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Anthropogenic disturbances caused declines in the wetland area and carbon pool in China during the last four decades

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Abstract

Wetlands are among the natural ecosystems with the highest soil carbon stocks on Earth. However, how anthropogenic disturbances have impacted the quantity and distribution of wetland carbon pool in China is not well understood. Here we used a comprehensive countrywide wetland inventory and Landsat 8 data to document the spatial patterns in China's wetland areas and carbon pools and to understand the underlying causes of their changes from the 1980s to 2010s. We found that the wetland area and carbon pool have decreased from 4.11×10^5 km^2 and 15.2 Pg C in the 1980s to 2.14×10^5 km^2 and 7.6 Pg C in the 2010s, respectively. Using the human influence index (HII) as a quantitative measure of anthropogenic disturbance intensity, we found a positive relationship between the HII values and wetland decreases in many regions and across China as a whole—which have increased 17% during the time period—indicating that anthropogenic disturbances have been a major factor causing wetland destruction in recent decades. This study provides new evidence for recent changes in China's wetland carbon pool and emphasizes the importance of mitigating anthropogenic disturbances for wetland conservation.

KEYWORDS

anthropogenic disturbances, China's wetland, human influence index, wetland area, wetland soil carbon pool

1 | INTRODUCTION

Wetlands have formed and evolved due to long-term natural processes and have served as a persistent carbon pool and nutrient reactor (Bossio et al., 2020; Lal et al., 2004; Mitsch & Gosselink, 2015). In a natural state, the waterlogged and anaerobic environment of a wetland enables plant organic matter to be buried belowground for a long period of time. Wetlands represent a large carbon pool among terrestrial ecosystems (Gorham, 1991). The world's wetlands cover 7–10 million km^2, or about 5%–8% of the total land surface area (Mitsch & Gosselink, 2015). Since the industrial revolution, however, wetlands have increasingly been influenced by anthropogenic disturbances, which have impacted the wetland structure, function, and its carbon pool size. Since 1900 AD, more than half of wetlands have disappeared globally (Davidson, 2014). This loss of wetland area and reduction in carbon sequestration capacity due to anthropogenic disturbances have played an important role in reducing carbon storage on land (Moomaw et al., 2018).

Previous studies tend to estimate carbon pools in different wetland types globally, such as tidal wetlands and freshwater wetlands (Bernal & Mitsch, 2012; Chmura et al., 2003). Estimates of wetland carbon stocks based on published data in China are highly variable, ranging from 5.39 to 16.56 Pg (Xiao et al., 2019; Zheng et al., 2013). Also, carbon pools in China's wetlands change from 4.51 ± 1.63 Pg in the 1980s to 3.75 ± 0.89 Pg in the 2010s for the top-100 cm wetland soil (Xu et al., 2019). Furthermore, there are some carbon sequestration rate estimates for different types of wetlands, such as 0.2–0.5 t C/ha/a in peatlands and 1.0–2.8 t C/ha/a in mangrove forests (Duan et al., 2008), and 4.91×10^6 t/a in all marshes (Lu et al., 2013). Despite these previous studies, there are still significant uncertainties and knowledge gaps in the understanding of this large land carbon stock.

Anthropogenic disturbances have a double-edged role in affecting wetland carbon pools. On the one hand, wetland reclamation, drainage, and human-induced fires and even the disruption of wetland ecosystem functions caused by anthropogenic activities enhance CO_2 releases from wetlands, and anthropogenic disturbances can negatively affect the soil structure, wetland vegetation, and the carbon sequestration rate (Lal, 1989; Lenart, 2009). On the other hand, wetland conservation and restoration are believed to be some of the most effective ways to mitigate global warming by limiting the processes causing the increases in greenhouse gases emissions to the atmosphere (Davidson, 2014). Furthermore, the wise use of wetlands is irreplaceable in reaching sustainable development goals, such as alleviating poverty and providing clean drinking water in addition to climate change mitigation (Xu et al., 2020).

Data on changes in wetland area, distribution, carbon density, and carbon pool in China are available in the First National Peatland Resources Inventory in the 1980s, the Second National Wetland Resources Inventory in 2013, and other studies (Institute of Soil Science, 1982; Ma, 2015; Niu et al., 2012; Zheng et al., 2013). It has always been a challenge to estimate the impacts of anthropogenic disturbances on wetlands in a systematic and quantitative way, and there are few methods for quantifying the relationship between wetland carbon pools and anthropogenic disturbances. Therefore, for the first time, we performed an analysis using the human influence index (HII)—which has been used to quantify the magnitude of anthropogenic disturbances in the natural environment (Sanderson et al., 2002)—as a surrogate index to correlate with wetland changes in China over the last four decades.

2 | DATA SOURCES AND METHODS

Two datasets were used for the assessment of the relationship between wetland change and anthropogenic disturbance: wetland physical characteristics and wetland management characteristics (Figure S1). The first section presents data on from the 1980s and 2010s. The 1980s wetland distribution map was created by digitizing the "Mire Map of China" and combining it with the findings of the 1980 First National Peatland Resources Inventory. The accuracy of the wetland map is approximately 73%. Landsat 8 imagery is used to obtain the 2010 wetlands distribution map with an overall accuracy of 83%. The distribution maps of national wetland soil carbon pools in the 1980s and 2010s were estimated using the universal kriging method from the soil property data in "Supplementary Tables of Survey Report on China's Peatland Resources (1980)" and "Map of Soil Organic Matter Content at 1-km Grid in China (1990)," respectively, as well as digital elevation model data (Table S1).

Wetland polygons in the 2010s were subtracted from those in the 1980s to estimate changes in wetland areas over this period of time. Since the mapping resolution (minimum unit sizes) in the two wetland maps are very different (i.e., 100 ha in 1983 versus 8 ha in 2013), the wetland polygons in the 2010s were combined to match the 1980s map, resulting a total of 2409 wetland polygons. All the analyses presented in this study were based on these 2409 individual wetlands.

The HII map in the 1980s was extracted from the dataset "Global Human Influence Index (Geographic), v1." The 2010s HII map was calculated using the method in Venter et al. (2016a). The wetlands and HII maps in the 1980s and 2010s were overlain to obtain HII maps of various wetlands. Once all the maps were obtained, we resampled all the map grids into uniform 0.5 km grids for the subsequent calculations.

Finally, the correlation analyses between the wetland's maps and the HII maps were used to determine the relationship between wetland changes and anthropogenic disturbances. Using the gradient descent method, we calculated the possible HII value when the wetland area or carbon pool would approach zero. The key assumption for the calculation of carbon pools is that over the past four decades, the soil carbon density in wetlands had not significantly decreased, because the former survey and research findings revealed that organic matter changes in soils are primarily concentrated above 100 cm, having little effect on deeper soil layers, and that changes in surface soils are not significant in different years (Gao et al., 2010; Institute of Soil Science, 1982; National Soil Survey Office, 1993). Differences in wetland locations (i.e., the Zoigê Plateau and the Sanjiang Plain) were calculated according to the published data. The data sources and method details are available in Supporting Information, including an overall flowchart (Figure S1; Table S1).

3 | RESULTS

3.1 | Wetland and carbon pools change from the 1980s to 2010s

On the basis of 2409 individual mapped wetlands, we found that the wetland area and carbon pool in China have decreased from 4.11×10^5 km^2 and 15.2 Pg C in the 1980s to 2.14×10^5 km^2 and 7.6 Pg C in the 2010s, an average reduction in almost by a half across the China, respectively (Figure 1; Table S2). Furthermore, wetland-abundant regions showed great reductions in the wetland area and carbon pools. For example, the wetland carbon pools in the two major wetland regions that contain 80% wetlands in the entire country—Northeast China (including the Greater Khingan Range, Sanjiang Plain, and Changbai Mountains) and Southwest China (including the Zoigê Plateau)—decreased by 55%–56% from the 1980s to 2010s. Except for the carbon pool in East China, all regions show decrease in the total wetland areas and carbon pools from the 1980s to 2010s (Figure 2; Table S2). The dominant type of wetlands (Marsh) in East China shows an increase of 50% in the carbon pool (Figure 2; Table S2).

3.2 | Wetland carbon pools under different HII intensities

Anthropogenic disturbances have greatly increased since 1980 in China. In general, the HII has shown an increasing trend from 6 to 7 in all the wetland distribution regions nationwide over the past four decades (Figure 1a,b). In the wetland region of Northeast China, the overall average HII has been stable at 8. For most wetland types in this region, the average HII increased from 5 to 10, but the HII decreased for inland and seasonal salt marsh localities. In North China, the HII index increased in every type of wetlands, with a total average increase from 6 to 8 (an increase of 33%). But in East China, the HII calculated for marshes, a major wetland type there, decreased from 7 to 6 overall (a decrease of 14%). The main wetland types in Central China—marsh and forested wetland—showed little change in HII at approximately 12. In Southwest China, the HII of all the wetland types increased significantly from 4 to 6 (an increase of 50%; Figure 1).

The average HII is greater than 27 when the wetlands are located around towns, roads, and canals, especially in the Greater Khingan Range and the Zoigê Plateau (Figure 1). For reference, the area-weighted average HII in built up areas of major cities changed from 38 in the 1980s to 46 in the 2010s (Table S3).

The carbon pools show a decreasing trend nationwide, with the HII increasing from 6 in the 1980s to 7 in the 2010s. We found that only 51%–55% of wetlands were affected by anthropogenic disturbances below the average HII from the 1980s to 2010s (Figure 3). Based on our machine learning analysis, there is a 99% probability that the wetland area would have totally disappeared if the HII value had approached a value of 31 during the 1980s–2010s.

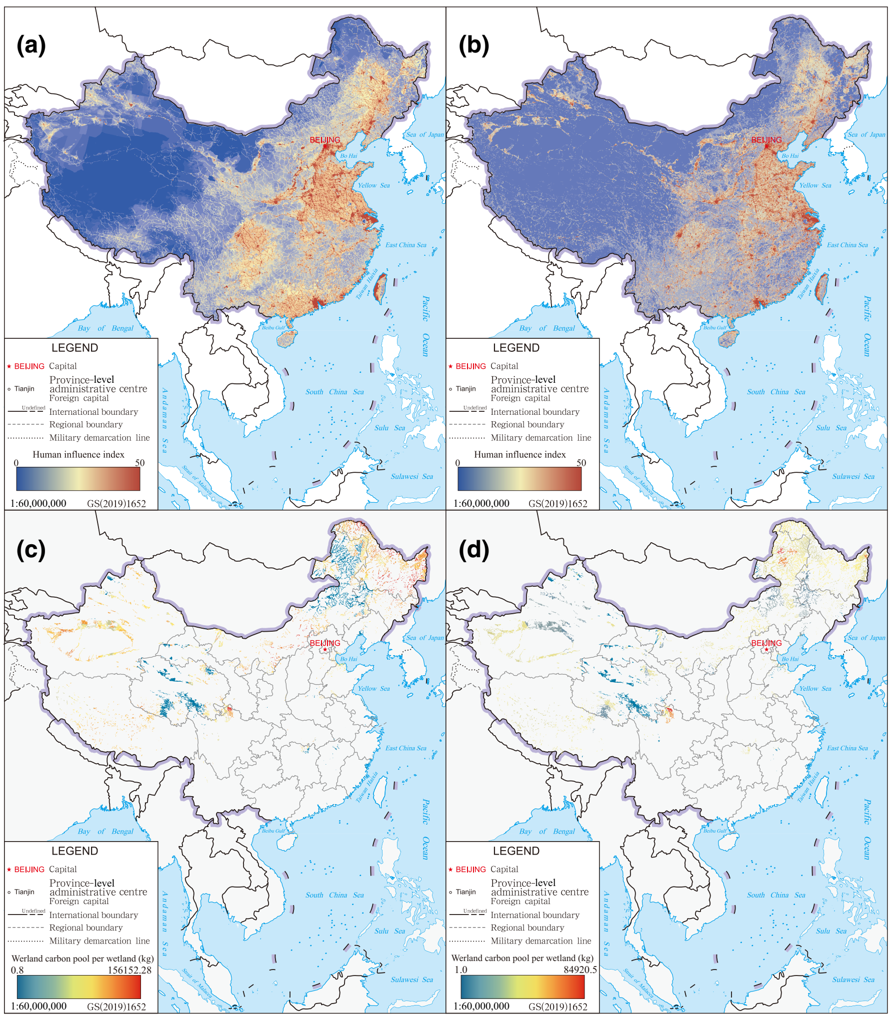

FIGURE 1 Maps of anthropogenic disturbances, wetland distributions, and wetland carbon pools in China. (a) Map of the human influence index (HII) of China in 1980s (Venter et al., 2018). (b) Map of the HII for China in 2010s; the map was created using the HII method (Sanderson et al., 2002). (c) Map of the wetland carbon pool (kg per wetland) in China in 1980s. (d) Map of the wetland carbon pool in China in 2010s. Both (c) and (d) were derived using the universal kriging method (Hengl et al., 2007) and the legend refers to kg C per mapping unit (individual wetlands)

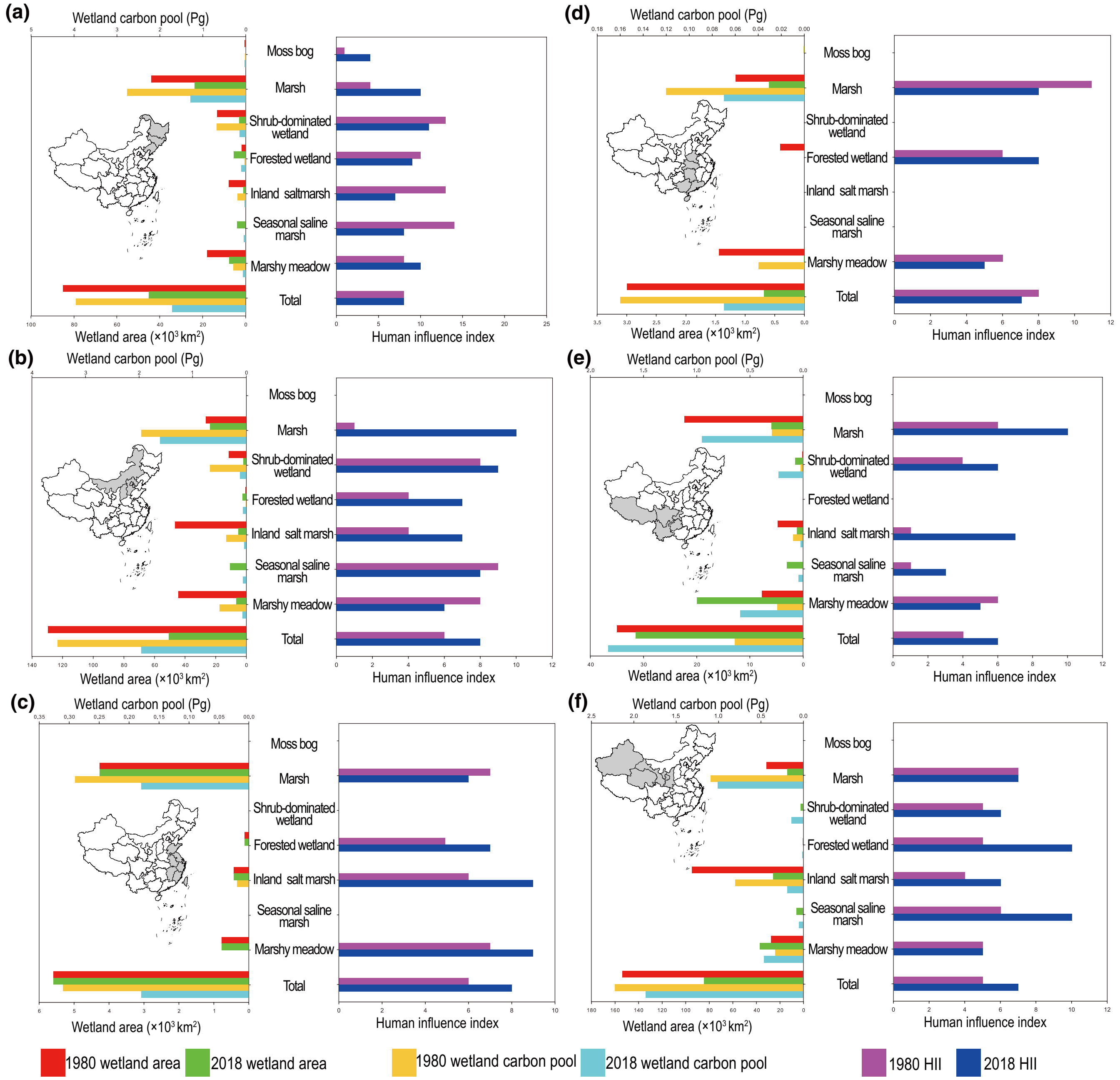

FIGURE 2 Variations in the changes in wetland area, wetland carbon pool, and human influence index (HII). Changes in the area, carbon pool, and HII due to anthropogenic disturbances in seven wetland types in (a) Northeast China, (b) North China, (c) East China, (d) Central China, (e) Southwest China, and (f) Northwest China. Detail number in chart available in Table S2

4 | DISCUSSION

4.1 | Regional anthropogenic activities affecting wetlands

The HII has successfully been used as a tool for mapping cumulative pressure from anthropogenic activities, and it has shown great effectiveness in depicting low-intensity human pressures, linear infrastructures, and pasture lands (Wassenaar et al., 2007). During the last several decades, anthropogenic disturbances such as drainage and agricultural practices have affected organic carbon burial (Simola et al., 2012). In recent years, compared to natural factors, anthropogenic disturbances have become a dominant factor in affecting ecosystem functioning in both aboveground and belowground ecosystem functioning, including carbon cycling (Venter et al., 2016b). Our results showed that the number of wetlands decreased when the HII increased (Figures 1 and 2), indicating that anthropogenic disturbances exert a negative effect on the extent of wetlands and on soil organic carbon pools. The clear negative relationship between the wetland area and the HII could

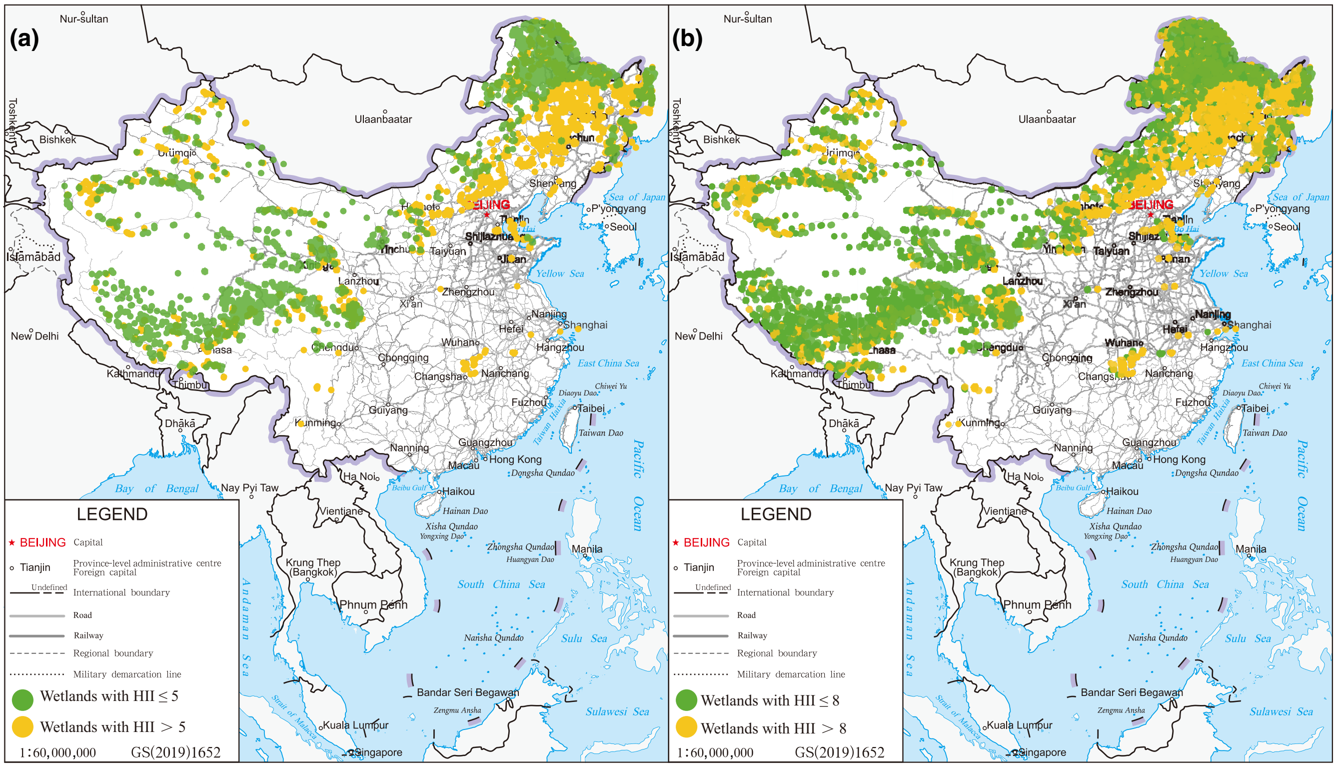

FIGURE 3 Geographic distributions of wetland sites and human influence index (HII) values in 1980s (a) and 2010s (b)

be attributed to the rapid urbanization that has occurred over the last four decades (Figure 2).

Urbanization is identified as one of the most important factors driving the increase in HII (Liu et al., 2019). To further to discuss the role of this specific disturbance, we use the changes in the population of major cities from the 1980s to 2010s as an example (Table S2). The population in most of these major cities shows growth. There is a significant correlation between the population and the HII (Figure S2). These urban HII values (between 38 and 46) were significantly higher than that of wetlands (HII values between 6 and 7). The regressions between the population and the HII in these cities (Figure S2) and between the wetland soil carbon pool size and the HII (Figure 3) revealed that there is a significant linkage between the urban population and the magnitude of wetland changes. Although anthropogenic disturbances of the natural environment would have a lag effect (Bürgi et al., 2017), they would change the wetland environment eventually.

4.2 | Wetland changes and their impacts on ecosystem services

Anthropogenic disturbances have negative impacts on ecological services (Sunil et al., 2011) while many types of damage would require long periods of time for recovery (Moreno-Mateos et al., 2017). Wetland soil carbon pools are unevenly distributed and have changed greatly in China. Previous studies found that China's wetland area decreased from 3.1×10^5 km^2 in 1978 to 2.1×10^5 km^2 in 2008 (Niu et al., 2012); while the wetland soil carbon pool was estimated as 5.4–7.3 Pg in 2009 (Zheng et al., 2013) or 16.87 Pg in 2013 (Xiao et al., 2019; Zheng et al., 2013). After four decades of anthropogenic disturbances, the distribution pattern of inland wetlands has undergone great changes. The carbon pools of wetland soils, particularly in peatlands, have declined greatly over four decades. For example, wetlands surrounding the Tarim Basin have basically disappeared, and inland wetlands in East China and Central China have also been largely lost (Figure 1). In addition to the reduction in the wetland area, the impact of wetland conversion on carbon pools cannot be ignored because it can be considered as a result of wetland degradation to some extent (Lou et al., 2018).

In Millennium Ecosystem Assessment, wetlands provide many provisioning services, including the harvesting of wetland-dependent fish, shellfish, fur-bearing animals, waterfowl, timber, and peat. Regulating ecosystem services from wetlands include moderating the effects of floods, improving the water quality, protecting coastlines from storms, hurricanes, and tsunamis, climate regulation, and aquifer recharge (Reid et al., 2005). China's wetlands are widely distributed, but the area of wetlands in different regions is not proportional to the scale of the soil carbon pool it represents. These regional differences in soil carbon pools are of even greater significance when implementing wetland protection policies. Anthropogenic disturbances will lead to the degradation of wetlands, which, in turn, will cause changes in wetland ecosystem services (Mitsch & Gosselink, 2015). Soil carbon, vegetation health, and waterfowl activities are closely linked in wetlands. The vegetation abundance in the wetland is regarded as an important carbon sequestration factor. Anthropogenic disturbances can affect the soil structure (Lal et al., 1989), which, in turn, affects the vegetation (Zimmermann & Elsenbeer, 2008). Herbivorous waterfowl in wetlands usually follow the status of wetland vegetation (Geremia et al., 2019; Thorup et al., 2017), and waterfowl change their migration timing and routes due to change in plant phenology caused by anthropogenic disturbances (Wang et al., 2019). The size of the national wetland soil carbon pool was reduced to only a half of what it was in 1980 after a 25% increase in the average HII. Moreover, the impact of anthropogenic disturbances on wetlands will change the role of wetlands in responding to and regulating climate change (Masson-Delmotte et al., 2018).

4.3 | Impacts of climate change on spatiotemporal variations in wetlands

Wetlands could be more sensitive to anthropogenic disturbances than either upland or aquatic ecosystems. The wetlands in the areas with higher HIIs are usually distributed around cities or around railway, towns, roads, or canals, which are more easily influenced by anthropogenic disturbances, especially in some water source areas (Figure 3). The wetland net carbon sequestration accounts for 12% of anthropogenic carbon emissions globally (Lenart, 2009). It is likely that carbon pools in natural wetland soil swill continue to decrease with increasing anthropogenic disturbance intensities. The protection of natural wetland carbon pools is more critical at the early stage when anthropogenic disturbances exert a limited impact. Compared with having more anthropogenic disturbances, early protection can achieve twice the result with half the effort and deserves more attention from wetland management departments (Figure 4).

Wetlands and their soil carbon losses might contribute to climate warming effects. In the four decades, not only the soil carbon pools of wetlands in China have been shrinking but also the soil carbon pools of grasslands and forests have shown the tendency of reduction (Table 1). Although China's wetland soil carbon pools account for 30% of the China's terrestrial soil carbon (Niu et al., 2012; Xiao et al., 2019). And there are records showing that China's carbon dioxide emissions have increased by 560% in the four decades (Ritchie & Roser, 2017). Studies indicated that if the carbon in the carbon-rich wetlands in the northern hemisphere is released into the atmosphere, the global temperature would rise by 6–8°C without considering the disturbance of anthropogenic carbon emissions (Hugelius et al., 2020). China's wetlands have lost about 50% of its carbon pool, which causes carbon releasing to the atmosphere through various ways, and thereby has a potential impact on increasing the temperature. In the previous four decades, the difference in land-use and land-cover change has exerted greater influence on surface soils than climate change (Godfray et al., 2010; Miao et al., 2016; Ross et al., 2018; Zhang et al., 2011).

Given the critical threshold in the temperature increase of below 1.5°C by 2030 suggested by the latest IPCC report (Masson-Delmotte et al., 2018), more effective and strict protection measures should be deployed for natural wetland conservation and restoration in China, especially for the main wetland regions with low HII values. A substantial organic carbon pool has been stored in wetland soils, and wetland conservation has played important roles in mitigating climate change impacts and can be monetarily valued and traded in compliance and voluntary carbon markets (Moomaw et al., 2018; Sapkota & White, 2020). Therefore, quantifying the national wetland carbon pool is a prerequisite for participating in global diplomatic climate negotiations and carbon trading systems. This study provides important baseline data for the ongoing conservation of wetlands in China. Using wetlands to reduce carbon emissions and store organic carbon costs much less and is more sustainable than industrial carbon sequestration techniques. It is necessary to establish laws and regulations to restrict the artificial unreasonable use of wetland resources. The protection and

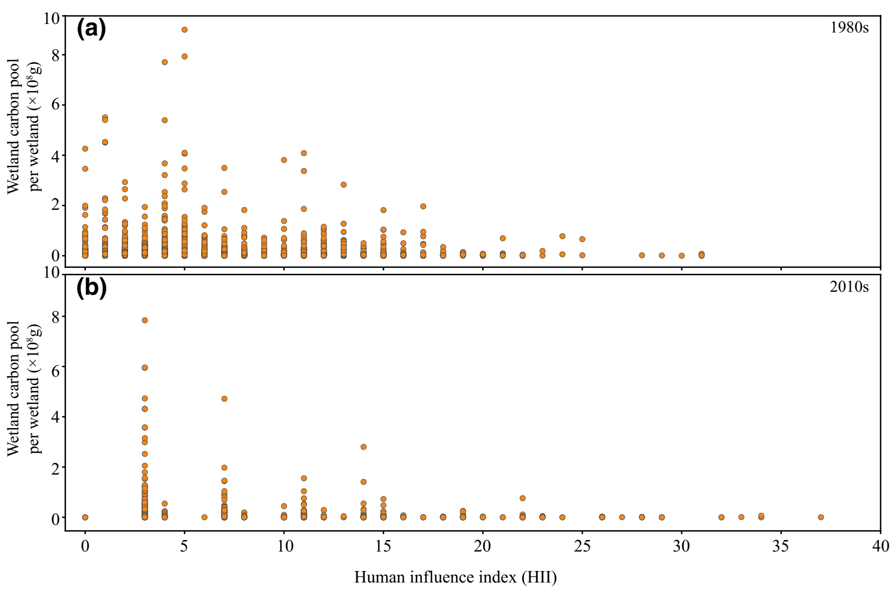

FIGURE 4 Relationship between the wetland soil carbon pool size and the human influence index (HII) in 1980s (a) and 2010s (b). The axis *Y* shows the size of the wetland carbon pool (×10^8 g per wetland), while the axis *X* indicates the intensity of the HII

TABLE 1 Changes in CO_2 and in major terrestrial carbon pools in China

	Year			
	1980	2018	POC	Reference
Wetland soil carbon pool (Pg C)	15.17	7.61	−50%	This study
Grassland soil carbon pool (Pg C)	28.81	24.03	−17%	Li et al. (2019), Tang et al. (2018)
Forest soil carbon pool (Pg C)	82.65	25.89	−69%	Li et al. (2019), Tang et al. (2018)
CO_2 emissions (Pg C)	14.58	100.64	590%	Ritchie and Roser (2017)

Abbreviation: POC, percentage of change.

restoration of degraded wetlands, particularly the protection and restoration of carbon-rich wetlands, must be strengthened, and these carbon-rich wetlands should be considered when formulating climate change policies.

5 | CONCLUSIONS

This study examines the connection between anthropogenic disturbances and wetland changes. Our results show that anthropogenic disturbances were the primary factors impacting the wetland soil carbon pool in China, although the impact of climatic factors on the degradation of wetland soil carbon pools cannot be ignored. Further losses of wetland carbon could occur if the HII continues to increase in coming decades. Despite the serious threat to the future of wetlands, growing concern for environmental issues, the implementation of new environmental and administrative strategies and international agreements are positive signs of changes that should improve the ability to manage both old and new and yet undiscovered environmental threats. China began its reform four decades, and some problems have gradually emerged over this time period. Based on the results of this study, laws and regulations for the management and utilization of wetlands should be enforced in China. Underpinning the protection and restoration of natural wetlands, China's green development approach may reverse the trend of declining carbon pools in wetlands, and facilitate achieving the goals of the Paris Agreement and UN Sustainable Development Goals.

CONFLICT OF INTEREST

The authors declare no competing interests.

AUTHOR CONTRIBUTION

Mingzhi Lu, Lianxi Sheng, Xianguo Lu, Ming Jiang, and Deli Wang designed this study based on publicly available data from the Ministry of Natural Resources of the People's Republic of China; Mingzhi Lu and Qilei Xun performed the data analysis and designed the figures; and together, Mingzhi Lu, Yuanchun Zou, and Zicheng Yu discussed the results and wrote the manuscript.

DATA AVAILABILITY STATEMENT

The Landsat 8 OLI data that support the findings of this study are available from the Earth Resources Observation and Science (EROS) Center with the identifier Landsat 8 OLI/TIRS Surface Reflectance DOI number: 10.5066/F78S4MZJ. The NPP-VIIRS data that support the findings of this study are available from the Atmosphere Archive & Distribution System Distributed Active Archive Center with the identifier http://dx.doi.org/10.5067/VIIRS/VNP46A1.001. The GPW (v4) and Global HII (v1) data that support the findings of this study are available from the SEDAC under the identifiers https://doi.org/10.7927/H49C6VHW and https://doi.org/10.7927/H4BP00QC, respectively. *Code availability*: The code to replicate all the gradient descent analyses is available at https://github.com/lumz231/Manuscript-code-for-Hii.git

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REFERENCES

Bernal, B., & Mitsch, W. J. (2012). Comparing carbon sequestration in temperate freshwater wetland communities. *Global Change Biology*, *18*(5), 1636–1647. https://doi.org/10.1111/j.1365-2486.2011.02619.x

Bossio, D. A., Cook-Patton, S. C., Ellis, P. W., Fargione, J., Sanderman, J., Smith, P., Wood, S., Zomer, R. J., von Unger, M., Emmer, I. M., & Griscom, B. W. (2020). The role of soil carbon in natural climate solutions. *Nature Sustainability*, *3*(5), 391–398. https://doi.org/10.1038/s41893-020-0491-z

Bürgi, M., Östlund, L., & Mladenoff, D. J. (2017). Legacy effects of human land use: Ecosystems as time-lagged systems. *Ecosystems*, *20*(1), 94–103. https://doi.org/10.1007/s10021-016-0051-6

Chmura, G. L., Anisfeld, S. C., Cahoon, D. R., & Lynch, J. C. (2003). Global carbon sequestration in tidal, saline wetland soils. *Global Biogeochemical Cycles*, *17*(4). https://doi.org/10.1029/2002GB001917

Cooley, T., Anderson, G. P., Felde, G. W., Hoke, M. L., Ratkowski, A. J., Chetwynd, J. H., Gardner, J. A., Adler-Golden, S. M., Matthew, M. W., Berk, A., & Bernstein, L. S. (2002). FLAASH, a MODTRAN4-based atmospheric correction algorithm, its application and validation. *IEEE International Geoscience and Remote Sensing Symposium*, *3*, 1414–1418. https://doi.org/10.1109/IGARSS.2002.1026134

Davidson, N. (2014). How much wetland has the world lost? Long-term and recent trends in global wetland area. *Marine and Freshwater Research*, *65*, 936–941. https://doi.org/10.1071/MF14173

Duan, X., Wang, X., Fei, L., & Ouyang, Z. (2008). Primary evaluation of carbon sequestration potential of wetlands in China. *Acta Ecologica Sinica*, *28*(2), 463–469. https://doi.org/10.1016/S1872-2032(08)60025-6

Gao, J. Q., Lei, G. C., Li, L., Cai, L., & Bai, M. Y. (2010). The distribution characteristics of soil organic carbon in three kinds of wetland soils in Zoigê Plateau. *Wetland Science*, *8*(4), 327–330.

Geremia, C., Merkle, J. A., Eacker, D. R., Wallen, R. L., White, P. J., Hebblewhite, M., & Kauffman, M. J. (2019). Migrating bison engineer the green wave. *Proceedings of the National Academy of Sciences of the United States of America*, *116*(51), 25707–25713. https://doi.org/10.1073/pnas.1913783116

Godfray, H. C., Beddington, J. R., Crute, I. R., Haddad, L., Lawrence, D., Muir, J. F., Pretty, J., Robinson, S., Thomas, S. M., & Toulmin, C. (2010). Food security: the challenge of feeding 9 billion people. *Science*, *327*(5967), 812–818. https://doi.org/10.1126/science.1185383

Gorham, E. (1991). Northern peatlands: Role in the carbon cycle and probable responses to climatic warming. *Ecological Applications*, *1*(2), 182–195. https://doi.org/10.2307/1941811

Hengl, T., Heuvelink, G. B. M., & Rossiter, D. G. (2007). About regression-kriging: From equations to case studies. *Computers & Geosciences*, *33*(10), 1301–1315. https://doi.org/10.1016/j.cageo.2007.05.001

Hugelius, G., Loisel, J., Chadburn, S., Jackson, R. B., Jones, M., MacDonald, G., Marushchak, M., Olefeldt, D., Packalen, M., Siewert, M. B., & Treat, C. (2020). Large stocks of peatland carbon and nitrogen are vulnerable to permafrost thaw. *Proceedings of the National Academy of Sciences of the United States of America*, *117*(34), 20438–20446. https://doi.org/10.1073/pnas.1916387117

Institute of Soil Science. (1982). *Soils of China* (in Chinese). China Science Publishing & Media.

Jia, K., Wei, X., Gu, X., Yao, Y., Xie, X., & Li, B. (2014). Land cover classification using landsat 8 operational land imager data in Beijing, China. *Geocarto International*, *29*(8), 941–951. https://doi.org/10.1080/10106049.2014.894586

Lal, R. (1989). Soil management options in the tropics as alternatives to splash and burn. *Soil Technology*, *2*(3), 253–270. https://doi.org/10.1016/0933-3630(89)90010-X

Lal, R., Griffin, M., Apt, J., Lave, L., & Morgan, M. G. (2004). Managing soil carbon. *Science*, *304*(5669), 393. https://doi.org/10.1126/science.1093079

Lal, R., Logan, T. J., & Fausey, N. R. (1989). Long-term tillage and wheel traffic effects on a poorly drained mollic ochraqualf in northwest Ohio. 2. Infiltrability, surface runoff, sub-surface flow and sediment transport. *Soil and Tillage Research*, *14*(4), 359–373. https://doi.org/10.1016/0167-1987(89)90055-X

Lenart, M. (2009). An unseen carbon sink. *Nature Climate Change*, *1*(912), 137–138. https://doi.org/10.1038/climate.2009.125

Levin, N., & Phinn, S. (2016). Illuminating the capabilities of landsat 8 for mapping night lights. *Remote Sensing of Environment*, *182*, 27–38. https://doi.org/10.1016/j.rse.2016.04.021

Li, X., Guirui, Y., & Nianpeng, H. (2019). Changes of soil organic carbon storage in Chinese terrestrial ecosystems from the 1980s to the 2010s. *Journal of Geographical Sciences*, *29*(01), 49–66.

Liu, X., Pei, F., Wen, Y., Li, X., Wang, S., Wu, C., Cai, Y., Wu, J., Chen, J., Feng, K., Liu, J., Hubacek, K., Davis, S. J., Yuan, W., Yu, L. E., & Liu, Z. (2019). Global urban expansion offsets climate-driven increases in terrestrial net primary productivity. *Nature Communications*, *10*(1), 5558. https://doi.org/10.1038/s41467-019-13462-1

Lou, Y., Gao, C., Pan, Y., Xue, Z., Liu, Y., Tang, Z., Jiang, M., Lu, X., & Rydin, H. (2018). Niche modelling of marsh plants based on occurrence and abundance data. *Science of the Total Environment*, *616–617*, 198–207. https://doi.org/10.1016/j.scitotenv.2017.10.300

Lu, M., Sheng, L., & Zhang, L. (2013). A review on carbon fluxes for typical wetlands in different climates of China. *Wetland Science*, *1*, 114–120.

Ma, G. (2015). *China wetland resources (total volume)*. China Forestry Press.

Masson-Delmotte, V., Zhai, P., Pörtner, H.-O., Roberts, D., Skea, J., Shukla, P. R., Pirani, A., Moufouma-Okia, W., Péan, C., Pidcock, R., & Connors, S. (2018). IPCC 2018: Summary for policymakers. In T. Waterfield (Ed.), *Global warming of 1.5°C. An IPCC special report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty* (pp. 7–8). Geneva, Switzerland: World Meteorological Organization.

Miao, L., Zhu, F., Sun, Z., Moore, J. C., & Cui, X. (2016). China's land-use changes during the past 300 years: A historical perspective. *International Journal of Environmental Research and Public Health*, *13*(9), 847. https://doi.org/10.3390/ijerph13090847

Miller, S. D., Straka, W. C., Yue, J., Smith, S. M., Alexander, M. J., Hoffmann, L., Setvák, M., & Partain, P. T. (2015). Upper atmospheric gravity wave details revealed in nightglow satellite imagery. *Proceedings of the National Academy of Sciences of the United States of America*, *112*(49), E6728–E6735. https://doi.org/10.1073/pnas.1508084112

Mitsch, W. J., & Gosselink, J. G. (2015). *Wetlands*. John Wiley & Sons Inc.

Moomaw, W. R., Chmura, G. L., Davies, G. T., Finlayson, C. M., Middleton, B. A., Natali, S. M., Perry, J. E., Roulet, N., & Sutton-Grier, A. E. (2018). Wetlands in a changing climate: Science, policy and management. *Wetlands*, *38*(2), 183–205. https://doi.org/10.1007/s13157-018-1023-8

Moreno-Mateos, D., Barbier, E. B., Jones, P. C., Jones, H. P., Aronson, J., López-López, J. A., McCrackin, M. L., Meli, P., Montoya, D., & Rey Benayas, J. M. (2017). Anthropogenic ecosystem disturbance and the recovery debt. *Nature Communications*, *8*(1), 14163. https://doi.org/10.1038/ncomms14163

National Soil Survey Office. (1993). *Soil species of China* (in Chinese). China Agriculture Press.

Niu, Z. G., Zhang, H. Y., Wang, X. W., Yao, W. B., Zhou, D. M., Zhao, K. Y., Zhao, H., Li, N. N., Huang, H. B., Li, C. C., Yang, J., Liu, C. X., Liu, S., Wang, L., Li, Z., Yang, Z. Z., Qiao, F., Zheng, Y. M., Chen, Y. L., … Gong, P. (2012). Mapping wetland changes in China between 1978 and 2008. *Sci. Bull.*, *57*(1001–6538), 2813–2823. https://doi.org/10.1007/s11434-012-5093-3

Reid, W., Mooney, H., Cropper, A., Capistrano, D., Carpenter, S. R., Chopra, K., Dasgupta, P., Dietz, T., Duraiappah, A. K., Hassan, R., Kasperson, R., Leemans, R., May, R. M., McMichael, A. J., Pingali, P., Samper, C., Scholes, R., Watson, R. T., Zakri, A. H., … Zurek, M. B. (2005). *Ecosystems and human well-being – Synthesis: A report of the millennium ecosystem assessment*. Island Press.

Ritchie, H., & Roser, M. (2017). CO_2 and greenhouse gas emissions. In *Our world in data*. https://ourworldindata.org/co2-and-other-greenhouse-gas-emissions

Robbins, H., & Monro, S. (1951). A stochastic approximation method. *The Annals of Mathematical Statistics*, *22*(3), 400–407. https://doi.org/10.1214/aoms/1177729586

Ross, G., Ligang, S., Cai, F. (2018). *China's 40 years of reform and development 1978–2018*. China Update Series (pp. 1–4). ANU Press.

Sanderson, E. W., Jaiteh, M., Levy, M. A., Redford, K. H., Wannebo, A. V., & Woolmer, G. (2002). The human footprint and the last of the wild: The human footprint is a global map of human influence on the land surface, which suggests that human beings are stewards of nature, whether we like it or not. *BioScience*, *52*(10), 891–904. https://doi.org/10.1641/0006-3568(2002)052[0891:THFATL]2.0.CO;2

Sapkota, Y., & White, J. R. (2020). Carbon offset market methodologies applicable for coastal wetland restoration and conservation in the United States: A review. *Science of the Total Environment*, *701*, 134497. https://doi.org/10.1016/j.scitotenv.2019.134497

Simola, H., Pitkänen, A., & Turunen, J. (2012). Carbon loss in drained forestry peatlands in Finland, estimated by re-sampling peatlands surveyed in the 1980s. *European Journal of Soil Science*, *63*(6), 798–807. https://doi.org/10.1111/j.1365-2389.2012.01499.x

Snyder, J. P. (1987). *Map projections – A working manual, US Geological Survey professional paper 1395*. US Government Printing Office.

Sunil, C., Somashekar, R. K., & Nagaraja, B. C. (2011). Impact of anthropogenic disturbances on riparian forest ecology and ecosystem services in Southern India. *International Journal of Biodiversity*

Science, Ecosystem Services & Management, *7*, 273–282. https://doi.org/10.1080/21513732.2011.631939

Tang, X., Zhao, X., Bai, Y., Tang, Z., Wang, W., Zhao, Y., Wan, H., Xie, Z., Shi, X., Wu, B., Wang, G., Yan, J., Ma, K., Du, S., Li, S., Han, S., Ma, Y., Hu, H., He, N., … Zhou, G. (2018). Carbon pools in China's terrestrial ecosystems: New estimates based on an intensive field survey. *Proceedings of the National Academy of Sciences of the United States of America*, *115*(16), 4021–4026. https://doi.org/10.1073/pnas.1700291115

Thorup, K., Tøttrup, A. P., Willemoes, M., Klaassen, R. H. G., Strandberg, R., Vega, M. L., Dasari, H. P., Araújo, M. B., Wikelski, M., & Rahbek, C. (2017). Resource tracking within and across continents in long-distance bird migrants. *Science Advances*, *3*(1), e1601360. https://doi.org/10.1126/sciadv.1601360

Venter, O., Sanderson, E. W., Magrach, A., Allan, J. R., Beher, J., Jones, K. R., Possingham, H. P., Laurance, W. F., Wood, P., Fekete, B. M., Levy, M. A., & Watson, J. E. M. (2016a). Global terrestrial human footprint maps for 1993 and 2009. *Scientific Data*, *3*(1), 160067. https://doi.org/10.1038/sdata.2016.67

Venter, O., Sanderson, E. W., Magrach, A., Allan, J. R., Beher, J., Jones, K. R., Possingham, H. P., Laurance, W. F., Wood, P., Fekete, B. M., Levy, M. A., & Watson, J. E. M. (2016b). Sixteen years of change in the global terrestrial human footprint and implications for biodiversity conservation. *Nature Communications*, *12558*(7). https://doi.org/10.1038/ncomms12558

Venter, O., Sanderson, E. W., Magrach, A., Allan, J. R., Beher, J., Jones, K. R., & Watson, J. E. (2018). *Last of the wild project, version 3 (LWP-3): 1993 Human footprint, 2018 release*. NASA Socioeconomic Data and Applications Center (SEDAC).

Wang, X., Cao, L., Fox, A. D., Fuller, R., Griffin, L., Mitchell, C., Zhao, Y., Moon, O. K., Cabot, D., Xu, Z., & Batbayar, N. (2019). Stochastic simulations reveal few green wave surfing populations among spring migrating herbivorous waterfowl. *Nature Communications*, *10*(1), 2187. https://doi.org/10.1038/s41467-019-09971-8

Wassenaar, T., Gerber, P., Verburg, P. H., Rosales, M., Ibrahim, M., & Steinfeld, H. (2007). Projecting land use changes in the neotropics: The geography of pasture expansion into forest. *Global Environmental Change*, *17*(1), 86–104. https://doi.org/10.1016/j.gloenvcha.2006.03.007

Xiao, D., Deng, L., Kim, D.-G., Huang, C., & Tian, K. (2019). Carbon budgets of wetland ecosystems in China. *Global Change Biology*, *25*(6), 2061–2076. https://doi.org/10.1111/gcb.14621

Xu, B., Chen, J., & Yu, P. (2017). Vectorization of classified remote sensing raster data to establish topological relations among polygons. *Earth Science Informatics*, *10*(1), 99–113. https://doi.org/10.1007/s12145-016-0273-3

Xu, L., Yu, G., & He, N. (2019). Increased soil organic carbon storage in Chinese terrestrial ecosystems from the 1980s to the 2010s. *Journal of Geographical Sciences*, *29*(1), 49–66. https://doi.org/10.1007/s11442-019-1583-4

Xu, Z., Chau, S. N., Chen, X., Zhang, J., Li, Y., Dietz, T., Wang, J., Winkler, J. A., Fan, F., Huang, B., & Li, S. (2020). Assessing progress towards sustainable development over space and time. *Nature*, *577*(7788), 74–78. https://doi.org/10.1038/s41586-019-1846-3

Zhang, D. D., Lee, H. F., Wang, C., Li, B., Pei, Q., Zhang, J., & An, Y. (2011). The causality analysis of climate change and large-scale human crisis. *Proceedings of the National Academy of Sciences of the United States of America*, *108*(42), 17296–17301. https://doi.org/10.1073/pnas.1104268108

Zheng, Y., Niu, Z., Gong, P., Dai, Y., & Shangguan, W. (2013). Preliminary estimation of the organic carbon pool in China's wetlands. *Chinese Science Bulletin*, *58*(6), 662–670. https://doi.org/10.1007/s11434-012-5529-9

Zimmermann, B., & Elsenbeer, H. (2008). Spatial and temporal variability of soil saturated hydraulic conductivity in gradients of disturbance. *Journal of Hydrology*, *361*(1), 78–95. https://doi.org/10.1016/j.jhydrol.2008.07.027

SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

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