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Perspective

Oxygen Footprint Regulates Dryland Carbon Cycling

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Abstract

In the Anthropocene, dryland ecosystems—natural and semi-natural ecosystems—are highly sensitive to anthropogenic warming, and their carbon cycling dynamics are easily disrupted by this trend. In this perspective, we propose a novel yet long-overlooked conceptual framework. It reveals that the oxygen footprint, defined as the atmospheric oxygen consumption-to-production ratio, could serve as an important diagnostic indicator for assessing the impacts of anthropogenic warming on dryland carbon cycling. This framework can be divided into three parts, including the increasing oxygen footprint, warming effects on dryland carbon cycling, and direct or indirect links between oxygen footprint and carbon-cycle responses. In short, it centers on the core logical chain: oxygen footprint-anthropogenic warming-dryland carbon cycling. This work strives to enhance dryland sustainability by filling essential knowledge gaps, combining separate research findings, and providing actionable field guidance for ecosystem management.

Keywords: oxygen footprint; anthropogenic warming; carbon cycling; dryland sustainability; human well-being

1. Introduction

Globally, dryland areas, where precipitation is less than 65% of potential evapotranspiration demand, that is, aridity index (AI) < 0.65, are characterized by intensive human disturbance, low vegetation coverage, and severe soil degradation [1,2]. Dryland carbon pools are closely linked to soil fertility, sustain key ecosystem services [3,4], support regional food security and human livelihoods [5], and are thus vital for human well-being across dryland regions [6–8]. From 2001 to 2019, distinct average normalized difference vegetation index (NDVI) values for plant cover have been reported across four dryland types, with mean values (standard deviation) of 0.26 (0.11), 0.18 (0.10), 0.09 (0.06), and 0.06 (0.03) for dry sub-humid ($0.5 \leq AI < 0.65$), semi-arid ($0.2 \leq AI < 0.5$), arid ($0.05 \leq AI < 0.2$), and hyper-arid ($AI < 0.05$) lands, respectively [9]. When considering soils, as the largest land-based carbon reservoir, they hold approximately 3600 petagrams (Pg) of soil carbon; this pool is nearly five times the atmospheric carbon stock (750 Pg) and six times plant-stored carbon (560 Pg); dryland soils store roughly 52% of total global soil carbon stocks, 32% of which corresponds to global soil organic carbon [10–13]. In soils, soil humic substances, newly formed from plant and microbial organic fragments, exert a critical control over the transformation and persistence of soil organic carbon. Soil humic substances are complex, recalcitrant compounds synthesized from plant and microbial organic fragments; they govern soil organic carbon turnover via physicochemical protection (mineral-organic

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association), chemical recalcitrance, and modulation of microbial decomposition activities, thereby controlling both transformation pathways and long-term persistence of soil organic carbon; in general, humic substances account for 60–80% of total soil organic carbon in mineral soils based on conventional alkaline-extraction methods [10,12,14]. The microbial carbon pool constitutes an important component of the soil carbon pool and can reflect microbial biomass to a certain extent. Soil microorganisms carry out two contrasting functions—mineralizing soil organic carbon and stabilizing carbon inputs via their conversion into organic compounds—and the balance between these two competing processes controls the net CO_2 flux released to the atmosphere [14].

As CO_2 provides the substrate for photosynthesis, rising atmospheric CO_2 can stimulate photosynthesis through increased carboxylation rates, which is known as the CO_2 fertilization effect; in addition, elevated CO_2 induces partial stomatal closure, enhancing water-use efficiency [15]. This may relieve water-imposed restrictions on plant growth and favor carbon sequestration, especially in drylands. According to this driving mechanism, croplands feature greater photosynthetic capacity than grassland and forestland due to irrigation and fertilization and contributes considerably to plant carbon accumulation [16]. Rising temperatures may suppress plant growth across tropical zones, where prevailing temperatures already lie near the thermal optimum for vegetation [17]. By contrast, warmer conditions can boost plant metabolic activity and prolong the length of the growing season in boreal and Arctic areas, thereby promoting vegetation productivity [18]. Simulations derived from dynamic global vegetation models indicate that climate-driven positive impacts, largely associated with rising temperatures, are the dominant driver promoting plant productivity across more than 55% of northern high-latitude areas and the Tibetan Plateau [19]. Collectively, the CO_2 fertilization effect, photosynthetic capacity, and temperature fluctuations are critical key drivers of terrestrial carbon cycling.

Four key interfaces, namely atmosphere–plant, plant–soil, soil–microbe, and microbe–atmosphere, characterize the correlations and interaction intensities of dryland carbon cycles under conditions of continuous anthropogenic warming. Firstly, as the dominant component of natural and semi-natural terrestrial ecosystems in drylands, plants are highly vulnerable to warming [20,21]. Along with weakened water transport function, such heat stress eventually triggers plant decline and death, further causing substantial loss of plant carbon [21]. Secondly, long-term warming breaks down soil aggregate structure when fresh plant litter is lacking [1]. Such warming further converts recalcitrant carbon into very labile carbon, labile carbon and less labile carbon components. It also accelerates the mineralization of soil labile organic carbon, promotes soil heterotrophic respiration and weakens the stability of organic carbon bound to soil aggregates of different sizes [1,3,6]. Thirdly, warming restricts microbial activities and hinders nutrient movement, which diminishes soil microbial diversity and biomass [1,6]. This change reduces the carbon sequestration efficiency of microbial biomass, disrupts the original microbial carbon transformation pathways and reshapes key microbial functions related to carbon fixation and release. These changes ultimately modify carbon cycling processes in dryland ecosystems.

Under complex human-natural coupled systems conditions, we seek to develop a tentative research framework centering on oxygen footprint-anthropogenic warming-dryland carbon cycling, with the hope of fostering further interdisciplinary discussions within atmospheric science and terrestrial ecology. The atmospheric oxygen footprint (AOF, ratio of anthropogenic oxygen consumption (AOC) to natural oxygen production (NOP), see Ref. [3] for details) could serve as a diagnostic indicator for the effects of anthropogenic warming on dryland carbon cycling (Figure 1). This is because, within coupled human-natural systems, anthropogenic oxygen consumption (CO_2 emission) connects with heating mechanisms such as urban heat island (core logical chain: oxygen footprint-heatwaves-

terrestrial water storage in cities) [22] and reflects social development. In contrast, natural oxygen production (O_2 generation) relates to cooling mechanisms like the oxygen barrier effect (core logical chain: oxygen footprint-radiation-soil quality on the Tibetan Plateau) [1] and denotes ecological conditions. Therefore, AOC is primarily governed by four major components: fossil-fuel combustion (FFC, including gas fuel, biofuel, flared gas, solid fuel and liquid fuel), human respiration (HR, covering both females and males), livestock respiration (LR, comprising sheep, duck, cattle, horses, goats, buffaloes, chicken and pigs), and wildfires (WF, encompassing tropical forest fires, peat land fires, agricultural waste burning, temperate forest fires, savanna fires and boreal forest fires). The calculation formula is expressed as: AOC = FFC + HR + LR + WF [23]. In contrast, NOP is predominantly controlled by four key constituents: net primary productivity (NPP), net ecosystem productivity (NEP), heterotrophic respiration (HetR), and net oxidative ratio (NOR). Its computational equation is formulated as: NOP = ((NPP − HetR) = NEP) ∗ NOR [24] (Figure 1). Together, this temperature variation regulates dryland plant-, soil-, and microbial carbon dynamics and establishes direct or indirect links between oxygen footprint and carbon-cycle responses [14,20].

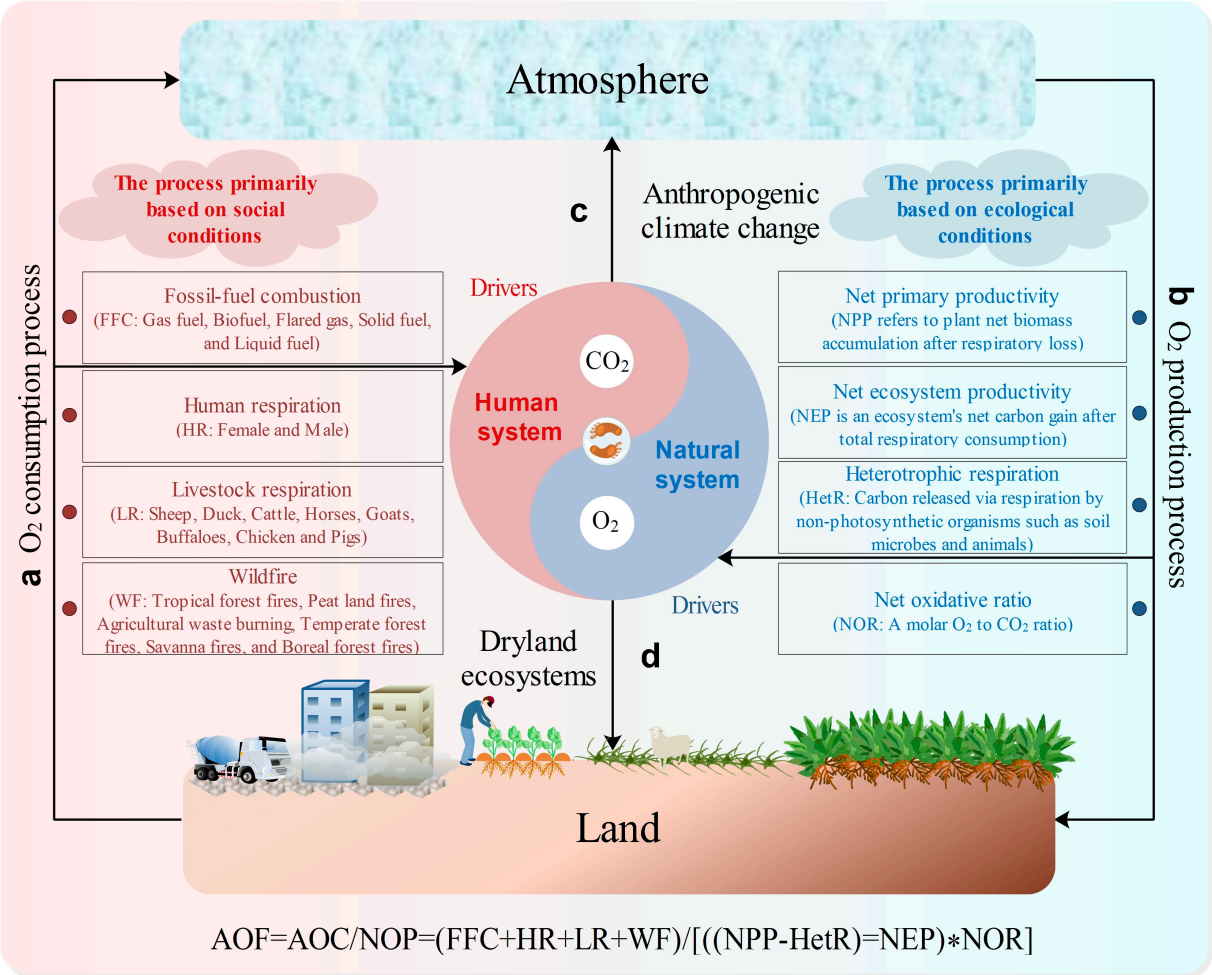


Figure 1. The atmospheric oxygen footprint (AOF) derived from anthropogenic oxygen consumption ((**a**), AOC, CO_2 emission)) and natural oxygen production ((**b**), NOP, O_2 generation)) is closely associated with anthropogenic climate change (**c**) and affects dryland carbon cycling (**d**). Note: AOF = AOC/NOP = (FFC + HR + LR + WF)/[((NPP − HetR) = NEP) ∗ NOR], where "+", "−", "∗", "/" denote addition, subtraction, multiplication, and division, respectively.

The primary processes responsible for long term changes in CO_2 and $\delta(O_2/N_2)$ involve fossil fuel combustion, which generates CO_2 while consuming O_2—creating an opposite trend where CO_2 rises and $\delta(O_2/N_2)$ declines [25,26]. The ocean provides a buffering effect by absorbing large amounts of extra CO_2 from the atmosphere. This offset rising CO_2 concentrations but exerts no influence over atmospheric O_2 levels [27]. Accordingly, considering both terrestrial and oceanic scales and integrating the oxygen-production and consumption drivers from this work, Huang et al. [27] demonstrated that the atmosphere would lose roughly 100 Gt of O_2 annually through by 2100 under a high emissions scenario. Specifically, unlike carbon, water and other environmental footprints, the oxygen footprint could serve as an indicator for anthropogenic warming research for two reasons. First, in the Anthropocene [28], the dynamics of oxygen footprints, which cover drivers of oxygen consumption and oxygen production, reflect human activities (e.g., fossil-fuel combustion) and natural circumstances (e.g., net ecosystem productivity), and their mutual interplay can help us better understand human-driven climate warming. Second, in a given region over a certain period, if AOC persistently exceeds NOP and AOF is greater than 1, the oxygen footprint rises rapidly, which is dominated by the heating mechanism; by contrast, if AOC is continuously lower than NOP and AOF is less than 1, the oxygen footprint declines rapidly, with the cooling mechanism playing a dominant role. Therefore, in this perspective, we highlight that the oxygen footprint may represent a potential diagnostic indicator for accelerated anthropogenic warming, which could further destabilize dryland carbon cycling and might trigger adverse ecological regime shifts. Our objective is to clarify how anthropogenic warming reshapes the fragile dryland carbon cycle within a *three-part* conceptual framework—increasing oxygen footprint, warming effects on dryland carbon cycling, and direct or indirect links between oxygen footprint and carbon-cycle responses—that could guide future research and academic debates.

2. Increasing Oxygen Footprint

The atmospheric oxygen footprint (AOF), defined as anthropogenic oxygen consumption (AOC) divided by natural oxygen production (NOP), will rise rapidly across global drylands. Han et al. [3] suggested that imbalanced oxygen production and consumption might contribute to dryland ecosystem degradation, potentially weakening its capacity to sustain key ecosystem services.

Changes in the AOC. (i) Urban expansion. Cities represent hotspots for massive consumption of multiple resources including oxygen. Ongoing urban related activities such as automobile emissions, industrial production, and space heating, driven by urban expansion, contribute to the formation of the urban heat island effect and alter land surface characteristics. Large scale losses in vegetation cover, a key outcome of urban expansion, can reduce plant transpiration and raise surface albedo, which may further amplify human induced warming [29]. (ii) Economic development. As socioeconomic advancement continues at a fast pace across many regions, industrial expansion stands as one prominent driver behind rising energy demands. To sustain mining operations, freight transport and other essential production activities, societies have increasingly relied on fossil-fuel-based energy supplies. Widespread combustion of coal, oil and natural gas for these sectors consequently elevates the overall rate of atmospheric oxygen consumption, alongside the continuous release of carbon-containing greenhouse gases [30]. (iii) Population growth. Rapidly growing populations in developing countries may soon exacerbate multiple ecological-environmental risks. This is because population expansion is often coupled with intensive human activities such as agricultural-waste burning. Furthermore, within dryland regions of developing countries, continuously expanding livestock rearing represents a major anthropogenic pressure [3]. Rising livestock numbers raise overall biological respiration

across animal populations, which can considerably boost atmospheric oxygen consumption at local and regional scales [27]. Such animal-related biological demands thus become a non-negligible driver modifying dryland oxygen budgets and potentially promoting anthropogenic warming.

Changes in the NOP. (i) Rising CO_2 fertilization. Atmospheric CO_2 plays a vital part in regulating terrestrial oxygen production. Elevated CO_2 concentrations stimulate photosynthetic activity by accelerating the Rubisco-catalyzed carboxylation reaction (ribulose-1,5-bisphosphate carboxylase-oxygenase) [15,20]. Rising atmospheric CO_2 is widely acknowledged as a dominant driver of enhanced terrestrial vegetation productivity and associated oxygen production [24]. This effect further boosts oxygen generation and accounts for roughly 70% of the observed trend in the global leaf-area index [20,24]. Nevertheless, such beneficial effects may be constrained by common limiting conditions within dryland ecosystems, including water scarcity and nutrient deficiency, and may be insufficient to fully offset oxygen losses stemming from various human-driven disturbances. (ii) Land-use expansion. Dryland cropping/planting raises the risk of soil water deficit: plants consume soil water to offset insufficient atmospheric precipitation, and this progressive soil water depletion often manifests with multiyear lags [3,20,24]. Furthermore, human driven agricultural intensification enhances oxygen output via high photosynthetic rates [16], yet tillage and other farm related disturbances may break down soil aggregate protection for soil organic carbon, lower groundwater tables, trigger land degradation and desertification, and eventually offset such oxygen producing benefits. (iii) Greater nitrogen deposition. Across nearly all plant functional groups, leaf-related traits including count, dimension and packing density respond markedly to nitrogen inputs. Even so, such nitrogen-triggered leaf variations exert barely detectable control over oxygen production when evaluated at both regional and global extents. Human activities substantially shape nitrogen-deposition pathways which, when coupled with climatic warming, creates large uncertainties regarding how these processes deliver eco-environmental benefits among diverse land-use categories [31].

Overall, across global land and ocean domains [27], urban areas [22] and dryland regions [3], the AOF is rising at an accelerated rate [32].

3. Warming Effects on Dryland Carbon Cycling

The oxygen footprint may act as a diagnostic indicator of anthropogenic warming and ecosystem imbalance associated with carbon-cycle risks in drylands. Atmospheric oxygen depletion may well amplify CO_2-driven anthropogenic warming, and its synergistic interaction with rising CO_2 could further reinforces this combined forcing, potentially accelerating ongoing global climate warming and affecting plant-, soil-, and microbial carbon dynamics (Figure 2). However, the climatic role of contemporary oxygen decline remains uncertain and requires further empirical testing.

Variations in atmospheric oxygen concentration can alter overall atmospheric density, which further modulates solar optical depth in the atmosphere [33]. Existing studies suggest that dryland ecosystems may exhibit distinctly higher sensitivity to oxygen dynamics relative to carbon dioxide fluctuations [1,3,6]. From a surface energy balance perspective, solar radiative forcing outweighs greenhouse forcing in regulating land surface conditions due to its stronger surface effects, and over geological timescales (millions of years) per 1 W m^{-2} total radiative forcing, surface forcing rises by 2.1 W m^{-2} via pO_2 and 0.63 W m^{-2} via pCO_2 [33]. For modern atmospheric oxygen, according to the ensemble mean projections of the Fifth Coupled Model Intercomparison Project (CMIP5) under the Representative Concentration pathway (RCP) 8.5 scenario, Huang et al. [27] showed that governed by oxygen consumption and production factors, atmospheric O_2 will, in merely a few cen-

turies, drop below 20.0% by the 26th century and decline to 19.5% in the early 29th century. If such a declining trend continues alongside the potential for anthropogenic warming—jointly driven by the CO_2 greenhouse effect and the radiative effect of O_2—the original dryland carbon-cycle pathways could be rapidly disrupted, with such changes likely to be irreversible. In this context, continuous atmospheric oxygen depletion is not merely an independent environmental change. Such oxygen loss could potentially amplify and exacerbate the effects of anthropogenic warming that are initially linked to rising CO_2 levels. This process may give rise to a compound warming mechanism, which has the potential to jointly reshape regional and global climatic patterns. Such combined warming perturbations could further interfere with dryland carbon-cycle pathways, altering carbon source-sink behaviors across arid and semi-arid ecosystems. Nevertheless, the magnitude of these interactive effects remains poorly constrained and requires more targeted observational and modeling evidence.

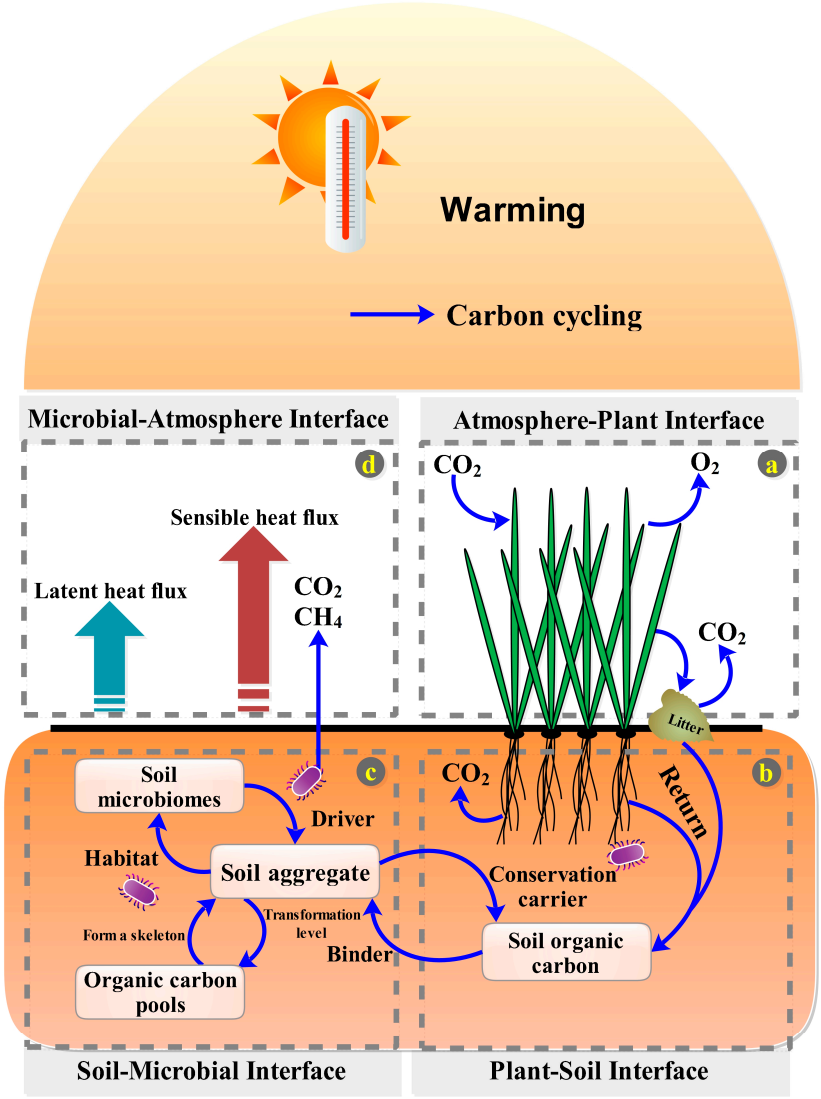


Figure 2. Anthropogenic warming affects dryland carbon cycling through four interfaces including the atmosphere–plant interface (**a**), the plant–soil interface (**b**), the soil–microbial interface (**c**), and the microbial–atmosphere interface (**d**).

Taken together, geological-scale oxygen variations and the ongoing gradual decline in modern oxygen differ substantially in magnitude, timescale, and their plausible climatic impacts. Future modern-day oxygen depletion may substantially amplify CO_2-driven

warming, yet additional empirical data are needed to validate this scenario. Based on current understanding, the oxygen footprint, which serves better as a potential diagnostic indicator, may help us further disentangle anthropogenic pressure and ecosystem imbalance that drive carbon-cycle risks within dryland ecosystems.

4. Direct or Indirect Links Between Oxygen Footprint and Carbon Cycle Responses

The dynamics of the oxygen footprint are inherently intertwined with the carbon cycle. Meanwhile, the oxygen footprint–anthropogenic warming–carbon dynamic shift chain may form a positive feedback loop, which could potentially disrupt the original pathways of dryland carbon cycling and trigger adverse ecological consequences.

Shifts in the oxygen footprint exhibit direct human-nature coupled linkages with the carbon cycle. Such direct connections arise from anthropogenic activities that simultaneously reshape oxygen and carbon budgets across terrestrial systems [25,26]. Human-driven oxygen-consuming activities, ranging from fossil fuel combustion to land-use modification, directly alter carbon storage by disturbing terrestrial carbon reservoirs. In this context, variations in the oxygen footprint can directly reflect human-induced perturbations to plant, soil, and microbial carbon pools, serving as a valuable diagnostic indicator for dryland carbon cycling and ecosystem imbalance (Figure 1).

The oxygen footprint–anthropogenic warming–carbon dynamic shift chain may constitute an indirect putative positive feedback loop, which could potentially perturb inherent dryland carbon-cycling pathways and bring about adverse ecological outcomes (Figure 2). Of note, warming exerts dual controls over terrestrial carbon pools: it may accelerate organic matter decomposition to trigger carbon efflux, yet can also boost plant carbon fixation under certain environmental contexts [20]. As such, oxygen footprint signals alone cannot confirm the occurrence of such feedback but can serve as a valuable diagnostic indicator to track possible shifts within this coupled system. Once this hypothetical feedback takes effect, heightened carbon release from dryland ecosystems may further amplify local warming signals. Higher temperatures could in turn accelerate oxygen-consuming biogeochemical processes, reinforcing alterations in the regional oxygen footprint [21,32]. Drylands are particularly susceptible to such cascading effects given their fragile substrate conditions and limited carbon storage capacity under human pressures. Even so, the actual strength of this feedback remains poorly constrained, and substantial uncertainties persist concerning its spatiotemporal performance across various dryland subtypes. Further empirical data are therefore required to validate this hypothesized feedback mechanism.

In summary, the oxygen footprint serves as a promising diagnostic indicator for both direct human-nature couplings and potential indirect feedbacks linking anthropogenic warming to dryland carbon dynamics, with further empirical evidence still needed.

5. Outlook

Water serves as the primary limiting factor for dryland carbon cycling. Variations in drought severity, precipitation, soil moisture and evaporation may govern plant and microbial metabolism, and could further shape ecosystem photosynthesis and oxygen production. Coupled with anthropogenic oxygen consumption, shifts in regional oxygen budgets can potentially trigger temperature fluctuations and subsequently may impact the stability of key interfaces, thereby helping regulate the dynamics of dryland carbon cycles. Following the research framework of oxygen footprint–anthropogenic warming–dryland carbon cycling, this work examines the response mechanisms of dryland carbon cycling under interactions among multiple environmental factors (Table 1). Subsequent research should focus on filling existing research gaps, clarifying the internal mechanisms of various

carbon cycling processes, especially in extreme high-temperature environments [34], and promoting the transformation of theoretical findings into practical management strategies. These efforts would not only help deepen our understanding of dryland carbon cycle dynamics under global change, but also provide important scientific support for maintaining dryland ecosystem stability, ensuring regional food security, and promoting human well-being.

Table 1. Listed studies relating oxygen footprint to dryland carbon cycling with direct and indirect evidence.

Classification	Research Form	Temporal Scale	Study Area	*N*	Ref.
(I) Increasing oxygen footprint					
Anthropogenic oxygen consumption	Sam/Obs	1974–1985	South Pole	12	[25]
	Obs/Mod	1975–2018	Global land	44	[23]
Natural oxygen production	Obs	1991–1994	Alert/La Jolla/Cape Grim	4	[35]
	Obs/Mod	2001–2100	Global land	100	[24]
Ascending oxygen footprint	Obs/Mod	1948–2099	Global dryland	152	[3]
(II) Warming effects on dryland carbon cycling					
Atmosphere-plant interface	Obs/Mod/Rev	1981–2100	Global land	120	[20]
	Obs	2000–2014	Yellow River Basin	15	[36]
Plant–soil interface	Rev	/	Site-to-global scale soils	/	[37]
	Obs/Mod	2000–2100	Global (in)-secure regions	101	[38]
Soil-microbial interface	Sam/Exp/Obs	2016–2018	Site-scale soils	2	[39]
	Exp/Obs/Mod	1900–2099	Arid-cold regions	200	[1]
Microbial-atmosphere interface	Rev	/	Global soil microbiomes	/	[14]
	Exp/Obs/Mod	1990–2099	Tibetan Plateau	110	[6]
(III) Direct or indirect links between oxygen footprint and carbon-cycle responses					
Direct interconnection	Obs	1989–1992	Alert/La Jolla/Cape Grim	4	[26]
Indirect interconnection	Rev	/	Global land and ocean	/	[32]
	Obs/Mod	1948–2100	Global (in)-secure regions	153	[21]

Note: Obs, observed; Mod, model; Rev, review; Sam, sampling; Exp, experimental; *N*, number of annual data points.

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References

1. Han, D.; Huang, J.; Liu, X.; Fu, L.; Ding, L.; Zhang, G.; Li, C.; Yang, F.; Shi, J.; Zhang, B. Silent soils have been awakened by climate change. *Catena* **2025**, *252*, 108777. [CrossRef]
2. Kandhol, N.; Pandey, S.; Singh, V.P.; Herrera-Estrella, L.; Tran, L.P.; Tripathi, D.K. Link between plant phosphate and drought stress responses. *Research* **2024**, *7*, 0405. [CrossRef] [PubMed]
3. Han, D.; Huang, J.; Ding, L.; Liu, X.; Li, C.; Yang, F. Oxygen footprint: An indicator of the anthropogenic ecosystem changes. *Catena* **2021**, *206*, 105501. [CrossRef]
4. Yang, C.; Li, Q.; Wang, X.; Cui, A.; Chen, J.; Liu, H.; Ma, W.; Dong, X.; Shi, T.; Meng, F.; et al. Human expansion-induced biodiversity crisis over Asia from 2000 to 2020. *Research* **2023**, *6*, 0226. [CrossRef] [PubMed]

5. Bernardino, P.N.; De Keersmaecker, W.; Horion, S.; Oehmcke, S.; Gieseke, F.; Fensholt, R.; De Kerchove, R.V.; Lhermitte, S.; Abel, C.; Meerbeek, K.V.; et al. Predictability of abrupt shifts in dryland ecosystem functioning. *Nat. Clim. Change* **2025**, *15*, 86–91. [CrossRef]
6. Han, D.; Huang, J.; Ding, L.; Zhang, G.; Liu, X.; Li, C.; Yang, F. Breaking the ecosystem balance over the Tibetan Plateau. *Earth's Future* **2022**, *10*, e2022EF002890. [CrossRef]
7. Lian, X.; Piao, S.; Chen, A.; Huntingford, C.; Fu, B.; Li, L.Z.X.; Huang, J.; Sheffield, J.; Berg, A.M.; Keenan, T.F.; et al. Multifaceted characteristics of dryland aridity changes in a warming world. *Nat. Rev. Earth Environ.* **2021**, *2*, 232–250. [CrossRef]
8. Zhao, Y.; Ma, J.; Li, Y.; Cheng, K.; Zhang, M.; Liu, Z.; Yang, F. Carbon emission based predictions of anthropogenic impacts on groundwater storage at typical basins in 2050. *Research* **2025**, *8*, 0680. [CrossRef] [PubMed]
9. Maestre, F.T.; Benito, B.M.; Berdugo, M.; Concostrina-Zubiri, L.; Delgado-Baquerizo, M.; Eldridge, D.J.; Guirado, E.; Gross, N.; Kéfi, S.; Bagousse-Pinguet, Y.L.; et al. Biogeography of global drylands. *New Phytol.* **2021**, *231*, 540–558. [CrossRef] [PubMed]
10. Plaza, C.; Zaccone, C.; Sawicka, K.; Mendez, A.M.; Tarquis, A.; Gasco, G.; Heuvelink, G.B.M.; Schuur, E.A.G.; Maestre, F.T. Soil resources and element stocks in dryland to face global issues. *Sci. Rep.* **2018**, *8*, 13788. [CrossRef] [PubMed]
11. Puetz, S.; Groeneveld, J.; Henle, K.; Knogge, C.; Martensen, A.C.; Metz, M.; Metzger, J.P.; Ribeiro, M.C.; de Paula, M.D.; Huth, A. Long-term carbon loss in fragmented neotropical forests. *Nat. Commun.* **2014**, *5*, 5037. [CrossRef] [PubMed]
12. Lal, R. Digging deeper: A holistic perspective of factors affecting soil organic carbon sequestration in agroecosystems. *Glob. Change Biol.* **2018**, *24*, 3285–3301. [CrossRef] [PubMed]
13. Ren, Z.; Li, C.; Fu, B.; Wang, S.; Stringer, L.C. Effects of aridification on soil total carbon pools in China's drylands. *Glob. Change Biol.* **2023**, *30*, 17091. [CrossRef] [PubMed]
14. Jansson, J.K.; Hofmockel, K. Soil microbiomes and climate change. *Nat. Rev. Microbiol.* **2020**, *18*, 35–46. [CrossRef] [PubMed]
15. Farquhar, G.D.; Sharkey, T.D. Stomatal conductance and photosynthesis. *Annu. Rev. Plant. Physiol.* **1982**, *33*, 317–345. [CrossRef]
16. Huang, K.; Xia, J.; Wang, Y.; Ahlström, A.; Chen, J.; Cook, R.B.; Cui, E.; Yang, F.; Fisher, J.B.; Huntzinger, D.N.; et al. Enhanced peak growth of global vegetation and its key mechanisms. *Nat. Ecol. Evol.* **2018**, *2*, 1897–1905. [CrossRef] [PubMed]
17. Huang, M.; Piao, S.; Ciais, P.; Peñuelas, J.; Wang, X.; Keenan, T.F.; Peng, S.; Berry, J.A.; Wang, K.; Mao, J.; et al. Air temperature optima of vegetation productivity across global niomes. *Nat. Ecol. Evol.* **2019**, *3*, 772–779. [CrossRef] [PubMed]
18. Keenan, T.F.; Riley, W.J. Greening of the land surface in the world's cold regions consistent with recent warming. *Nat. Clim. Change* **2018**, *8*, 825–828. [CrossRef] [PubMed]
19. Zhu, Z.; Piao, S.; Myneni, R.B.; Huang, M.; Zeng, Z.; Canadell, J.G.; Ciais, P.; Sitch, S.; Friedlingstein, P.; Arneth, A.; et al. Greening of the Earth and its drivers. *Nat. Clim. Change* **2016**, *6*, 791–795. [CrossRef]
20. Piao, S.; Wang, X.; Park, T.; Chen, C.; Lian, X.; He, Y.; Bjerke, J.W.; Chen, A.; Ciais, P.; Tømmervik, H.; et al. Characteristics, drivers and feedbacks of global greening. *Nat. Rev. Earth Environ.* **2020**, *1*, 14–27. [CrossRef]
21. Huang, J.; Yu, H.; Han, D.; Zhang, G.; Wei, Y.; Huang, J.; An, L.; Liu, X.; Ren, Y. Declines in global ecological security under climate change. *Ecol. Indic.* **2020**, *117*, 106651. [CrossRef]
22. Wei, Y.; Wu, J.; Huang, J.; Liu, X.; Han, D.; An, L.; Yu, H.; Huang, J. Declining oxygen level as an emerging concern to global cities. *Environ. Sci. Technol.* **2021**, *55*, 7808–7817. [CrossRef] [PubMed]
23. Liu, X.; Huang, J.; Huang, J.; Li, C.; Ding, L.; Meng, W. Estimation of gridded atmospheric oxygen consumption from 1975–2018. *J. Meteorol. Res.* **2020**, *34*, 646–658. [CrossRef]
24. Ding, L.; Huang, J.; Li, C.; Han, D.; Liu, X.; Li, H.; Bai, Y.; Huang, J. Variations in terrestrial oxygen sources under climate change. *Sci. China Earth Sci.* **2022**, *65*, 1810–1823. [CrossRef]
25. Battle, M.; Bender, M.; Sowers, T.; Tans, P.P.; Butler, J.H.; Elkins, J.W.; Ellis, J.T.; Conway, T.; Zhang, N.; Lang, P.; et al. Atmospheric gas concentrations over the past century measured in air from firn at the South Pole. *Nature* **1996**, *383*, 231–235. [CrossRef]
26. Keeling, R.F.; Shertz, S.R. Seasonal and interannual variations in atmospheric oxygen and implications for the global carbon cycle. *Nature* **1992**, *358*, 723–727. [CrossRef]
27. Huang, J.; Huang, J.; Liu, X.; Li, C.; Ding, L.; Yu, H. The global oxygen budget and its future projection. *Sci. Bull.* **2018**, *63*, 1180–1186. [CrossRef] [PubMed]
28. Crutzen, P.J. Geology of mankind. *Nature* **2002**, *415*, 23. [CrossRef] [PubMed]
29. Oke, T.R. *Boundary Layer Climates*; Routledge: London, UK, 1978.
30. Barnett, J.; O'Neill, S. Maladaptation. *Glob. Environ. Change* **2010**, *20*, 211–213. [CrossRef]
31. Zaehle, S.; Medlyn, B.E.; De Kauwe, M.G.; Walker, A.P.; Dietze, M.C.; Hickler, T.; Luo, Y.; Wang, Y.; El-Masri, B.; Thornton, P.; et al. Evaluation of 11 terrestrial carbon-nitrogen cycle models against observations from two temperature Free-Air CO_2 Entrichment studies. *New Phytol.* **2014**, *202*, 803–822. [CrossRef] [PubMed]
32. Huang, J.; Liu, X.; He, Y.; Shen, S.; Hou, Z.; Li, S.; Li, C.; Yao, L.; Huang, J. The oxygen cycle and a habitable Earth. *Sci. China Earth Sci.* **2021**, *64*, 511–528. [CrossRef]
33. Poulsen, C.; Tabor, C.; White, J.D. Long-term climate forcing by atmospheric oxygen concentrations. *Science* **2015**, *348*, 1238–1241. [CrossRef] [PubMed]

34. Noba, W.G.; Poan, D.E.; Guigma, K.H.; Vogel, M.M.; Béré, T.R. Deep diving into the "Post 1.5 °C Climate" heatwave events in Ouagadougou during spring 2024. *Climate* **2026**, *14*, 5. [CrossRef]
35. Keeling, R.F.; Piper, S.C.; Heimann, M. Global and hemispheric CO_2 sinks deduced from changes in atmospheric O_2 concentration. *Nature* **1996**, *381*, 218–221. [CrossRef]
36. Zhang, G.; Huang, J.; Liu, X.; Guan, X.; Wei, Y.; Ding, L.; Han, D. The evolution of ecological security and its drivers in the Yellow River Basin. *Environ. Sci. Pollut. Res.* **2023**, *30*, 47501–47515. [CrossRef] [PubMed]
37. Bünemann, E.K.; Bongiorno, G.; Bai, Z.; Creamer, R.E.; De Deyn, G.; De Goede, R.; Fleskens, L.; Geissen, V.; Kuyper, T.W.; Mäder, P.; et al. Soil quality-A critical review. *Soil Biol. Biochem.* **2018**, *120*, 105–125. [CrossRef]
38. Fu, L.; Huang, J.; Zhang, G.; Han, D.; Ding, L.; Wei, Y.; Liu, X.; Li, C.; Yu, H. Abrupt loss of species richness caused by ecosystem transition. *Sci. Bull.* **2025**, *70*, 1523–1532. [CrossRef] [PubMed]
39. Nottingham, A.T.; Meir, P.; Velasquez, E.; Turner, B.L. Soil carbon loss by experimental warming in a tropical forest. *Nature* **2020**, *584*, 234–237. [CrossRef] [PubMed]

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