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Perspective

Achieving carbon neutrality through ecological carbon sinks: A systems perspective

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1. Introduction

Carbon neutrality have become a consensus for all of humanity [1,2]. As of April, 2023, 132 countries have announced carbon neutrality targets [3]. To achieve carbon neutrality, efforts need to be made from multiple aspects, including decarbonization of the power sector [4,5], electrification of the end-use sectors [6,7], and greening of other industries [8]. Ecological carbon sinks play a unique role in these strategies to offset hard-to-reduce greenhouse gas (GHG) emissions by reabsorbing or storing carbon that has already been emitted.

Ecological carbon sinks refer to the process by which natural ecosystems, such as forests, grasslands, wetlands, and oceans, absorb carbon dioxide from the atmosphere and store it as plant tissues and soil organic matter [9]. When the produced emissions exceed the absorption capacity of the sinks, we face a carbon budget imbalance, threatening our carbon neutrality efforts. According to the Global Carbon Budget 2022, of the annual anthropogenic carbon emissions globally, approximately 48% ultimately enter the atmosphere, with 5.2 ± 0.02 GtC yr^{-1} growth during 2012–2021 [10]. Ocean CO_2 sink is referred as the blue carbon sink which absorbs about 26% of carbon emissions (2.9 ± 0.4 GtC yr^{-1} during 2012–2021) [10]. Forms of carbon fixation in the ocean include dissolved inorganic carbon, carbonate carbon, organic carbon, and microbial organic carbon, which contribute significantly to carbon sequestration through the biological processes of marine ecosystems [11,12]. Land CO_2 sink, referred as green carbon sink, is the largest organic carbon storage reservoir on earth (3.1 ± 0.6 GtC yr^{-1} during 2012–2021) absorbing about 29% of carbon emissions (the carbon budget imbalance is a measure of imperfect data and understanding of the contemporary carbon cycle) [10]. Soil green carbon sink converts carbon dioxide into organic matter through the carbon cycle processes of soil ecosystems [13–15]. In addition, above ground biomass, belowground biomass, and dead organic matter are also important forms of carbon storage. The increase of blue carbon sink in the ocean and green carbon sink in the soil can not only enhance the stability and sustainability of ecosystems, but also make significant contributions to global carbon neutrality targets. To achieve carbon neutrality, it is necessary to strengthen carbon sink management and protection, increase ecological carbon sinks, and enhance ecosystem resilience and sustainability through ecological restoration and conservation measures.

2. Ecological carbon sinks from a systems perspective

To fully appreciate and effectively manage ecological carbon sinks, a systems perspective is invaluable. Such a perspective takes into account the interconnectedness and interdependence of the various components within an ecological carbon sink and the larger environment. For instance, the impact of human activities, such as deforestation or industrial pollution, is not isolated but affects the entire ecosystem, influencing the carbon sequestration capacity of the carbon sink. As a systemic environmental phenomenon, ecological carbon sinks are an ecological outcome of systemic processes which are influenced by ecological structures and functions. Viewing ecological carbon sinks from the perspective of environmental systems engineering can better understand and manage the complexity and interconnectivity of ecological carbon sinks [16,17]. Environmental systems engineering

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emphasizes systems thinking and optimization, and focuses on holistic analysis and integrated governance of environmental problems.

There are four related scientific issues that need to be considered in the context of achieving carbon neutrality, from the perspective of environmental systems engineering. Firstly, ecological carbon sinks are emerging as a new factor in environmental governance. Carbon sinks have dual attributes of being both carbon sources and carbon sinks, as they can release carbon through natural processes or absorb carbon through photosynthesis. Understanding the dynamics of ecological carbon sinks and their role in the carbon cycle is crucial in designing effective strategies for carbon reduction and sequestration. Secondly, contradictions and synergies may exist between different environmental objectives such as pollution reduction, carbon emission reduction, and the enhancement of carbon sequestration through ecological carbon sinks. For instance, certain pollution reduction measures like the installation of air pollution control devices in power plants may inadvertently increase energy consumption and thus, carbon emissions. On the other hand, the enhancement of ecological carbon sinks can serve the dual purposes of reducing carbon emissions and sequestering carbon simultaneously. The delicate balance of these diverse objectives and the discovery of potential synergies among them is a critical aspect in formulating comprehensive and sustainable strategies for achieving carbon neutrality. Thirdly, realizing the value of ecological products, such as the ecosystem services, to which ecological carbon sinks contribute significantly, play an important role in incentivizing and promoting their conservation and restoration. Ecosystem services, such as carbon sequestration, water purification, and biodiversity conservation, have economic, social, and cultural values that can be integrated into decision-making processes. Valuing and incorporating these ecosystem services into policies and market mechanisms can create incentives for their protection, leading to more effective and sustainable management of ecological carbon sinks. Lastly, the environmental impacts of geoengineering approaches for increasing carbon sinks, such as ocean fertilization and mineral carbonation, need to be carefully evaluated. While these techniques can potentially enhance carbon sequestration, they may also have unintended consequences, such as changes in water use, biodiversity loss, and alteration of local and global climate patterns. Considering the potential environmental risks and benefits of these geoengineering approaches is crucial to ensure their effectiveness and sustainability in the context of zero carbonization strategies.

2.1. Dual attributes of ecological carbon sinks

Ecological carbon sinks, integral to environmental governance, embody dual properties as they can function as both carbon sources and sinks under varying circumstances. This duality, reflecting the two sides of the same coin, necessitates a comprehensive consideration from lifecycle and temporal dimensions. For instance, in the case of solid waste disposal, incineration of wood products for energy recovery may release carbon dioxide, which reduces carbon sinks, despite the energy being recovered [18]. Landfilling solid waste may generate methane emissions which are released over a long period of time in the future [19,20]. Determining the more favorable method of disposal requires comprehensive consideration that integrates carbon reduction at the source and deep integration of solid waste disposal in the industry [21]. Moreover, from a life cycle perspective, the paper industry has dual attributes of carbon source and carbon sink. From the perspective of carbon sinks, well-managed landfilling could be a preferable disposal method for forestry products that cannot be recycled [22]. However, the optimal pathways for achieving carbon neutrality in the paper industry may differ significantly among different countries due to factors such as the level of solid waste management, energy structure, and other considerations. Therefore, a holistic consideration is necessary to evaluate the complexity and interrelatedness of various factors in managing ecological carbon sinks and achieving sustainable environmental outcomes. Understanding this duality is critical to devising strategies for achieving carbon neutrality as it underscores the importance of not only enhancing the sink capacity of these ecosystems but also minimizing their potential as carbon sources.

2.2. Contradiction and synergy

The relationships between pollution reduction, carbon reduction, and carbon sinks are complex and can manifest as both contradictions and synergies. These relationships are dependent on various environmental, geographical, and human factors. For instance, efforts to reduce pollution in water bodies can sometimes have unintended negative effects on carbon sequestration. Specifically, in the northeastern part of Canada near the river estuaries, brown water with high organic matter content has sufficient dissolved oxygen, and eels can live normally in the rich organic brown water in the river estuaries [23]. Reducing nutrient inputs can increase the ratio of carbon to nitrogen and phosphorus, making dissolved organic carbon more inert, reducing microbial respiration, increasing carbon accumulation, and ultimately storing it in the deep sea. Efforts to reduce pollution levels in Canadian water bodies have led to an increase in eel populations. While this has positive effects on biodiversity, the resurgent eel population could potentially diminish these water bodies' carbon sequestration capacity due to the eels' dietary habits. This presents a contradiction between pollution reduction and carbon sequestration. In addition, carbon offset technologies require a huge demand for mineral resources. To achieve the global warming target of below 2 degrees Celsius, the demand for mineral production in 2050 will significantly increase compared to 2018, with demand for nickel doubling and demand for vanadium tripling [24]. However, mineral extraction not only creates environmental problems, but also reduces ecological carbon sinks.

Therefore, the contradictions and synergies between pollution reduction, carbon reduction, and carbon sinks need to be systematically examined, considering the synergistic effects of pollution reduction and carbon increase in ecological restoration projects. Coordinating and optimizing these factors is a complex issue that needs to be considered carefully.

2.3. Realizing the value of ecological products

The value of ecological products is currently largely undervalued. Current research focuses on the macro-regional scale ecosystem services valuation (ESV) [25], which is not sufficient to support the establishment of a mechanism for realizing the value of ecological products. Establishing a mechanism for realizing the value of ecological products requires clear understanding of the principles of ecological product realization, accurate ecological product valuation methods, and clarification of the institutional arrangements for realizing the value of ecological products [26]. To effectively manage and optimize ecological carbon sinks, we propose a sequential three-step approach. Firstly, it is vital to understand the natural evolutionary principles of ecological assets and the impact of human interventions on these assets. This fundamental understanding provides the groundwork for the subsequent steps. Secondly, we must measure the characteristics of changes in ecological product attributes and understand the rules that govern the generation of ecological product values. Such measures allow us to quantify the effects of human interventions and lay the groundwork for policy implications. Finally, we need to clarify the mechanisms to actualize the value of ecological products and provide real-world demonstration cases. This last step ensures the practical application of our findings and recommendations. Land is an important interface between the socio-economic system and the natural ecosystem, and changes in land use significantly impact ecological assets such as carbon sinks. The use of entity-based land and ecological asset occupation and metabolism models can provide new ideas for accurate calculation and value realization of ecological products. The integration of emerging data and artificial intelligence tools can help us identify the land occupation of economic entities (such as enterprises and factories) and accurately measure ecological product valuation [27].

2.4. Environmental impacts of geoengineering

Geoengineering strategies for carbon sequestration, while promising, require a thorough consideration of their potential environmental impacts. These impacts can be diverse and might inadvertently exacerbate climate change or lead to other environmental problems if not managed effectively. The environmental impacts of geoengineering for carbon sequestration need to be considered systematically. These impacts must be thoroughly considered in the context of carbon sequestration efforts.

Afforestation and reforestation: While large-scale tree planting and forest restoration projects can promote carbon uptake and storage, these activities can also induce negative impacts on ecosystems. For instance, if not properly managed, they can lead to soil erosion, increase competition for water resources, and cause biodiversity loss. They can also introduce socio-economic changes in local communities, such as the displacement of local livelihoods dependent on land use types replaced by these projects [28,29].

Soil carbon sequestration: Alterations in soil management practices can increase organic carbon storage in soils. However, these changes may also affect agricultural production and ecosystems. For example, modifications in field drainage and irrigation management may lead to water scarcity in certain regions, while changes in crop yield and quality could affect food security [30,31].

Ocean fertilization: While ocean fertilization can stimulate the growth of marine biomass and increase carbon uptake, this method can have irreversible impacts on marine ecosystems. Excessive nutrient inputs can lead to harmful algal blooms and biodiversity loss, potentially disrupting fishery resources and marine food chains [32,33].

Mineral carbonation: The sequestration of carbon dioxide gas in rocks to form carbonate minerals can provide a permanent solution for carbon storage. Nevertheless, this process may require significant energy and water resources, potentially exacerbating resource scarcity issues. Moreover, potential impacts on groundwater quality, rock stability, and ecosystems should be thoroughly evaluated to prevent unforeseen environmental damage [34,35].

In conclusion, while these geoengineering strategies hold potential for carbon sequestration, it is essential to critically evaluate and manage their environmental impacts to prevent unintended negative consequences. This underscores the need for a careful balance between carbon sequestration efforts and environmental protection.

3. Outlook

Carbon peaking and carbon neutrality have become a global consensus among countries to address the challenges of climate change. To achieve these goals, efforts need to be made in multiple aspects, including decarbonization of the power sector, electrification of end-use sectors, and greening of other industries. However, achieving complete decarbonization and electrification faces challenges in terms of technology, sustainability, environment, and funding. Ecological carbon sinks, such as forests, grasslands, wetlands, oceans, and soil, play a crucial role in achieving carbon neutrality. These carbon sinks absorb carbon dioxide from the atmosphere and store it as plant tissues and organic matter. Ecological carbon sinks are highly complex and interconnected, reflecting the myriad processes that occur within ecosystems. For instance, the carbon sequestration process is connected to water, nutrient cycles, biodiversity, and climatic factors. The interconnectivity between different carbon sinks like forests, soil, and oceans also adds another layer of complexity. For example, forests not only sequester carbon but also impact soil carbon storage by influencing soil organic matter content and turnover, while oceans and terrestrial ecosystems interact via the carbon flux across the land-ocean interface. Viewing ecological carbon sinks from the perspective of environmental systems engineering can help better understand and manage their complexity and interconnectivity. Several related scientific issues need to be considered: 1) ecological carbon sinks, as a new variable in environmental governance, have the dual attributes of carbon source and carbon sink; 2) the contradiction and synergy between pollution reduction, carbon emission reduction, and carbon sequestration; 3) the realization of the value of ecological products; and 4) the environmental impacts of geoengineering for increasing carbon sinks.

The following policy suggestions could be made to effectively manage ecological carbon sinks and achieve carbon neutrality:

3.1. Promoting cross-sectoral policy consistency

To achieve synergistic effects of pollution reduction, carbon reduction, and carbon sink enhancement, policymakers need to promote policy consistency across related fields such as environment, agriculture, forestry, energy, etc. For example, encouraging the agricultural sector to adopt sustainable land management methods like organic farming can both enhance soil carbon sink capacity and reduce the use of pesticides and fertilizers, thus reducing environmental pollution.

3.2. Implementing carbon pricing policies

By establishing a carbon trading market or imposing carbon taxes, economic incentives for reducing carbon emissions and increasing carbon sinks can be provided. Such carbon pricing policies will encourage businesses and individuals to adopt more environmentally friendly actions, such as adopting low-carbon production methods, and protecting and restoring carbon sinks.

3.3. Developing green finance

Policymakers should urge banks and other financial institutions to offer more green finance products to support projects for the protection and restoration of carbon sinks, such as investments in forestry or wetland conservation projects. At the same time, governments can raise funds for these projects by issuing green bonds, among other methods.

3.4. Promoting technological innovation

Policymakers should encourage technological advancements that boost ecosystem carbon sink capacity. This includes creating incentives for research in areas such as carbon capture and storage technologies or bioengineering, implementing tax breaks, subsidies, or grants for industries adopting low-carbon technologies, and promoting international technology transfer, particularly to developing nations.

3.5. Strengthening environmental education and public participation

A comprehensive approach to the protection and restoration of carbon sinks requires public awareness and participation. This can be fostered by integrating environmental education into all levels of schooling, encouraging public involvement in local conservation projects, and including diverse stakeholders in decision-making processes regarding carbon sinks and carbon neutrality.

Declaration of Competing Interest

Ming Xu is an editorial board member for Green Carbon and was not involved in the editorial review or the decision to publish this article. 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.

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References

[1] Z. Liu, Z. Deng, G. He, H. Wang, X. Zhang, J. Lin, Y. Qi, X. Liang, Challenges and opportunities for carbon neutrality in China, Nat. Rev. Earth Environ. 3 (2) (2022) 141–155.
[2] R.B. Jackson, J.G. Canadell, C. Le Quéré, R.M. Andrew, J.I. Korsbakken, G.P. Peters, N. Nakicenovic, Reaching peak emissions, Nat. Clim. Change 6 (1) (2016) 7–10.
[3] Unit, E. C. I. The Net Zero Tracker. https://eciu.net/netzerotracker.
[4] G. Luderer, M. Pehl, A. Arvesen, T. Gibon, B.L. Bodirsky, H.S. de Boer, O. Fricko, M. Hejazi, F. Humpenöder, G. Iyer, Environmental co-benefits and adverse side-effects of alternative power sector decarbonization strategies, Nat. Commun. 10 (1) (2019) 5229.
[5] S. Luo, W. Hu, W. Liu, Z. Zhang, C. Bai, Q. Huang, Z. Chen, Study on the decarbonization in China's power sector under the background of carbon neutrality by 2060, Renew. Sustain. Energy Rev. 166 (2022) 112618.
[6] S. Ebrahimi, Mac Kinnon, M. Brouwer, J, California end-use electrification impacts on carbon neutrality and clean air, Appl. Energy 213 (2018) 435–449.
[7] Steinberg, D., Bielen, D., Eichman, J., Eurek, K., Logan, J., Mai, T., McMillan, C., Parker, A., Vimmerstedt, L., Wilson, E. Electrification and decarbonization: exploring US energy use and greenhouse gas emissions in scenarios with widespread electrification and power sector decarbonization; National Renewable Energy Lab. (NREL), Golden, CO (United States), 2017.
[8] J. Zhu, M.R. Chertow, Greening industrial production through waste recovery:"Comprehensive utilization of resources" in China, Environ. Sci. Technol. 50 (5) (2016) 2175–2182.
[9] K. Trumper, The natural fix?: the role of ecosystems in climate mitigation: a UNEP rapid response assessment, UNEP/Earthprint (2009).
[10] P. Friedlingstein, M. O'Sullivan, M.W. Jones, R.M. Andrew, L. Gregor, J. Hauck, C. Le Quéré, I.T. Luijkx, A. Olsen, G.P. Peters, W. Peters, J. Pongratz, C. Schwingshackl, S. Sitch, J.G. Canadell, P. Ciais, R.B. Jackson, S.R. Alin, R. Alkama, A. Arneth, V.K. Arora, N.R. Bates, M. Becker, N. Bellouin, H.C. Bittig, L. Bopp, F. Chevallier, L.P. Chini, M. Cronin, W. Evans, S. Falk, R.A. Feely, T. Gasser, M. Gehlen, T. Gkritzalis, L. Gloege, G. Grassi, N. Gruber, Ö. Gürses, I. Harris, M. Hefner, R.A. Houghton, G.C. Hurtt, Y. Iida, T. Ilyina, A.K. Jain, A. Jersild, K. Kadono, E. Kato, D. Kennedy, K. Klein Goldewijk, J. Knauer, J.I. Korsbakken, P. Landschützer, N. Lefèvre, K. Lindsay, J. Liu, Z. Liu, G. Marland, N. Mayot, M.J. McGrath, N. Metzl, N.M. Monacci, D.R. Munro, S.I. Nakaoka, Y. Niwa, K. O'Brien, T. Ono, P.I. Palmer, N. Pan, D. Pierrot, K. Pocock, B. Poulter, L. Resplandy, E. Robertson, C. Rödenbeck, C. Rodriguez, T.M. Rosan, J. Schwinger, R. Séférian, J.D. Shutler, I. Skjelvan, T. Steinhoff, Q. Sun, A.J. Sutton, C. Sweeney, S. Takao, T. Tanhua, P.P. Tans, X. Tian, H. Tian, B. Tilbrook, H. Tsujino, F. Tubiello, G.R. van der Werf, A.P. Walker, R. Wanninkhof, C. Whitehead, A. Willstrand Wranne, R. Wright, W. Yuan, C. Yue, X. Yue, S. Zaehle, J. Zeng, B. Zheng, Global Carbon Budget 2022, Earth Syst. Sci. Data 14 (11) (2022) 4811–4900.
[11] C. Nellemann, E. Corcoran, Blue carbon: the role of healthy oceans in binding carbon: a rapid response assessment, UNEP/Earthprint (2009).
[12] J. Tang, S. Ye, X. Chen, H. Yang, X. Sun, F. Wang, Q. Wen, S. Chen, Coastal blue carbon: Concept, study method, and the application to ecological restoration, Sci. China Earth Sci. 61 (2018) 637–646.
[13] C.L. Goodale, M.J. Apps, R.A. Birdsey, C.B. Field, L.S. Heath, R.A. Houghton, J.C. Jenkins, G.H. Kohlmaier, W. Kurz, S. Liu, Forest carbon sinks in the Northern Hemisphere, Ecol. Appl. 12 (3) (2002) 891–899.
[14] S. Wang, Y. Huang, Determinants of soil organic carbon sequestration and its contribution to ecosystem carbon sinks of planted forests, Glob. Change Biol. 26 (5) (2020) 3163–3173.
[15] R. Lal, Soil carbon sequestration to mitigate climate change, Geoderma 123 (1–2) (2004) 1–22.
[16] B. Allenby, Earth systems engineering: the role of industrial ecology in an engineered world, J. Ind. Ecol. 2 (3) (1998) 73–93.
[17] S.H. Schneider, Earth systems engineering and management, Nature 409 (6818) (2001) 417–420.
[18] H.A. Arafat, K. Jijakli, A. Ahsan, Environmental performance and energy recovery potential of five processes for municipal solid waste treatment, J. Clean. Prod. 105 (2015) 233–240.
[19] S. Kumar, S. Gaikwad, A. Shekdar, P. Kshirsagar, R. Singh, Estimation method for national methane emission from solid waste landfills, Atmos. Environ. 38 (21) (2004) 3481–3487.
[20] M. El-Fadel, A.N. Findikakis, J.O. Leckie, Environmental impacts of solid waste landfilling, J. Environ. Manag. 50 (1) (1997) 1–25.
[21] J. Dong, Y. Chi, D. Zou, C. Fu, Q. Huang, M. Ni, Comparison of municipal solid waste treatment technologies from a life cycle perspective in China, Waste Manag. Res. 32 (1) (2014) 13–23.
[22] R. Sathre, J. O'Connor, Meta-analysis of greenhouse gas displacement factors of wood product substitution, Environ. Sci. Policy 13 (2) (2010) 104–114.
[23] N. Jiao, Developing ocean negative carbon emission technology to support national carbon neutralization, Bull. Chin. Acad. Sci. (Chin. Version) 36 (2) (2021) 179–187.
[24] D.L.P. Kirsten Hund, P. Fabregas Thao, Tim Laing, John Drexhage, Minerals for climate action: the mineral intensity of the clean energy transition, World Bank Group (2020).
[25] B. Fisher, R.K. Turner, Ecosystem services: classification for valuation, Biol. Conserv. 141 (5) (2008) 1167–1169.
[26] H. Zheng, L. Wang, W. Peng, C. Zhang, C. Li, B.E. Robinson, X. Wu, L. Kong, R. Li, Y. Xiao, Realizing the values of natural capital for inclusive, sustainable development: informing China's new ecological development strategy, Proc. Natl. Acad. Sci. USA 116 (17) (2019) 8623–8628.
[27] W. Xie, H. Yu, Y. Li, M. Dai, X. Long, N. Li, Y. Wang, Estimation of entity-level land use and its application in urban sectoral land use footprint: a bottom-up model with emerging geospatial data, J. Ind. Ecol. 26 (1) (2022) 309–322.
[28] A. Malmer, D. Murdiyarso, L. Bruijnzeel, U. Ilstedt, Carbon sequestration in tropical forests and water: a critical look at the basis for commonly used generalizations, Glob. Change Biol. 16 (2) (2010) 599–604.
[29] C.L. Parr, C.E. Lehmann, W.J. Bond, W.A. Hoffmann, A.N. Andersen, Tropical grassy biomes: misunderstood, neglected, and under threat, Trends Ecol. Evol. 29 (4) (2014) 205–213.
[30] J. Sanderman, Can management induced changes in the carbonate system drive soil carbon sequestration? A review with particular focus on Australia, Agric. Ecosyst. Environ. 155 (2012) 70–77.
[31] J.M. Baker, T.E. Ochsner, R.T. Venterea, T.J. Griffis, Tillage and soil carbon sequestration—what do we really know? Agric. Ecosyst. Environ. 118 (1–4) (2007) 1–5.
[32] P. Williamson, D.W. Wallace, C.S. Law, P.W. Boyd, Y. Collos, P. Croot, K. Denman, U. Riebesell, S. Takeda, C. Vivian, Ocean fertilization for geoengineering: a review of effectiveness, environmental impacts and emerging governance, Process Saf. Environ. Prot. 90 (6) (2012) 475–488.
[33] R.S. Lampitt, E.P. Achterberg, T.R. Anderson, J. Hughes, M. Iglesias-Rodriguez, B.A. Kelly-Gerreyn, M. Lucas, E. Popova, R. Sanders, J. Shepherd, Ocean fertilization: a potential means of geoengineering? Philos. Trans. R. Soc. A: Math. Phys. Eng. Sci. 366 (1882) (2008) 3919–3945.
[34] R.T. Wilkin, D.C. DiGiulio, Geochemical impacts to groundwater from geologic carbon sequestration: controls on pH and inorganic carbon concentrations from reaction path and kinetic modeling, Environ. Sci. Technol. 44 (12) (2010) 4821–4827.
[35] S.Ó. Snæbjörnsdóttir, B. Sigfússon, C. Marieni, D. Goldberg, S.R. Gislason, E.H. Oelkers, Carbon dioxide storage through mineral carbonation, Nat. Rev. Earth Environ. 1 (2) (2020) 90–102.