuscript.

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/s43247-022-00481-y.

Correspondence and requests for materials should be addressed to Yanfeng Ding, Songhan Wang or Yu Jiang.

Peer review information *Communications Earth & Environment* thanks the anonymous reviewers for their contribution to the peer review of this work. Primary Handling Editor: Clare Davis.