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EDITORIAL

Towards carbon-neutral sustainable development of China

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Abstract

As a major economy with large amounts of greenhouse gas (GHG) emissions and ecosystem carbon sink, China's commitment and pathway towards carbon neutrality is of global importance. Faced with the dual challenges of sustained economic growth and environmental protection, there is pressing need to integrate scientific knowledge from multiple disciplines to support policymaking on emission mitigation and carbon sink enhancement. This focus issue, with a companion workshop with the same theme, offers an opportunity to meet such need. With a total of 21 published papers, the focus issue provides more solid evidence of intensifying weather extremes caused by anthropogenic emissions, evaluates the potential of exploitation of terrestrial carbon sink which is in turn under the threat of warming, and reveals the challenges and opportunities of anthropogenic emission mitigation from perspectives of GHG types, economic sectors, environmental co-benefits, and disproportional impacts across the stakeholders. A comprehensive framework to combine data and models from related disciplines is a crucial next step to form integrated information much needed for climate action.

1. Introduction

China is the world's second largest economy and the top exporter to supply global demand. Economic activities in China, such as industry, cause substantial emissions of greenhouse gases (GHGs) and air pollutants (a.k.a., short-lived climate forcers) [1, 2]. China's vast area of vegetation is an important ecological carbon sink [3]. Thus the nation's effort to mitigate climate change and air pollution attracts global attention. Meanwhile, China is still a developing country with its per capita income about one sixth of the United States in 2022, thus sustained economic growth remains a leading task of China. On 22 September 2020, China announced its ambitious goal of carbon neutrality by 2060. Prior to announcing its carbon neutrality goal, China determined to substantially improve its air quality and achieve 'Beautiful China' by 2035. The carbon neutrality and 'Beautiful China' targets mean fundamental socioeconomic changes such that its economic development syncs with ecological–environmental protection. A paramount question arises on the pathway of China towards carbon neutral sustainable development.

A feasible carbon neutrality pathway must consider potential costs, impacts and benefits from social, economic, technological and environmental perspectives. Such policymaking requires support from a combination of scientific studies in multiple areas to address these pressing cross-disciplinary issues. To provide a platform for inter-disciplinary research discussions and collaborations, the Institute of Physics Press, working with the World Young Scientist Summit, launched a China-focused satellite workshop on 13–14 November 2021 as part of its 'Environmental Research 2021' International Conference. The theme of the satellite workshop was 'Towards carbon neutral sustainable development of China', and a companion focus issue was launched in *Environmental Research Letters*. The workshop and focus issue attempted to cover a wide range of topics from natural and social sciences related to carbon neutrality, including but not limited to extreme weather under climate warming, GHG emissions and carbon sinks, environmental nexus, and economic and energy pathways. The focus issue invited speakers of the workshop to submit relevant manuscripts while also welcoming unsolicited submissions; all submissions underwent regular editorial assessments and peer review processes. In the end, a total amount of 21 papers are published in the focus issue, which are summarized in this Editorial.

2. Intensifying extreme weather risks under global warming

Intensification of extreme weather events, a major risk for health and properties, has been tied to anthropogenic climate warming by increasing amounts of observational analyses. More solid and reliable evidence of an increase in extreme precipitation due to anthropogenic influence is now appearing in the observations since the 1960s, regardless of extreme precipitation indices or data treatment methods used [4]. However, it remains difficult to separate the anthropogenic influence into GHGs and aerosols. Under global warming, the adjustment of atmospheric circulation may induce new teleconnection patterns that intensify extreme weather. For example, the sea ice retreat across the Barents–Kara Seas warms the atmosphere at the surface, causing an abnormal high-pressure center over northern Siberia and an anomalous low-pressure center over high-latitude North America [5]. The high- and low-pressure anomalies lead to more frequent cold and warm extremes over central Eurasia and the east-central part of North America, respectively. Due to the large populations in these regions, the dipole pattern may have significant impacts on the local economic and public health.

Compound extreme weather events, the occurrence of two or more extreme weather events happening simultaneously or in close succession, have a much larger significant impact than single ones, and often, they are more sensitive to global warming. An increased risk of daytime–nighttime compound heatwaves is projected to occur in China by the end of the 21st Century under the shared socioeconomic pathway (SSP245 and SSP585) scenarios, with southwestern and southern China experiencing the most changes [6]. The proportion of such compound heatwaves to all heatwave occurrences would also rise, with an increase in population exposure over the entire nation by 16 times under SSP585. Due to the significant increase in heatwaves by the late 21st Century, the currently infrequent landfall-causing tropical cyclone-heatwave compound events would become 5–10 times more frequent in coastal Southeast China under the medium emission scenario (RCP4.5) [7].

An effective climate mitigation strategy could limit the increases of extreme weather and the associated health and economic risks. An example is the projection of global heat stress, measured by a combination of daily maximum temperature and water vapor pressure, in the late 21st century [8]. If the ambitious 2 °C global warming goal is achieved, the frequency, duration, and cumulative severity of heat stress would be reduced by 30%–40% compared to the intended nationally determined contributions mitigation effort submitted to the United Nations Framework Convention on Climate Change. In contrast, a delayed climate action would worsen the heat stress risk. Future changes in heat stress are especially important in low latitudes, which are home to the majority of developing nations.

3. Role of ecosystems toward carbon neutrality

To date, terrestrial ecosystems have served as a major carbon sink reducing the rate of growth in atmospheric carbon dioxide (CO_2) concentrations due to anthropogenic emissions. The future change in terrestrial carbon sinks therefore plays an important role in carbon neutrality and becomes a question of substantial concern. Climate change and rising CO_2 concentrations are expected to enhance terrestrial ecosystem carbon sinks in China, but their efficiency in offsetting contemporary fossil-fuel emissions would decline in a warmer future. For example, Chinese ecosystems would absorb carbon at a rate of 0.33 PgC a^{-1} under the low emission scenario (SSP126) by 2060, offsetting half of the corresponding fossil-fuel emissions [9]. Increasing vegetation biomass accounts for more than 80% of the carbon sink. But the efficiency of land carbon sinks in offsetting the contemporary fossil-fuel emissions would decrease to ∼23% and 6% by 2060 under the medium (SSP245) and high (SSP585) emission scenarios, respectively. Furthermore, China holds more than 75% of alpine permafrost in the Northern Hemisphere, and the potential of large carbon release from its permafrost in a warming world would compromise China's 2060 carbon neutral goal. An unprecedented data containing 7196 observations of plant and soil carbon pools show that the total ecosystem carbon stock over the Tibetan Plateau amounts to 35.8 PgC [10]. This estimate implies that a 1% decrease in Tibetan Plateau permafrost carbon storage could completely erode Chinese land carbon sink at present.

In addition to the climate and CO_2, changes of air pollution might exert large impacts on land carbon fluxes through biogeochemical processes. For example, present-day surface ozone pollution is estimated to inhibit regional gross primary productivity in Yangtze River Delta by 10% [11]. Such damaging ratio could be reduced to 8% with 50% reductions in all anthropogenic pollutant emissions in China, especially in industrial and transportation sectors, and to only 2% with all anthropogenic emissions removed. Thus a deeper emission cut under the carbon neutrality target would bring additional benefits to the land carbon uptake through reduction of ozone-associated vegetation damage. Meanwhile, a total of 18 year N additions in a primary tropical forest significantly increase the soil dissolved organic matter (DOM) content under medium-N (10 g m^{-2} yr^{-1}) and high-N (15 g m^{-2} yr^{-1}) treatments, with the DOM average molecular weight increasing by 12% [12]. Such long-term N addition increases recalcitrant DOM components but decreases other DOM components. Thus the reduction of N deposition by air pollution control might weaken forest soil organic carbon storage, highlighting the nexus between pollution mitigation and soil carbon uptake.

Natural climate solutions (NCS) are increasingly considered to enhance land carbon sinks in a warmer future. An analysis of 18 NCS pathways in China from a cost-effective perspective showed that an average of 0.67–1.65 Gt of CO_2 equivalent could be offset each year in the next four decades by fully utilizing the NCS, offering a total mitigation volume larger than current terrestrial carbon sink in China [13]. Moreover, over 80% of the NCS-based mitigation could be achieved at a reasonable economic cost. These results highlight the important role of NCS in regional carbon neutrality, and set the stage for practical NCS prioritization and actions in the near future. The effects of NCS are also studied at a smaller spatial scale, for four different agroforestry systems in bamboo forests of China [14]. In particular, including chickens in the bamboo forests increases soil CO_2 emissions but reduces nitrous oxide emissions; while mixing plantation of bamboo and *Bletilla striata* results in the lowest equivalent CO_2 emissions and external carbon fixation and thus the highest ecological benefits.

4. Anthropogenic emission mitigation faced with nexus

Reducing anthropogenic carbon emissions remains the main pathway to mitigate climate change effectively. The challenge is how to cut emissions over the course towards carbon neutrality while maintaining a healthy economy and social fairness. For example, switching from fossil fuels to renewable energy in the power sector in China would cause 1.4 million employment loss in the fossil sector between 2012 and 2017 while providing about 4 million jobs in the renewable energy sector by 2050 under the 1.5 °C goal [15]. This drastic change calls for effective measures to ensure that those unemployed workers in the fossil sectors could find proper alternative jobs and those new labor demand could be met by suitable workers. The clean heating policy could generally improve public awareness of climate change mitigation, not only among residents who have experienced the policy but also reaching those who are not covered directly [16]. At the same time, attaining the target of carbon neutrality or 1.5 °C goal would significantly increase the demand for key minerals, and shortages of rare earth materials, such as tellurium and selenium, will severely restrict the deployment scale of solar and wind power [17]. Climate warming could deteriorate the potential of photovoltaic power generation, with the frequency of extremely low solar photovoltaic events on the Tibetan Plateau expected to reach nearly three times of the 1986–2005 level under global warming of 3 °C [18].

The strategies for emission reductions are vital to climate change mitigation. Green fiscal policies would both pressure and stimulate enterprises to invest in carbon mitigation [19]. To achieve the carbon neutral target by 2060 in China, an emission reduction scheme that covers multiple GHGs (including CO_2, CH_4 and N_2O) would alleviate the negative economic impacts on carbon-intensive industries and improve the national GDP by 0.41%, compared with a CO_2-only scheme [20]. As demonstrated for the Guangdong-Hong Kong-Macao Greater Bay Area, the sectors with great emission reduction space should be given more priority, such as transportation and power sectors; and more efforts should be made to reduce energy intensity and accelerate economic structural transformation persistently [21]. In addition, as synthetic ammonia is the largest energy consumer among China's chemical industries, energy-efficient synthetic technologies would reduce air pollutant emissions effectively, with additional benefits of CO_2 emission reduction by 33% by 2060 [22].

The emission trading system (ETS), a market-based emission reduction measure, has been explored in terms of its effectiveness in economic development and emission abatement. Based on plant-level panel data over 2010–2016, the current emission trading pilot policy for power plants might have lowered carbon emissions by 39% with substantial co-benefits in air pollutant emission reductions, primarily by cutting coal consumption [23]. In addition, extending the ETS from electricity production to five other high-emission sectors (metallurgy, transport and storage, petroleum and gas, nonmetal mining, and 'other service') could reduce the marginal abatement cost by more than 80% and reach a balance between market activation and market manipulation risk [24]. The ETS covering seven high-emitting sectors might have increased the green total factor productivity by 8.5% between 2006 and 2019 while allowing the carbon reduction target to be attained through technological upgradation rather than production reduction [25].

Overall, the above studies provide positive evidence for climate change mitigation, consider strategies to reduce emissions from perspectives of GHG coverage, sectors, and technologies, and highlight that the ETS benefits a zero-carbon economy. However, achieving the carbon neutrality goal remains an extremely difficult task, given multiple socioeconomic challenges such as shortage of rare earth materials to support renewable energy development, unequal impacts on sectors and labors involved, and insufficient awareness on climate warming.

5. Concluding remarks

Focusing on China, studies in this focus issue contribute to the literature by providing observational, modeling and scenario analyses of pressing social, economic and environmental questions related to China's strategy towards carbon neutrality. Stronger evidence arises that anthropogenic climate change is a key driver to the past and future intensification of extreme weather, particularly those extremes related to heatwaves. Terrestrial ecosystem carbon sink might be used as a valuable approach to partly offset anthropogenic carbon emissions, but the efficacy of carbon sink depends on the degree of warming and the type and magnitude of mitigation measures through environmental nexus effects. Measures to cut GHG emissions deeply will be beneficial for both climate change mitigation and pollution control, but the potential disproportional impacts on individual economic sectors and groups of people should be well taken into account in order to ensure sustained policy implementation.

Challenging questions remain on the combined effects of specific pathways for the whole socioeconomy, including how to compensate for those stakeholders which/who are negatively affected by such pathways through administrative and/or market mechanisms. Continuous monitoring of GHGs [26], air pollution and their relationships is necessary to assess emission mitigation effectiveness. As economies, climates and environments in different countries are closely tied through trade and atmospheric mechanisms [27, 28], to what extent China's international collaborations and partnerships would contribute to global climate change adaptation and mitigation are also an important question [29]. Fully addressing these questions will require harmonization and integration of data and models from multiple disciplines to establish a complete framework concerning human-Earth interactions within and beyond China.

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