Natural climate solutions for China: The last mile to carbon neutrality

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"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), December 12, 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 with 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 preindustrial level and pursue efforts to keep warming below 1.5℃, 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℃ 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 this article), referring to net zero emissions of all three major GHGs i.e., carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). In some instances though, they can differ in terms of inclusion of non-CO_2 gases, aerosol forcing or other short-lived climate forcers (IPCC, 2018).

The energy and industrial sectors are widely accepted as the major player in mitigating climate change, primarily due to their significant contributions to global GHG emissions. Over 50 Pg CO_2e yr^{-1} of GHG emissions are currently released to the atmosphere, about 65% of which are fossil CO_2 emissions (UNEP, 2020). Even with current policies (e.g., Nationally Determined Contributions), the global temperature would still rise at least 3℃ by the end of the century (UNEP, 2020) (Fig.1). During the past few decades, energy related emissions (mainly CO_2 and CH_4) have dominated global GHG emissions, contributing over 60% of emissions annually (Olivier & 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℃ climate target can be met without significant removal of CO_2 and other major GHGs, mainly CH_4 and N_2O, from the atmosphere (Fig. 1, *light green line*) (IPCC, 2018; Roe et al., 2019). Among many technologies designed for CO_2 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 (Goldstein et al., 2020; Griscom et al., 2017; Qin et al., 2021; Roe et al., 2019). 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 & Mach, 2017; Fuss et al., 2018). It's estimated that NCS can deliver about 1/3 of 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); 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) (Griscom et al., 2017; Hu et al., 2016), reduce overall GHG emissions (e.g., agricultural nitrogen management, livestock management) (Nayak et al., 2015; Zhang et al., 2013), and/or increase carbon sequestration in biomass and soils (e.g., reforestation, biochar, and wetland restoration) (Bossio et al., 2020; Paustian et al., 2016; Qin et al., 2013).

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 (Griscom et al., 2017; Paustian et al., 2016; 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 CO_2e yr^{-1} of global maximum potential from 20 NCS pathways, with consideration of constraints in food security, fiber security, and biodiversity conservation (Fig. 2a). Forest sector makes the most contribution to the overall mitigation potential, with 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). If considering social cost of CO_2, about half of the maximum potential cannot be deemed cost-effective (over 100 USD Mg CO_2e^{-1}) (Fig. 2c).

Adding another layer of uncertainty to NCS, the delays in NCS deployment can impact the time taken for action and 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 Pg CO_2e 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 largest 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 in 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 (Chen et al., 2019; Hu et al., 2016). 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 Pg CO_2e 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 Pg CO_2e 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 Pg CO_2e

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 observation 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 extent (Ministry of Agriculture, 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 (Ministry of Agriculture, 2017), that is 50% additional coverage to 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 (Ministry of Agriculture, 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 took 40 years and several phases to finally re-shape its degraded landscapes, especially in the North and Northwest (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, 2014). Secondly, worldwide NCS needs global governance and involvement of government, 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 (Bossio et al., 2020; Bradford et al., 2019). Thirdly, the delays in NCS of various forms could be further shortened providing local and global management efforts directed towards sustainable ecosystems. For instance, 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 energy and industrial sectors must be immediately and aggressively reduced, but all NCS pathways, either land- or 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 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 alkalinization, and ocean fertilization) are not immediately available for large-scale deployment safely and cost-effectively (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).

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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	- **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) (Bradford et al., 2019; Liu et al., 2008)
Ecosystem management	- 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 (Cao et al., 2011; Liu et al., 2008; Ma et al., 2013) - **Protecting** existing ecosystems with rich and irrecoverable carbon pools (e.g., wetlands, peatlands and tropical forest) (Goldstein et al., 2020; Roe et al., 2019); 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 require less intensive investment, e.g., using alternatives to avoid woodfuel, managing crop nutrient uses, growing trees in agricultural lands (Chapman et al., 2020; Y. Chen et al., 2010; Law et al., 2018) - **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)

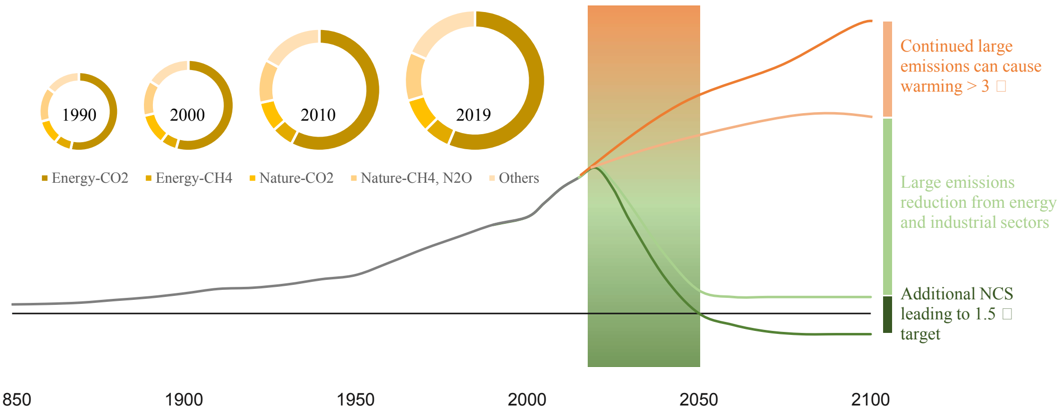
- **Avoiding** failure and unintended consequences, e.g., inappropriate species or ecosystem choice may cause water stress in arid regions (Cao et al., 2011; Feng et al., 2016)
- **Managing** emission intensive nutrients, e.g., increasing farm size and using new technologies to reduce excessive use of synthetic nitrogen in China (Ju et al., 2016; Zhang et al., 2013)
- **Improving** feed quality and manure management to reduce GHG emissions in livestock sector, especially CH_4 and N_2O (Bai et al., 2018)
- Exploring **alternative** options to woodfuel, 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):
  - Forests: applied nucleation strategy to facilitate forest recovery and thus increase decadal growth rates (Corbin & 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 (Soper et al., 2019; Ström et al., 2005)

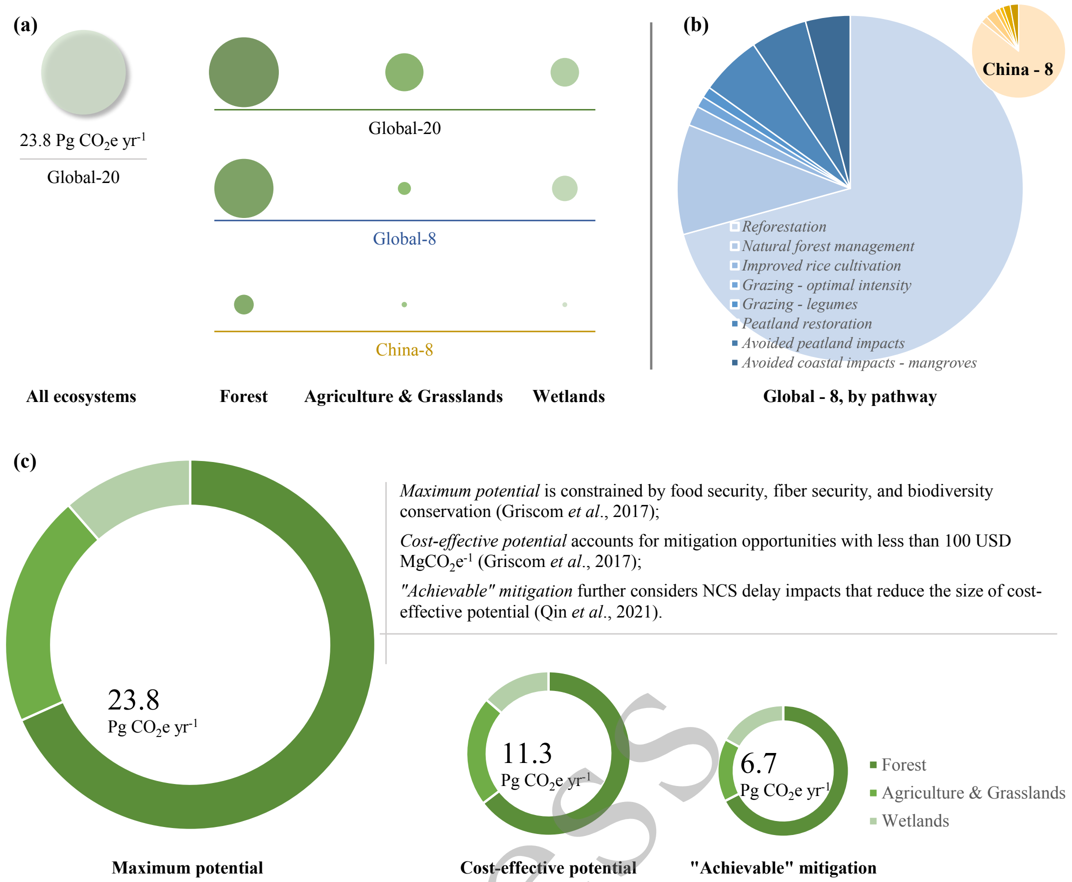
*Many actions align with the UN Sustainable Development Goals (SDGs) (UN, 2020), particularly climate action (*Goal 13, 'stop global warming'*), life on land (*Goal 15, 'sustainably manage forests, combat desertification, halt and reverse land degradation, halt biodiversity loss'*), and partnerships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

Figures

Fig. 1. A schematic graph showing historical annual GHG emissions and future emission scenarios. The lines and circles show relative size of annual emissions. The circled figures indicate global emissions directly related to energy use ('energy'), agriculture, and land use, land use change and forestry (LULUCF) ('nature'), and "others" (including CO_2 from international transport and non-energy, CH_4 from waster and others, N_2O from industrial processes and energy indirect/waste, and F-gases) (Olivier & 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), and the emission reduction scenarios reflect potential climate mitigation from both energy & industrial systems and natural systems (IPCC, 2018).

Fig. 2. The mitigation potentials of NCS by ecosystem and by specific pathway. Totally, 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), and the time taken to reach designed extent and maximum intensity is 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.


1990
2000
2010
2019
Energy-CO2
Energy-CH4
Nature-CO2
Nature-CH4, N2O
Others
Continued large emissions can cause warming > 3
Large emissions reduction from energy and industrial sectors
Additional NCS leading to 1.5
target
1850
1900
1950
2000
2050
2100


(a)
23.8 Pg CO2e yr-1
Global-20
Global-20
Global-8
China-8
All ecosystems
Forest
Agriculture & Grasslands
Wetlands
(b)
China - 8
Reforestation
Natural forest management
Improved rice cultivation
Grazing - optimal intensity
Grazing - legumes
Peatland restoration
Avoided peatland impacts
Avoided coastal impacts - mangroves
Global - 8, by pathway
(c)
Maximum potential is constrained by food security, fiber security, and biodiversity conservation (Griscom et al., 2017);
Cost-effective potential accounts for mitigation opportunities with less than 100 USD MgCO2e-1 (Griscom et al., 2017);
"Achievable" mitigation further considers NCS delay impacts that reduce the size of cost-effective potential (Qin et al., 2021).
23.8
Pg CO2e yr-1
11.3
Pg CO2e yr-1
6.7
Pg CO2e yr-1
Forest
Agriculture & Grasslands
Wetlands
Maximum potential
Cost-effective potential
"Achievable" mitigation