Geography and Sustainability 4 (2023) 179–182

Contents lists available at ScienceDirect

Geography and Sustainability

journal homepage: www.elsevier.com/locate/geosus

Highlight

Natural climate solutions. The way forward

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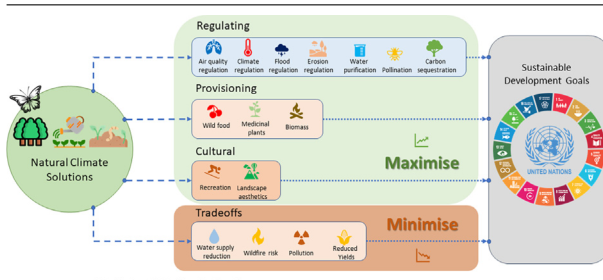
HIGHLIGHTS

- Natural climate solutions (NCS) are vital for tackling climate change
- NCS supply key regulating, provisioning and cultural ecosystem services
- NCS have some tradeoffs (water availability, wildfire risk or reduced yields)
- NCS are important, but not enough for an effective climate mitigation
- NCS are essential to support global strategies (Sustainable Development Goals)

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 10 February 2023
Received in revised form 20 March 2023
Accepted 21 March 2023
Available online 30 March 2023

Keywords:
Natural climate solutions
Climate mitigation
Ecosystem services
Tradeoffs
Sustainable Development Goals

ABSTRACT

Climate change is a global challenge that threatens global ecological security and sustainable development. Finding ways to mitigate their impacts is paramount through engineering carbon storage, low-carbon energy transition, or natural climate solutions (NCS). NCS involve a set of measures (e.g., afforestation, land restoration, biochar reuse or sustainable land use practices). Implementing NCS increases carbon sequestration and mitigates climate change at the lowest costs and greenest ways. In addition, NCS practices can improve multiple ecosystem services (ES) such as air quality, flood and erosion regulation, pest control, water purification, wild food biomass, recreation or landscape aesthetics. However, unsustainable implementation of NCS, such as over-afforestation of dense mono-forest, can lead to tradeoffs with water supply, wildfire risk, and decreased grasslands and croplands. Therefore, to optimise the NCS implementation, reducing the tradeoffs associated and transforming the "expand ecosystem area" to "improve ecosystem management efficiency" is vital. Although NCS can contribute significantly to mitigating climate change, systematic climate actions must be accompanied by a transformation in the global society and investment in new technologies. This will be key to addressing global challenges such as the achievement of Sustainable Development Goals (SDGs), such as SDG 13 (Climate Action), SDG 15 (Life on Land), SDG 2 (Zero Hunger), SDG 3 (Good Health and Wellbeing), SDG 6 (Clean Water and Sanitation), and SDG 14 (Life Bellow Water).

It has become highly urgent to mitigate climate change impacts

Climate change has triggered extreme weather events threatening global ecological security and sustainable development. Around the globe, there are numerous examples, such as floods in Pakistan, wildfires in Mediterranean Europe, Siberia, Australia and the USA, heatwaves in central Europe and droughts in China (Toreti et al., 2022). Faced with enormous challenges induced by climate change, Paris Agreement established ambitious and needed challenges such as reaching net-zero carbon dioxide (CO_2) emissions by the middle of the 21st century and limiting global warming to 2°C and, if possible, to 1.5°C to pre-industrial levels (UNFCC, 2016). This target is so ambitious,

Given their roles as Associate Editor-in-Chief of this journal, Paulo Pereira and Wenwu Zhao had no involvement in the peer-review of this article and had no access to information regarding its peer-review. Full responsibility for the editorial process for this article was delegated to Junguo Liu.

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https://doi.org/10.1016/j.geosus.2023.03.005
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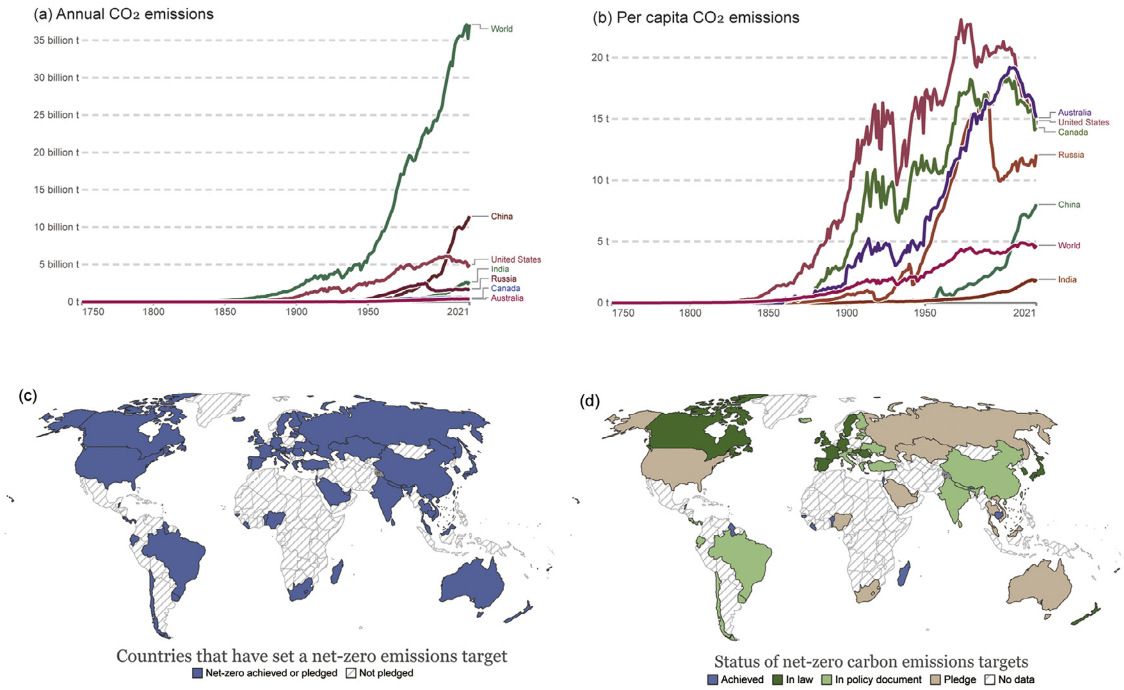

Fig. 1. Global annual CO_2 emissions (a), per capita CO_2 emissions (b), spatial distribution of countries that have a net-zero emissions target (c), and countries' statuses of net-zero carbon emissions targets (d). *Source*: https://ourworldindata.org/co2-and-other-greenhouse-gas-emissions.

involving the breakthrough of complex dimensions (e.g., technology, investment, and politics), that it is hard to achieve (Holden et al., 2018). If global warming continues, the impacts of a 2°C increase are considered devastating for biodiversity, society and the economy. In addition, the impacts will be unequal, and developing countries will be the most affected. In this context, it never was so needed to reduce CO_2 emissions dramatically and establish a net-zero carbon world. Profound transformations in global society are needed to achieve the Paris agreement. It is key to changing lifestyles and behaviour and reducing waste and food loss. Also, it is vital to increase energy efficiency, promote transport and energy decarbonisation, increase renewable share and implement sustainable land management (Huang and Zhai, 2021). In all scenarios, natural climate solutions (NCS) are the most feasible and cost-effective solutions to address climate change, given the current state of the art.

Natural climate solutions show great potential to mitigate climate change

Many countries around the world have set net-zero emissions targets. Nevertheless, only a few nations (primarily in the EU) have transposed this to a law document. From a legal perspective, this transposition is essential to make the initiatives more effective. Others incorporate the target in a policy document (China) or pledge (the USA) (Fig. 1). For instance, in 2021, China submitted its updated Nationally Determined Contributions and committed to achieving their CO_2 peak in 2030 and carbon neutrality by 2060. Since China is one of the countries with the highest annual CO_2 emissions (Fig. 1), it is paramount to find solutions to mitigate climate change through societal transformation, clean energy transition or nature-based solutions. Also, NCS are vital to storing carbon for achieving net-zero emissions. NCS comprise multiple measures based on land-use management options that consider ecosystems protection, restoration and sustainable management. These practices work in parallel with other policies, such as emission reduction and technology development, and do not aim to substitute them (Lu et al., 2022). As a major contributor to global greening, China has established many ecological restoration projects since 1999, contributing to global carbon sequestration. However, how NCS affect climate change mitigation is largely unknown in China. Lu et al. (2022), taking China as an example, using different data sources (e.g., public databases, inventories, literature or policy documents), quantified 16 different pathways (e.g., *Reforestation, Avoided forest conversion, Improved plantations, Natural Forest Management, Forest Fire Management, Biochar, Cropland Nutrient Management, Cover crops, Improving rice cultivation, Avoided grassland conversion, Grazing optimisation, Grassland Restoration, Avoided Coastal Impacts, Avoided Peatland Impacts, Coastal Wetland Restoration, Peatland Restoration*) to identify NCS climate mitigation capacity between 2000 and 2020, and in future scenarios for 2020–2030 and 2020–2060, respectively. Several ecosystems were considered, including forests, grasslands, croplands and wetlands. Between 2000 and 2020, NCS were estimated to store 0.6 $PgCO_2$ yr^{-1}, and it is forecasted that this capacity will increase to 0.6 $PgCO_2$ yr^{-1} in the period 2020–2030 and 1.0 $PgCO_2$ yr^{-1} in the period 2020–2060, respectively. Forest ecosystems can store 446 CO_2 yr^{-1} between 2000 and 2020 and 436 $TgCO_2$ yr^{-1} and 627 $TgCO_2$ yr^{-1} in 2030 and 2060, respectively. Grasslands stored 59 $TgCO_2$ yr^{-1} between 2000 and 2020, and it is predicted to increase to 68 $TgCO_2$ yr^{-1} in 2030 and 82 $TgCO_2$ yr^{-1} in 2060. Croplands stored 84 $TgCO_2$ yr^{-1} between 2000 and 2020 and these values can increase to 104 $TgCO_2$ yr^{-1} and 223 $TgCO_2$ yr^{-1} in 2030 and 2060, respectively. Finally, wetlands NCS stored <1 $TgCO_2$ yr^{-1}, and this capacity could increase to 31 $TgCO_2$ yr^{-1} by 2030 and 52 $TgCO_2$ yr^{-1} by 2060. As expected, the NCS with higher capacity for carbon storage were forest ecosystems followed by croplands, grasslands and wetlands. Overall, the areas with higher carbon storage capacity are located in northeast and southwest China with lower population density and urbanisation. Until 2020, ecosystem restoration and improvement measures contributed the most to carbon storage, while protection and improvement will be the most relevant. Based on marginal abatement cost, natural forest management is the most cost-effective among all the pathways considered.

The way forward—deepen NCS research

Studies are increasingly focusing on NCS and devote to maximising nature's contribution to addressing climate change (Anderson et al., 2019). NCS can provide around 30% of the emissions reductions needed to limit global warming to 1.5°C or 2°C, indicated by the Nature and Net Zero report of the World Economic Forum (World Economic Forum, 2021). Evidence also indicated that NCS can provide 37% of cost-effective CO_2 mitigation needed through 2030 for a >66% chance of holding warming to below 2 °C (Griscom et al., 2017). In addition to the pathways of terrestrial ecosystem highlighted by Lu et al. (2022), other aspects that must be considered include the role of urban green areas and blue-carbon ecosystems (e.g., mangroves and tidal swamps) in carbon sequestration. Urban sprawl is a global phenomenon that dramatically impacts ecosystems' ability to store carbon, especially in developing countries (Li and Li, 2019). Moreover, coastal social-ecological systems are more sensitive and vulnerable to climate change (Macreadie et al., 2021). In this context, future works could focus on the NCS climate mitigation capacity and the associated costs of urban green space and coastal ecosystems under global change scenarios. As climate change might induce high uncertainties in the carbon sequestration ability of NCS (Lu et al., 2022), areas where severe droughts are more frequent and ecosystems are more vulnerable to climate change need special attention. Data availability is currently a major obstacle to assessing the climate change mitigation potential of NCS. Studies on NCS impact on carbon sequestration at different scales (local, regional and global) need to be developed, and efforts need to be made to collect accurate and validated data, one of the important caveats recognised by Lu et al. (2022). For instance, several problems are associated with the model's validation in ecosystem service assessment. Several works were also conducted using low-reliability methods (e.g., matrix), reducing the credibility in policy-making and integration in planning.

The way forward—reduce tradeoffs associated with NCS implementation

Mitigating climate change is one of the major benefits of NCS. Numerous ecosystem services (ES) are also associated with NCS. By protecting, restoring, and managing ecosystems for carbon sequestration, NCS can increase the ES supply, including regulating (e.g., air and water quality; climate, flood and erosion regulation; pest control; pollination), provisioning (e.g., wild food, biomass) and cultural (e.g., recreation, landscape aesthetics) dimensions. However, unsustainable implementation of NCS, such as over-afforestation of dense mono-forest, can lead to tradeoffs between ecosystem services. For instance, planting trees without considering the land carrying capacity will reduce water supply, especially in drylands. This may further increase the conflicts for water with other activities (e.g., agriculture and tourism). Moreover, increasing biomass can enhance the wildfire risk, especially in a climate change context. Forest expansion also encroaches on grasslands and cropland areas, essential for pollination and food production. Also, although biochar is a crucial NCS to increase carbon sequestration, in some cases raised issues related to releasing metals and metalloids must be addressed. Regarding croplands, conventional agricultural practices such as cover crops are vital for increasing carbon sequestration and regulating ES (e.g., erosion and nutrient regulation). However, it may negatively affect water availability. Also, conservation practices have lower yield stability than conventional. Although conventional agricultural practices increase food production and security, several other ES are negatively affected. This is one of our biggest challenges, ensuring food security with sustainable agricultural management practices (Pereira et al., 2018). To sum up, although NCS is vital to mitigate climate change and maintain ES, there are still challenges ahead regarding implementing NCS to increase carbon sequestration. It is essential to reduce the tradeoffs associated with NCS establishment.

The way forward—"expand area" to "improve efficiency" for NCS implementation

Towards carbon neutrality in 2060, NCS can offset part of industrial carbon emissions to gain time for developing emission reduction technologies and integrating NCS into national carbon-neutral strategies, strengthening top-level design for ecosystem management at the national level. However, land-based NCS paths, such as afforestation and reforestation, have thresholds for carbon uptake and storage through biomass and soil. The net carbon uptake will decrease with the maturation of vegetation and the saturation of the ecosystem carbon pool. It is feasible that ecosystem management in the early stage focused on expanding the area of ecological land, such as afforestation and building nature reserves. In the middle and late stages, the space for ecological restoration is limited, given the competition with urban and agricultural land. The ecosystem management strategy needs to transform from "expanding the scope of the ecosystem" to "improving carbon density per unit area" (Lu et al., 2022), and regional targets for carbon sequestration and sink increase should be set according to local conditions to improve the efficiency of ecosystem management. On the other hand, NCS are not enough to address climate risks (Anderson et al., 2019) and need to be accompanied by a change in the global society and investment in new technologies. Assuming that NCS can act solely to increase carbon storage is unrealistic. As Lu et al. (2022) mentioned, NCS pathways can be an essential contribution. They will allow us only to buy some time to develop new technologies and are not the final solution. We cannot overlook that the most crucial aspect of tackling climate change is profound societal behaviour.

The way forward—integrate NCS into the Sustainable Development Goals progression

NCS are crucial to strengthening and implementing global strategies such as the Sustainable Development Goals (SDGs), mainly SDG 13 (Climate Action) and SDG 15 (Life on Land). Other SDGs can benefit enormously from NCS establishments such as SDG 2 (Zero Hunger) (e.g., maintain food production without increasing land degradation), SDG 3 (Good Health and Wellbeing) (e.g., improve air quality and areas for recreation), SDG 6 (Clean Water and Sanitation) (e.g., increase water purification), SDG 11 (Sustainable Cities and Communities) (e.g., increase urban green areas and city liveability) and SDG 14 (Life Bellow Water) (e.g., reduce diffuse pollution and eutrophication). NCS also contribute significantly to the coupling relationship between a social-ecological system such as the food-energy-water nexus (SDGs 2, 6, 7) (Zhao et al., 2022). Overall, NCS contribute to achieving the 2030 Agenda and multiple SDGs. Therefore, it is paramount to encourage countries to establish NCS as a robust climate mitigation solution and action for sustainability. The study of Lu et al. (2022) paved the way to assess the NCS impacts on carbon storage, which can be applied in other realms.

Declaration of Competing Interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

C.Y. and W.Z. were supported by National Natural Science Foundation of China (Grant No. 42271292), State Key Laboratory of Earth Surface Processes and Resource Ecology (Grant No. 2022-ZD-08), and the Fundamental Research Funds for the Central Universities of China. P.P. was supported by the project MApping and Forecasting Ecosystem Services in URban areas (MAFESUR), financed by the Lithuanian Research Council. Nr. P-MIP-23-426.

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