Natural Climate Solutions for China: The Last Mile to Carbon Neutrality

Zhangcai QIN^{*1}, Xi DENG¹, Bronson GRISCOM², Yao HUANG³, Tingting LI⁴, Pete SMITH⁵,
Wenping YUAN¹, and Wen ZHANG⁴

¹*School of Atmospheric Sciences, Guangdong Province Key Laboratory for Climate Change and Natural Disaster Studies, Sun Yat-sen University, and Southern Marine Science and Engineering Guangdong Laboratory (Zhuhai), Zhuhai 519000, China*

²*Conservation International, Arlington, Virginia VA 22202, USA*

³*State Key Laboratory of Vegetation and Environmental Change, Institute of Botany, Chinese Academy of Sciences, Beijing 100093, China*

⁴*State Key Laboratory of Atmospheric Boundary Layer Physics and Atmospheric Chemistry, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing 100029, China*

⁵*Institute of Biological and Environmental Sciences, University of Aberdeen, Aberdeen AB24 3UU, UK*

(Received 16 January 2021; revised 4 February 2021; accepted 7 February 2021)

Key words: carbon sequestration, ecosystem, emissions, energy, greenhouse gas, mitigation

Citation: Qin, Z., X. Deng, B. Griscom, Y. Huang, T. T. Li, P. Smith, W. P. Yuan, and W. Zhang, 2021: Natural climate solutions for China: The last mile to carbon neutrality. *Adv. Atmos. Sci.*, **38**(6), 889–895, <https://doi.org/10.1007/s00376-021-1031-0>.

“I call on all leaders worldwide to declare a State of Climate Emergency in their own countries until carbon neutrality is reached.”

– António GUTERRES (United Nations Secretary General), 12 December, 2020

There is no shortcut to a carbon neutral society; solutions are urgently required from both energy & industrial sectors and global ecosystems. While the former is often held accountable and emphasized in terms of its emissions reduction capability, the latter (recently termed natural climate solutions) should also be assessed for potential and limitations by the scientific community, the public, and policy makers.

1. Energy- and nature-based solutions to climate change

Global greenhouse gas (GHG) emissions have been increasing for centuries, especially since the Industrial Revolution due to rapidly growing consumption of fossil fuels, which has been a major factor driving climate change (IPCC, 2018; UNEP, 2020). To achieve the Paris Climate Agreement goal of limiting global temperature rise to well below 2°C above the preindustrial level and to pursue efforts to keep warming below 1.5°C, global efforts are urgently needed to greatly reduce GHG emissions. Global annual emissions need to drop by 50% in the next ten years and reach net zero by the 2050s so that the 1.5°C target can still be possible (IPCC, 2018; UNEP, 2020). Many countries, especially parties to the Paris Agreement, have made individual climate pledges to cut down GHG emissions, e.g., via Nationally Determined Contributions, or have declared a timeline to reach “carbon neutrality”, “climate neutrality” or net zero emissions (Iyer et al., 2017; Weitzel et al., 2019). The last three terms are often used interchangeably in literature (and in this article), referring to net zero emissions of all three major GHGs i.e., carbon dioxide (CO₂), methane (CH₄) and nitrous oxide (N₂O). In some instances though, they can differ in terms of inclusion of non-CO₂ gases, aerosol forcing or other short-lived climate forcers (IPCC,

* Corresponding author: Zhangcai QIN
Email: qinzhangcai@mail.sysu.edu.cn

2018).

The energy and industrial sectors are widely accepted as the major players in mitigating climate change, primarily due to their significant contributions to global GHG emissions. Over 50 Pg CO₂e yr⁻¹ of GHG emissions are currently released to the atmosphere, about 65% of which are fossil CO₂ emissions (UNEP, 2020). Even with current policies (e.g., Nationally Determined Contributions), the global temperature would still rise by at least 3°C by the end of the century (UNEP, 2020) (Fig. 1). During the past few decades, energy related emissions (mainly CO₂ and CH₄) have dominated global GHG emissions, contributing over 60% of emissions annually (Olivier and Peters, 2020). It is therefore essential, if the Paris Agreement is to be achieved, to reduce energy and industry related emissions, following global pathways such as lowering fossil fuel use, increasing renewable energy share, and deploying cost-effective technologies of decarbonization (IPCC, 2018).

However, while the energy and industrial sectors are essential to “reduce” emissions to close the gap, they are both insufficient, and unable to “remove” emissions. It is unlikely that the 1.5°C climate target can be met without significant removal of CO₂ and other major GHGs, mainly CH₄ and N₂O, from the atmosphere (Fig. 1, light green line) (IPCC, 2018; Roe et al., 2019). Among many technologies designed for CO₂ or overall GHG removal (Fuss et al., 2018), natural climate solutions (NCS) has been recognized to be one of the most cost-effective and readily available options that can be used to supplement energy and industrial mitigation in the climate portfolio (Anderson et al., 2019; Griscom et al., 2019). They offer opportunities to reduce/avoid GHG emissions and more importantly sequester additional carbon in biomass and soils across natural ecosystems, e.g., agriculture, grasslands, forest and wetlands (Griscom et al., 2017; Roe et al., 2019; Goldstein et al., 2020; Qin et al., 2021). Global NCS deployment can remove historical and newly released GHGs, and help with the “last mile delivery” to carbon neutrality or net zero target within a relatively short period of time (i.e. 30 years), with relatively affordable economic, environmental and societal price (Fig. 1, dark green line) (Field and Mach, 2017; Fuss et al., 2018). It is estimated that NCS can deliver approximately 1/3 of the cost-effective GHG mitigation required (to 2030) for holding warming to below 2°C (66% chance) (Griscom et al., 2017).

2. Natural climate solutions: time is of the essence to unleash the power of nature

Natural climate solutions, also termed nature-based climate solutions in a broader sense, often largely refer to measures leading to reduced GHG emissions and additional carbon sinks in natural ecosystems (mostly land-based) such as forests, agriculture, grasslands, and wetlands (Griscom et al., 2017; Roe et al., 2019; Zhang et al., 2020). Some ocean-based ecosystems (e.g., mangroves, seagrasses, and salt marshes) are also part of the NCS (Griscom et al., 2017), while others (e.g., seaweed farming, aquaculture) that have not yet been included in NCS synthesis studies but are conceptually aligned may also contribute to climate mitigation (Hoegh-Guldberg et al., 2019; Jiao et al., 2020). With appropriate management, selected NCS pathways can avoid GHG emissions that would otherwise be released (e.g., avoided conversion of forest and grassland) (Hu et al., 2016; Griscom et al., 2017), reduce overall GHG emissions (e.g., agricultural nitrogen management,

Fig. 1. A schematic graph showing historical annual GHG emissions and future emission scenarios. The lines and circles show relative sizes of annual emissions. The circled figures, each having five colors, indicate global emissions directly related to energy use (“energy”), agriculture, and land use, land use change and forestry (LULUCF) (“nature”, and “others”) (including CO₂ from international transport and non-energy, CH₄ from waste and others, N₂O from industrial processes and energy indirect/waste, and F-gases) (Olivier and Peters, 2020). The relative size of historical emissions (1850–2018) is based on Global Carbon Project (Le Quéré et al., 2018). Future temperature change under continued large emissions is based on “baseline” scenarios from IPCC AR5 (IPCC, 2014). The emission reduction scenarios reflect potential climate mitigation from both energy & industrial systems and natural systems (IPCC, 2018).

livestock management) (Zhang et al., 2013; Nayak et al., 2015), and/or increase carbon sequestration in biomass and soils (e.g., reforestation, biochar, and wetland restoration) (Qin et al., 2013; Paustian et al., 2016; Bossio et al., 2020).

The technical potential for any specific NCS pathway can be large (e.g., reforestation), but the applicable land extent and magnitude of mitigation can be further limited, for reasons including biological constraints (e.g., insects and growth rate), environmental constraints (e.g., water availability and biodiversity), availability and competing use of existing lands and ecosystems, and economic and social costs (Paustian et al., 2016; Griscom et al., 2017; Roe et al., 2019). Spatial limitations and operational feasibility should also be examined to avoid pitfalls and unintended consequences (e.g., water stress, yield loss) (Feng et al., 2016; Smith et al., 2020). Recently, Griscom et al. (2017) reported a total of 23.8 Pg CO₂e yr⁻¹ of global maximum potential from 20 NCS pathways, with consideration of constraints in food security, fiber security, and biodiversity conservation (Fig. 2a). The forest sector makes the greatest contribution to the overall mitigation potential, with the reforestation pathway being the largest contributor. In particular, China alone can contribute about 10% of global potential within eight of the pathways estimated by country, with reforestation playing the leading role (Fig. 2b). When considering the social cost of CO₂, about half of the maximum potential cannot be deemed cost-effective (over 100 USD Mg CO₂e⁻¹) (Fig. 2c).

Adding another layer of uncertainty to NCS, the delays in NCS deployment can impact the time taken for action and

Fig. 2. The mitigation potentials of NCS by ecosystem and by specific pathway. In total, 20 pathways (Global-20) were estimated for their individual NCS potentials at global scale, and eight pathways were specifically quantified for their potentials by country/region (Griscom et al., 2017). (a) Maximum potential by ecosystem, (b) maximum potential for eight specific pathways, and (c) global NCS potential constrained by cost and delay impacts. Maximum potential and cost-effective potential are estimated by Griscom et al. (2017). The "achievable" mitigation is cost-effective mitigation accounting for NCS delay impacts, annualized over 30 years (2020–2050), with the time taken to reach designed extent and maximum intensity being at 30 and 5 years, respectively (Qin et al., 2021). Global-8 and China-8 refer to potentials of the eight pathways worldwide and for China, respectively. The area of the pie represents the relative size of individual potential by category.

therefore actual mitigation, which further challenges our current understanding of the magnitude of mitigation potential in ecosystems (Qin et al., 2021). The time we spend to take meaningful NCS action, to fully deploy NCS technologies, and for ecosystems to reach potential mitigation intensity can all be delayed. For instance, if we set these three delays at 0, 30, and 5 years respectively, assuming aggressive NCS actions worldwide, the “achievable” potential ($6.7 \text{ Pg CO}_2\text{e yr}^{-1}$) that can actually happen is only about 60% of the total cost-effective potential and 28% of the maximum potential (Fig. 2c). Similar delays also apply to energy and industrial sectors, and should be avoided or minimized to the greatest extent possible (Qin et al., 2021).

Global challenges for deploying both NCS and energy and industry climate mitigation options are daunting. In the case of NCS, we emphasize here reasons for optimism indicated by actions that have been taken regionally and historically leading to measurable mitigation benefits. For instance, multiple policies since the 2000s contributed to decrease of Brazilian Amazon deforestation (Heilmayr et al., 2020); ecological restoration projects (e.g., forest, grasslands) over the past several decades have led to greening in China (Hu et al., 2016; Chen et al., 2019). The experience from the past can well inform future NCS actions.

3. Natural climate solutions for China: the future in the past

Human activities, if rationally planned and managed, are expected to bring “order” to the human-natural systems (Ye et al., 2001). Over the past half century, China has launched tens of ecological projects nationwide, with the main purposes of protection and restoration of forests and grasslands, primarily to prevent flooding, desertification and soil erosion, and to improve biomass productivity (Bryan et al., 2018; Lu et al., 2018). Now, in the context of climate change mitigation, they are becoming probably the world’s largest NCS program, in terms of scale and investment (Bryan et al., 2018; Lu et al., 2018). A recent report estimated about $0.5 \text{ Pg CO}_2\text{e}$ of sequestration in natural ecosystems during the 2000s, owing to six ecological projects started during 1978–2003. In particular, The “Natural Forest Protection Project” alone contributed over 50% of total carbon sinks, followed by “Three-North Shelter Forest Program” (19%) and “Returning Grazing Land to Grassland Project” (12%). Reforestation and afforestation alone contributed about $0.4 \text{ Pg CO}_2\text{e yr}^{-1}$ (Lu et al., 2018), that is already slightly higher than the size of cost-effective mitigation estimated for reforestation in China ($0.38 \text{ Pg CO}_2\text{e yr}^{-1}$) (Fig. 2a) (Griscom et al., 2017); however, deduction of “baseline” reforestation trends account for a more constrained estimate by Griscom et al. (2017). Recent top-down observational evidence also shows greening in China (Chen et al., 2019) and increasing land carbon sinks owing to large-scale ecological restoration (Wang et al., 2020).

In addition, many of the ecological projects in China are still active with plans to renew and expand their extent (MoA, 2017; NDRC, 2020). The legacy effects of existing restored ecosystems (i.e., forest and grassland) and continuing efforts for expansion of project extent could further augment carbon sequestration potentials in biomass and soils. For instance, the Returning Grazing Land to Grassland Project, among others, is still actively enrolling additional land. By 2020, a total of 90 Mha of grazing lands are expected to be restored to grasslands (MoA, 2017), which is 50% additional coverage from the 2010 level (Lu et al., 2018). Optimized management (e.g., grazing exclusion and reduced grazing intensity) would be applied to about 200 Mha of grazing lands (MoA, 2017), resulting in additional carbon sequestration, especially in soils (Nayak et al., 2015). Studies also suggest other NCS pathways leading to additional mitigation, e.g., China has the largest potential of any country for agroforestry and silvopasture – by integrating trees into crop and grazing lands without disrupting yields (Chapman et al., 2020).

What can we learn from current knowledge and China’s experience? Here we list some recommended practices for policy making, global coordination, and ecosystem management (Table 1), expanded from a previous estimate to reduce NCS delays (Qin et al., 2021). First of all, the best time to act is now (if not already) (Table 1). China started its first major project in the 1970s, and it took over 40 years and several phases to finally re-shape its degraded landscapes, especially in North and Northwest China (e.g., Loess Plateau) (Lu et al., 2018). It is a race against time to meet the Paris climate target, while delayed action is dragging the race from the starting line (IPCC, 2018). Secondly, worldwide NCS needs global governance and involvement of governments, stakeholders, land users and even other programs related to land management (Table 1). The ecological projects could serve multiple purposes such as increasing productivity, preventing soil erosion and improving biodiversity. Climate change mitigation often comes together with better management and soil health improvement (Bradford et al., 2019; Bossio et al., 2020). Thirdly, the delays in NCS of various forms could be further shortened providing local and global management efforts directed towards sustainable ecosystems, e.g., protecting ecosystems with rich and irrecoverable carbon pools, prioritizing certain NCS pathways (including ocean-based) with cost-effective mitigation potential, and minimizing ecosystem disturbances (Table 1). Finally, the NCS pathways need to be regularly revisited and often realigned to face challenges on the way (Bryan et al., 2018; Lu et al., 2018). Most of the six projects had multiple phases which allowed for potential pitfalls and corrections (Lu et al., 2018) emphasizing the need to anticipate unintended consequences and unexpected delays of various types when scaling NCS (Cao et al., 2011; Qin et al., 2021).

To conclude, there is no shortcut to a carbon neutral future; all efforts should be accounted for. Emissions from the

Table 1. An incomplete list of best management practices to deploy global NCS, based on current understanding and lessons learned from past experience.

Actions	Best practices and lessons learned*
Global governance	<ul style="list-style-type: none"> • Act now! Global immediate actions on NCS to avoid delays (Qin et al., 2021) • Government incentivization and subsidization, e.g., subsidizing farmers for rerunning degraded croplands to grasslands in China (Liu et al., 2008; Lü et al., 2012) • Global coordination efforts and engagement with stakeholders and land users (e.g., 4p1000, UN SDGs) (Bradford et al., 2019; Roe et al., 2019; Smith et al., 2020) • Increasing public awareness of climate change and multiple benefits of NCS (especially economic and social benefits) (Liu et al., 2008; Bradford et al., 2019)
Ecosystem management	<ul style="list-style-type: none"> • Developing project with multiple phases to allow for regular monitoring, potential pitfalls and corrections, e.g., inappropriate species selection in early reforestation projects in China was corrected by shifting species and combining other ecosystem types (Liu et al., 2008; Cao et al., 2011; Ma et al., 2013) • Protecting existing ecosystems with rich and irrecoverable carbon pools (e.g., wetlands, peatlands and tropical forest) (Roe et al., 2019; Goldstein et al., 2020); restricting harvest and lengthening harvest cycles in forests (Law et al., 2018) • Exploring ocean-based pathways that can also contribute to additional large-scale mitigation (e.g., aquaculture, seabed, seafood) (Hoegh-Guldberg et al., 2019; Jiao et al., 2020) • Prioritizing NCS pathways, starting with pathways with instantaneous mitigation responses and those requiring less intensive investment, e.g., using alternatives to avoid wood fuels, managing crop nutrient uses, or growing trees in agricultural lands (Chen et al., 2010; Law et al., 2018; Chapman et al., 2020) • Selecting region-specific best NCS pathway(s), e.g., plantation failed in some of China's arid and semi-arid areas, but grazing management can be effective (Cao et al., 2011; Ma et al., 2013) • Speeding up mitigation technology deployment by initializing NCS projects across the country, e.g., China's nationwide ecological projects on reforestation and grassland restoration (Liu et al., 2008; Lu et al., 2018) • Avoiding failure and unintended consequences, e.g., inappropriate species or ecosystem choice may cause water stress in arid regions (Cao et al., 2011; Feng et al., 2016) • Managing emission intensive nutrients, e.g., increasing farm size and using new technologies to reduce excessive use of synthetic nitrogen (Zhang et al., 2013; Ju et al., 2016) • Improving feed quality and manure management to reduce GHG emissions in livestock sector, especially CH₄ and N₂O (Bai et al., 2018) • Exploring alternative options to wood fuels, e.g., adopting household biogas (Chen et al., 2010) • Minimizing disturbances to native ecosystems during land transition, e.g., reducing soil disturbances during establishment of plantation and reforestation (Anderson-Teixeira et al., 2009; Ledo et al., 2020), and avoiding soil erosion by minimizing disturbance to surface crust in China's arid region (Cao et al., 2011) • Improving management practices to speed up carbon sequestration in vegetation and soils. For instance (still depend on location, climate and soil): <ul style="list-style-type: none"> • Forests: applied nucleation strategy to facilitate forest recovery and thus increase decadal growth rates (Corbin and Holl, 2012); • Agriculture & grasslands: increasing organic carbon inputs and reduce tillage intensity in agricultural soils (Qin et al., 2018; Sun et al., 2020); grazing exclusion, re-seeding, and reduced grazing intensity (adopted in China's grassland restoration project) (Hu et al., 2016; Lu et al., 2018); • Wetlands: shifting species or improving community composition to improve carbon storage, and reduce methane emissions (Ström et al., 2005; Soper et al., 2019)

*Many actions align with the UN Sustainable Development Goals (SDGs) (UN, 2020), particularly climate action (Goal 13, "stop global warming"), life on land (Goal 15, "sustainably manage forests, combat desertification, halt and reverse land degradation, halt biodiversity loss"), and partnerships (Goal 17, "revitalize the global partnership for sustainable development"). Just like the SDGs, these actions are all interconnected, one may deliver multiple goals.

energy and industrial sectors must be immediately and aggressively reduced, but all NCS pathways, both land- and ocean-based, should be embraced to help go the extra mile for hard-to-abate sectors and emission sources (Anderson et al., 2019; Griscom et al., 2019). China has been deeply involved in NCS, and we have reasons to believe that in the next 40 years, NCS can and should play a significant role in accomplishing the last mile delivery to nationwide carbon neutrality by 2060, as pledged by the Chinese government. Even globally, the power of nature should still be respected with regard to climate mitigation, especially if other substitutive negative emissions technologies (e.g., direct air capture, enhanced weathering, ocean alkalization, and ocean fertilization) are not immediately available for safe large-scale deployment in a cost-effective manner (Fuss et al., 2018). Global immediate actions on NCS are urgently required to avoid delays in delivering climate targets and potentially other sustainable development goals (Griscom et al., 2017; Qin et al., 2021).

Acknowledgements. This work was jointly supported by the National Basic Research Program of China (2016YFA0602701), the National Natural Science Foundation of China (41975113), the Guangdong Province Key Laboratory for Climate Change and Natural Disaster Studies (2020B1212060025) and the Guangdong Provincial Department of Science and Technology (2019ZT08G090). We appreciate the support from the China Association for Science and Technology Working Group for UN Environment Consultation.

REFERENCES

- Anderson, C. M., and Coauthors, 2019: Natural climate solutions are not enough. *Science*, **363**(6430), 933–934, <https://doi.org/10.1126/science.aaw2741>.
- Anderson-Teixeira, K. J., S. C. Davis, M. D. Masters, and E. H. Delucia, 2009: Changes in soil organic carbon under biofuel crops. *GCB Bioenergy*, **1**(1), 75–96, <https://doi.org/10.1111/j.1757-1707.2008.01001.x>.
- Bai, Z. H., and Coauthors, 2018: China's livestock transition: Driving forces, impacts, and consequences. *Science Advances*, **4**(7), eaar8534, <https://doi.org/10.1126/sciadv.aar8534>.
- Bossio, D. A., and Coauthors, 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>.
- Bradford, M. A., and Coauthors, 2019: Soil carbon science for policy and practice. *Nature Sustainability*, **2**(12), 1070–1072, <https://doi.org/10.1038/s41893-019-0431-y>.
- Bryan, B. A., and Coauthors, 2018: China's response to a national land-system sustainability emergency. *Nature*, **559**(7713), 193–204, <https://doi.org/10.1038/s41586-018-0280-2>.
- Cao, S. X., L. Chen, D. Shankman, C. M. Wang, X. B. Wang, and H. Zhang, 2011: Excessive reliance on afforestation in China's arid and semi-arid regions: Lessons in ecological restoration. *Earth-Science Reviews*, **104**(4), 240–245, <https://doi.org/10.1016/j.earscirev.2010.11.002>.
- Chapman, M., W. S. Walker, S. C. Cook - Patton, P. W. Ellis, M. Farina, B. W. Griscom, and A. Baccini, 2020: Large climate mitigation potential from adding trees to agricultural lands. *Global Change Biology*, **26**(8), 4357–4365, <https://doi.org/10.1111/gcb.15121>.
- Chen, C., and Coauthors, 2019: China and India lead in greening of the world through land-use management. *Nature Sustainability*, **2**(2), 122–129, <https://doi.org/10.1038/s41893-019-0220-7>.
- Chen, Y., G. H. Yang, S. Sweeney, and Y. Z. Feng, 2010: Household biogas use in rural China: A study of opportunities and constraints. *Renewable and Sustainable Energy Reviews*, **14**(1), 545–549, <https://doi.org/10.1016/j.rser.2009.07.019>.
- Corbin, J. D., and K. D. Holl, 2012: Applied nucleation as a forest restoration strategy. *Forest Ecology and Management*, **265**, 37–46, <https://doi.org/10.1016/j.foreco.2011.10.013>.
- Feng, X. M., and Coauthors, 2016: Revegetation in China's Loess Plateau is approaching sustainable water resource limits. *Nature Climate Change*, **6**(11), 1019–1022, <https://doi.org/10.1038/nclimate3092>.
- Field, C. B., and K. J. Mach, 2017: Rightsizing carbon dioxide removal. *Science*, **356**(6339), 706–707, <https://doi.org/10.1126/science.aam9726>.
- Fuss, S., and Coauthors, 2018: Negative emissions—Part 2: Costs, potentials and side effects. *Environmental Research Letters*, **13**(6), 063002, <https://doi.org/10.1088/1748-9326/aabf9f>.
- Goldstein, A., and Coauthors, 2020: Protecting irrecoverable carbon in Earth's ecosystems. *Nature Climate Change*, **10**(4), 287–295, <https://doi.org/10.1038/s41558-020-0738-8>.
- Griscom, B. W., and Coauthors, 2017: Natural climate solutions. *Proceedings of the National Academy of Sciences of the United States of America*, **114**(44), 11 645–11 650, <https://doi.org/10.1073/pnas.1710465114>.
- Griscom, B. W., and Coauthors, 2019: We need both natural and energy solutions to stabilize our climate. *Global Change Biology*, **25**(6), 1889–1890, <https://doi.org/10.1111/gcb.14612>.
- Heilmayr, R., L. L. Rausch, J. Munger, and H. K. Gibbs, 2020: Brazil's Amazon Soy Moratorium reduced deforestation. *Nature Food*, **1**(12), 801–810, <https://doi.org/10.1038/s43016-020-00194-5>.
- Hoegh-Guldberg, O., E. Northrop, and J. Lubchenco, 2019: The ocean is key to achieving climate and societal goals. *Science*, **365**(6460), 1372–1374, <https://doi.org/10.1126/science.aaz4390>.
- Hu, Z. M., S. G. Li, Q. Guo, S. L. Niu, N. P. He, L. H. Li, and G. R. Yu, 2016: A synthesis of the effect of grazing exclusion on carbon dynamics in grasslands in China. *Global Change Biology*, **22**(4), 1385–1393, <https://doi.org/10.1111/gcb.13133>.
- IPCC (Intergovernmental Panel on Climate Change), 2014: Climate change, 2014: Impacts, Adaptation and Vulnerability. Contribution of working groups I, II and III to the fifth assessment report of the intergovernmental panel on climate change, Pachauri, et al., Eds., Cambridge University Press, Cambridge, United Kingdom and New York USA.
- IPCC (Intergovernmental Panel on Climate Change), 2018: *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*, Delmotte et al., Eds., World Meteorological Organization, Geneva, Switzerland, 32 pp..
- Iyer, G., C. Ledna, L. Clarke, J. Edmonds, H. McJeon, P. Kyle, and J. H. Williams, 2017: Measuring progress from nationally determined contributions to mid-century strategies. *Nature Climate Change*, **7**(12), 871–874, <https://doi.org/10.1038/s41558-017-0005-9>.
- Jiao, N. Z., J. H. Liu, F. L. Jiao, Q. R. Chen, and X. X. Wang, 2020: Microbes mediated comprehensive carbon sequestration for negative emissions in the ocean. *National Science Review*, **7**(12), 1858–1860, <https://doi.org/10.1093/nsr/nwaa171>.
- Ju, X. T., B. J. Gu, Y. Y. Wu, and J. N. Galloway, 2016: Reducing China's fertilizer use by increasing farm size. *Global Environmental Change*, **41**, 26–32, <https://doi.org/10.1016/j.gloenvcha.2016.08.005>.
- Law, B. E., T. W. Hudiburg, L. T. Berner, J. J. Kent, P. C. Buotte, and M. E. Harmon, 2018: Land use strategies to mitigate climate change in carbon dense temperate forests. *Proceedings of the National Academy of Sciences of the United States of America*, **115**(14), 3663–3668, <https://doi.org/10.1073/pnas.1720064115>.
- Le Quéré, C., and Coauthors, 2018: Global carbon budget 2018. *Earth System Science Data*, **10**(4), 2141–2194, <https://doi.org/10.5194/essd-10-2141-2018>.

- Ledo, A., and Coauthors, 2020: Changes in soil organic carbon under perennial crops. *Global Change Biology*, **26**(7), 4158–4168, <https://doi.org/10.1111/gcb.15120>.
- Liu, J. G., S. X. Li, Z. Y. Ouyang, C. Tam, and X. D. Chen, 2008: Ecological and socioeconomic effects of China's policies for ecosystem services. *Proceedings of the National Academy of Sciences of the United States of America*, **105**(28), 9477–9482, <https://doi.org/10.1073/pnas.0706436105>.
- Lu, F., and Coauthors, 2018: Effects of national ecological restoration projects on carbon sequestration in China from 2001 to 2010. *Proceedings of the National Academy of Sciences of the United States of America*, **115**(16), 4039–4044, <https://doi.org/10.1073/pnas.1700294115>.
- Lü, Y. H., B. J. Fu, X. M. Feng, Y. Zeng, Y. Liu, R. Y. Chang, G. Sun, and B. F. Wu, 2012: A policy-driven large scale ecological restoration: Quantifying ecosystem services changes in the Loess Plateau of China. *PLoS One*, **7**(2), e31782, <https://doi.org/10.1371/journal.pone.0031782>.
- Ma, H., Y. Lv, and H. Li, 2013: Complexity of ecological restoration in China. *Ecological Engineering*, **52**, 75–78, <https://doi.org/10.1016/j.ecoleng.2012.12.093>.
- MoA (Ministry of Agriculture of the PRC), 2017: *National Grassland Protection and Utilization the 13th Five-year Plan*. Ministry of Agriculture of the PRC. (in Chinese)
- Nayak, D., and Coauthors, 2015: Management opportunities to mitigate greenhouse gas emissions from Chinese agriculture. *Agriculture, Ecosystems & Environment*, **209**, 108–124, <https://doi.org/10.1016/j.agee.2015.04.035>.
- NDRC (National Development and Reform Commission), 2020: *National key ecosystems' protection and restoration plan 2021–2035*. National Development and Reform Commission. (in Chinese)
- Olivier, J. G. J., and J. A. H. W. Peters, 2020: Trends in global CO₂ and total greenhouse gas emissions: 2020 report. PBL Publication Number: 4331, 85 pp.
- Paustian, K., J. Lehmann, S. Ogle, D. Reay, G. P. Robertson, and P. Smith, 2016: Climate-smart soils. *Nature*, **532**(7597), 49–57, <https://doi.org/10.1038/nature17174>.
- Qin, Z. C., Y. Huang, and Q. L. Zhuang, 2013: Soil organic carbon sequestration potential of cropland in China. *Global Biogeochemical Cycles*, **27**(3), 711–722, <https://doi.org/10.1002/gbc.20068>.
- Qin, Z. C., C. E. Canter, J. B. Dunn, S. Mueller, H. Kwon, J. Han, M. M. Wander, and M. Wang, 2018: Land management change greatly impacts biofuels' greenhouse gas emissions. *GCB Bioenergy*, **10**(6), 370–381, <https://doi.org/10.1111/gcbb.12500>.
- Qin, Z. C., and Coauthors, 2021: Delayed impact of natural climate solutions. *Global Change Biology*, **27**(2), 215–217, <https://doi.org/10.1111/gcb.15413>.
- Roe, S., and Coauthors, 2019: Contribution of the land sector to a 1.5°C world. *Nature Climate Change*, **9**(11), 817–828, <https://doi.org/10.1038/s41558-019-0591-9>.
- Smith, P., and Coauthors, 2020: Which practices co-deliver food security, climate change mitigation and adaptation, and combat land degradation and desertification? *Global Change Biology*, **26**(3), 1532–1575, <https://doi.org/10.1111/gcb.14878>.
- Soper, F. M., R. A. MacKenzie, S. Sharma, T. G. Cole, C. M. Litton, and J. P. Sparks, 2019: Non-native mangroves support carbon storage, sediment carbon burial, and accretion of coastal ecosystems. *Global Change Biology*, **25**(12), 4315–4326, <https://doi.org/10.1111/gcb.14813>.
- Ström, L., M. Mastepanov, and T. R. Christensen, 2005: Species-specific effects of vascular plants on carbon turnover and methane emissions from wetlands. *Biogeochemistry*, **75**(1), 65–82, <https://doi.org/10.1007/s10533-004-6124-1>.
- Sun, W. J., J. G. Canadell, L. J. Yu, L. F. Yu, W. Zhang, P. Smith, T. Fischer, and Y. Huang, 2020: Climate drives global soil carbon sequestration and crop yield changes under conservation agriculture. *Global Change Biology*, **26**(6), 3325–3335, <https://doi.org/10.1111/gcb.15001>.
- UN (United Nations), 2020: Take action for the sustainable development goals. [Available from <https://www.un.org/sustainabledevelopment/sustainable-development-goals/>]
- UNEP (United Nations Environment Programme), 2020: Emissions gap report 2020. United Nations Environment Programme, DEW/2310/NA, 128 pp.
- Wang, J., and Coauthors, 2020: Large Chinese land carbon sink estimated from atmospheric carbon dioxide data. *Nature*, **586**(7831), 720–723, <https://doi.org/10.1038/s41586-020-2849-9>.
- Weitzel, M., and Coauthors, 2019: Model-based assessments for long-term climate strategies. *Nature Climate Change*, **9**(5), 345–347, <https://doi.org/10.1038/s41558-019-0453-5>.
- Ye, D. Z., C. B. Fu, J. Ji, W. J. Dong, J. H. Lu, G. Wen, and X. D. Yan, 2001: Orderly human activities and subsistence environment. *Advance in Earth Sciences*, **16**(4), 453–460, <https://doi.org/10.3321/j.issn:1001-8166.2001.04.001>. (in Chinese with English abstract)
- Zhang, W. F., and Coauthors, 2013: New technologies reduce greenhouse gas emissions from nitrogenous fertilizer in China. *Proceedings of the National Academy of Sciences*, **110**(21), 8375–8380, <https://doi.org/10.1073/pnas.1210447110>.
- Zhang, X. Q., X. Xie, and N. Zeng, 2020: Nature-based Solutions to address climate change. *Climate Change Research*, **16**(3), 336–344, <https://doi.org/10.12006/j.issn.1673-1719.2019.294>. (in Chinese with English abstract)