**Evidence and attribution of the enhanced land carbon sink**

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### Abstract

**Climate change has been partially mitigated by an increasing net land carbon sink in the terrestrial biosphere; understanding the processes that drive the land carbon sink is thus essential for protecting, managing, and projecting this important ecosystem service. In this Review, we examine evidence for an enhanced land carbon sink and attribute the observed response to drivers and processes. The land carbon sink has doubled from 1.2 ± 0.5 PgC yr-1 in the 1960s to 3.1 ± 0.6 PgC yr-1 in the 2010s. This trend results largely from carbon dioxide (CO2) fertilization increasing photosynthesis (driving an increase in the annual land carbon sink of >2PgC globally since 1900), mainly in tropical forest regions, and elevated temperatures reducing cold-limitation, mainly at higher latitudes. Continued long term land carbon sequestration is possible through the end of this century under multiple emissions scenarios, especially if nature-based climate solutions and appropriate ecosystem management are deployed. A new generation of globally distributed field experiments are needed to improve understanding of future carbon sink potential by measuring belowground carbon release, the response to CO2 enrichment, and long-term shifts in carbon allocation and turnover .**

### [H1] Introduction

The terrestrial biosphere absorbs 15% of the carbon in the atmosphere on average each year through primary productivity, returning nearly all of it via ecosystem respiration [1–3](https://www.zotero.org/google-docs/?25Z0J9). These gross fluxes of photosynthesis and respiration would be expected to approach a long-term balance under steady climatic, atmospheric, edaphic, and disturbance conditions. However, fossil fuel combustion and land use change since the Industrial Revolution have increased atmospheric carbon dioxide (CO2) concentration, leading to an imbalance in the biosphere’s carbon fluxes [G] [4](https://www.zotero.org/google-docs/?BoWUW7). These emissions are offset when terrestrial ecosystems store carbon in the form of plant biomass or in soils, a quantity known as the natural land carbon sink **[G]**.

Several direct and indirect human influences determine the magnitude of the land carbon sink [G]. Land use change – particularly deforestation – has the most direct negative effect on the net land carbon sink **[G]** [5–7](https://www.zotero.org/google-docs/?qwtPfq). Other anthropogenic factors, such as elevated atmospheric CO2 concentrations [8](https://www.zotero.org/google-docs/?GNF78X) and changing nitrogen availability [9](https://www.zotero.org/google-docs/?86XBsX), air quality [10](https://www.zotero.org/google-docs/?s4Ia7y), temperature [1,11](https://www.zotero.org/google-docs/?FIq0j9) and precipitation patterns [12,13](https://www.zotero.org/google-docs/?9R01gq) influence the land carbon sink indirectly by stimulating plant photosynthesis and water use efficiency. Changes in fire frequency and intensity and more frequent climate extremes, including drought, wind storms, and flood events, can decrease the land sink [14,15](https://www.zotero.org/google-docs/?D5ot1y). Other factors also influence the land carbon sink, including changes in radiation from aerosol loading [16](https://www.zotero.org/google-docs/?TEszwg), biotic agents, and the melting of permafrost [17](https://www.zotero.org/google-docs/?diKNKN). The combined effects of these direct and indirect human influences determine the strength of the land carbon sink.

The land carbon sink offsets a portion of anthropogenic emissions and is essential in keeping atmospheric CO2 concentrations below specific anthropogenic warming targets. The land carbon sink has removed about 210 ± 45 PgC from the atmosphere between 1850 and 2021 (ref [18](https://www.zotero.org/google-docs/?sV3nMR)). As a result, atmospheric CO2 concentration remains 100 ppm lower than would otherwise be expected given historic anthropogenic emissions (grey lines in Fig. 1). Given the role of the land carbon sink in reducing emissions, understanding the historical patterns and potential future projections is paramount to addressing climate change. However, published projections of the land carbon sink are widely divergent, ranging from an expected acceleration in CO2 uptake to sink saturation or even a net release of carbon over time [4,19–21](https://www.zotero.org/google-docs/?5DAzNd). Obtaining accurate estimates of the land carbon sink and its feedback on atmospheric CO2 concentrations will help guide climate change mitigation efforts through the use of natural climate solutions such as reforestation, agroforestry, and sustainable land management practices [22](https://www.zotero.org/google-docs/?hPbAdV).

In this Review, we examine the evidence for and implications of an increased land carbon sink. First, we explore the evidence of land sink enhancement from various observations and methodologies. We then outline the key processes driving this change, followed by discussion of projected changes in the land carbon sink and associated implications for natural climate solutions and society. We end by outlining future research priorities to better understand and manage dynamic land carbon stocks and sinks.

### [H1] Trends in the land carbon sink

Numerous lines of evidence suggest that the natural land sink has consistently increased since 1850 (Fig. 1). These changes in the land carbon sink are estimated through various approaches, including global and regional observations, and terrestrial ecosystem models (**Table 1, Supplementary Table 1**)

#### [H2] Global

Observations of atmospheric CO2 provide the clearest information on the net land carbon sink globally [23](https://www.zotero.org/google-docs/?cwHTuc). Measurements from the 1960s to present indicate that only about 44% of anthropogenic CO2 emissions remain in the atmosphere each year [4,24–26](https://www.zotero.org/google-docs/?7q5fGW). Of the rest, about half is absorbed by the world’s oceans (~25% of the total) [27,28](https://www.zotero.org/google-docs/?N03wcS), and the other half (~25% of the total) is taken up by ecosystems on land [2,29–31](https://www.zotero.org/google-docs/?NeTKDY). Multiple lines of evidence agree that the land sink is estimated to have increased at an average rate of 0.1 PgC yr–1 since the 1960s [18,29,32–35](https://www.zotero.org/google-docs/?Gw14uZ).

Despite increasing anthropogenic emissions since the 1950s, the decadal average airborne fraction **[G]** (the portion of anthropogenic CO2 emissions that remain in the atmosphere and are not taken up by the land or oceanic sinks) has remained relatively steady [4,36](https://www.zotero.org/google-docs/?cAYuaI). This relatively constant airborne fraction implies that the land and ocean carbon sinks have doubled over time (black line in Fig. 1) [29,32,33](https://www.zotero.org/google-docs/?9ldKbI)without increasing land carbon sinks, atmospheric CO2 concentration would have reached >500 ppm by 2020 (dashed grey line in Fig. 1). Despite its overall temporal stability, the airborne fraction exhibits substantial interannual and decadal variability, including 1.8% growth per year in the 1960s-1990s and –2.2% reductions per year [31](https://www.zotero.org/google-docs/?lX52Jx) thereafter owing to macro-climatic or land use changes [37](https://www.zotero.org/google-docs/?c2xVpd).

13C stable isotopes—the atmospheric signature of which is altered by land plant photosynthesis—can also be used to estimate the land carbon sink [38](https://www.zotero.org/google-docs/?341uAB). Plants on land strongly fractionate stable isotope 13C during photosynthesis, thereby uniquely affecting δ13CO2 in the atmosphere 37 . Atmospheric δ13CO2 unequivocally points to the existence of a strong natural land carbon sink [39](https://www.zotero.org/google-docs/?zldj6S), which increased 0.2 PgC yr–1 during the 20th century [34](https://www.zotero.org/google-docs/?d5mU0U) (brown lines in Fig. 1). In addition, the differential rates of increase in atmospheric CO2 and decrease in oxygen (O2) allow partitioning of the global carbon sink into land and ocean components as gross land carbon uptake releases O2 whereas ocean uptake does not [40,41](https://www.zotero.org/google-docs/?yGIxG5). The δ13CO2 and O2-based methods provide independent observational constraints of the net land carbon sink, which was estimated to be 1.4 ± 0.9 PgC yr–1 from 1990 to 2015 [42](https://www.zotero.org/google-docs/?evy3VW).

The estimates of land carbon flux from δ13CO2 methods are similar to estimates derived from atmospheric inversions. Atmospheric inversions use atmospheric CO2 measurements to infer the magnitude of carbon fluxes at the surface over space and time (Table S1) [43,44](https://www.zotero.org/google-docs/?JNPsrf). Inversion-based estimates (blue lines in Fig. 1) suggest a land carbon sink of 1.1-1.7 PgC yr-1 [18,35](https://www.zotero.org/google-docs/?DoOJk6), which has increased by 0.1 PgC yr-1 since the 1990s.

Global inference about the size and trend of the land carbon sink can be derived after accounting for all other sources and sinks [18](https://www.zotero.org/google-docs/?Gd23k5). The Global Carbon Project, which annually releases a review of the various terms in the global carbon budget, uses estimates of global carbon emissions from cement and energy production data, the CO2 atmospheric growth rate **[G]**, and model and observational estimates of the ocean carbon sink to independently calculate components of the land carbon sink, which was estimated to be 1.5 ± 0.6 PgC yr-1 in the 2010s [2](https://www.zotero.org/google-docs/?bvqk14). An independent estimate of the net land carbon sink, provided by an ensemble of dynamic global vegetation models, is consistent with this value, with a mean net land sink of 1.5 ± 0.5 PgC yr-1 (2010s) [2](https://www.zotero.org/google-docs/?v80cRJ).

A substantial fraction of the land carbon sink is carbon stored in vegetation biomass. Since the 1980s, a growing constellation of Earth-observing satellites have measured leaf area index (LAI) [45,46](https://www.zotero.org/google-docs/?upZG4B), an indicator of vegetation greening (Fig. 2) [47–50](https://www.zotero.org/google-docs/?CixlWC). Approximately 15% of the Earth’s surface has experienced a significant increase in LAI [51](https://www.zotero.org/google-docs/?5ZP5D2), with about 12% of the increased global land carbon sink over the satellite era (1981-present) attributed to increased LAI [52](https://www.zotero.org/google-docs/?ZkyTP8). Estimates of the vertical structure of woody canopies derived from satellite LiDAR instruments further suggest that biomass stocks are increasing, with an average annual gain in woody carbon stocks of 0.23 ± 0.09 PgC yr-1 from 2000 to 2019 (ref [53](https://www.zotero.org/google-docs/?erTlJT)). Boreal and temperate biomass increased by 0.13 PgC yr-1 from 1993 to 2012, although this trend was offset at the global scale due to deforestation in the tropics [54](https://www.zotero.org/google-docs/?nOK0W9).

Multiple lines of evidence from emerging technologies suggest an increase in primary productivity, which could increase the land carbon sink. For example, extended records of solar-induced fluorescence (SIF), which is a proxy of ecosystem carbon fixation [55–58](https://www.zotero.org/google-docs/?2pCYp1) suggest an increasing trend in SIF globally since the early 2000s [59,60](https://www.zotero.org/google-docs/?wQXj57). Atmospheric carbonyl sulfide represents another proxy for carbon assimilation [61](https://www.zotero.org/google-docs/?vTcGsM) and records suggest a 31 ± 5% growth in primary productivity over the 20th century [62](https://www.zotero.org/google-docs/?d6GkIc). Although these methods are experimental [63–66](https://www.zotero.org/google-docs/?9TOIDA), they point to increasing rates of land carbon uptake, which could lead to a larger land carbon sink.

#### [H2] Regional

Despite ample evidence of an enhanced land carbon sink at the global scale, trends at regional scales are more challenging to identify. Atmospheric CO2 measurements reveal a strong enhancement of the seasonal cycle of atmospheric CO2 at northern latitudes, with amplitude increased 30-50% since the 1960s [67](https://www.zotero.org/google-docs/?AgILc8). This change reflects a larger summer uptake and a corresponding larger winter release [68](https://www.zotero.org/google-docs/?HjV6DY). Indeed, over the 2000s, land CO2 uptake increased by 0.6 ± 0.5 PgC yr-1  [25](https://www.zotero.org/google-docs/?Kldvr6).

Vegetation cover, LAI, and biomass also show trends that vary at sub-global scales (Fig. 2). A 10% increase in vegetation cover in semi-arid lands was observed globally [69](https://www.zotero.org/google-docs/?O7iMGH), corresponding to widespread greening in Australia [70](https://www.zotero.org/google-docs/?qfDzNF), which increased the land sink [71](https://www.zotero.org/google-docs/?Di0gkG). Strong greening trends have been detected over China and India, primarily from forest and agricultural expansion, and across the Arctic [49,50](https://www.zotero.org/google-docs/?aoT65B). A significant increase in LAI has also been observed over the Sahel, North America, Europe, and Brazil [51](https://www.zotero.org/google-docs/?Q54M4T). Satellite-derived estimates of gross primary productivity across Europe, Asia, and Africa also show positive trends [72](https://www.zotero.org/google-docs/?S1yf2m). However, greening could be slowing down or reversing, especially in tropical rainforests [73](https://www.zotero.org/google-docs/?eff2B8) such as the Amazon [72,74](https://www.zotero.org/google-docs/?YvcazM). Browning trends are also evident in the Amazon and elsewhere [75](https://www.zotero.org/google-docs/?C3MjIE), though to a much lesser extent than greening trends. Like LAI, forest biomass trends also show regional variation; positive trends in Amazon forest aboveground biomass slowed by one-third in the 2000s [76](https://www.zotero.org/google-docs/?AMbie3), as positive gains in biomass were outweighed by deforestation, but remained stable across Africa at 0.66 ± 0.13 MgC ha-1 yr-1 since 1985 [77](https://www.zotero.org/google-docs/?SSRogG).

**[H2] Plot- and ecosystem-level**

Repeated measures of plot level biomass indicate widespread increased tree growth [78–81](https://www.zotero.org/google-docs/?0KRLgf). In the tropics, analyses of standardized inventory data from forest plot networks such as RAINFOR, AfriTRON and CTFS suggest an overall annual increasing biomass trend of 0.5 ± 0.2 MgC ha−1 yr−1 [77,78,82](https://www.zotero.org/google-docs/?o1GqC6). Temperate forests in the United States have experienced significantincreases in wood volume since the 1990s [83](https://www.zotero.org/google-docs/?07Le71). This evidence is broadly consistent with a global review of biomass inventories suggesting that intact tropical forests contribute up to 50% of the global land sink [81](https://www.zotero.org/google-docs/?ZQHyEp) and also consistent with evidence of enhanced growth from temperate and boreal forests [79,80](https://www.zotero.org/google-docs/?hf0kU8).

Tree ring analyses provide similar evidence for enhanced growth [79](https://www.zotero.org/google-docs/?UP5sgh). For example, aspen trees in Wisconsin showed up to 0.7% yr-1 increases in growth, after accounting for effects of age, water stress and other variables [84](https://www.zotero.org/google-docs/?4rVBml). However, tree ring analyses in other locations have shown little to no growth enhancement [85–88](https://www.zotero.org/google-docs/?ee4BCX). An unexplained divergence in the relationship between ring width, temperature [89,90](https://www.zotero.org/google-docs/?ymVHaV) and nutrient limitation [91](https://www.zotero.org/google-docs/?DHNMpQ) has also been reported, which further complicates the interpretation and attribution of long-term trends. Emerging approaches that combine theory with statistical models or satellite observations should yield more accurate and insightful quantification of tree growth enhancement [92–94](https://www.zotero.org/google-docs/?MYpLcc).

An ecosystem-level approach is the eddy-covariance technique, which directly measures the net exchange of CO2 between ecosystems and the atmosphere [95](https://www.zotero.org/google-docs/?Jc2qGm). Of the over two thousand eddy-covariance sites around the world [96](https://www.zotero.org/google-docs/?Sr4bNJ), more than 100 have been operational since or before 2005, allowing estimates of annual net land carbon sinks or sources over long time scales [97,98](https://www.zotero.org/google-docs/?jHf4WR). Despite high background variability, long-term trends have emerged from many sites with records long enough to allow separation of signal from noise. Enhanced uptake has been observed at sites in North America and Europe [99–102](https://www.zotero.org/google-docs/?FbCEvo). Synthesis across the global network of observation sites with a light-use efficiency model indicates an annual increase in gross primary productivity of 0.46 ± 0.09 PgC yr-1 from 1982 to 2016 [103,104](https://www.zotero.org/google-docs/?uCOFR1). When eddy-covariance observations are combined with empirical [105](https://www.zotero.org/google-docs/?ibGiyQ) or process-based [104](https://www.zotero.org/google-docs/?wONymb) models, the scaled-up observations suggest an enhancement of global photosynthesis.

#### [H2] Terrestrial ecosystem models

Dynamic Global Vegetation Models (DGVMs) are state-of-the-art terrestrial ecosystem models that incorporate known physiological and biological mechanisms responsible for ecosystem function and carbon cycling. These models are used to project the future of the Earth System and delineate individual drivers of carbon fluxes into and out of the atmosphere. Model structure and parameters are optimized to best capture atmospheric and ground-based observation dynamics. An ensemble mean from 17 DGVM models indicates that the natural land sink increased from 1.2 ± 0.5 PgC yr-1 in the 1960s to 3.1 ± 0.6 PgC yr-1 in the 2010s [2](https://www.zotero.org/google-docs/?lhb4Rc) (red lines in Fig. 1). Between 1959 and 2020, estimates of net ecosystem exchange **[G]** derived from DGVMs have increased globally, with variation across regions. North America and Asia are estimated to have experienced the largest increase in net ecosystem exchange of 0.30 and 0.29 PgC yr-1, respectively. Europe, Africa, and Oceania experienced more moderate increases of 0.18, 0.06, and 0.04 PgC yr-1, respectively, while South America’s net ecosystem exchange decreased by –0.23 PgC yr-1, largely owing to land use change emissions.

#### [H2] Uncertainties

Atmospheric, satellite, and in situ observations, along with outputs of DGVM models, all provide ample evidence of an increase in the global land carbon sink. Several lines of evidence converge, estimating that the land sink has increased by approximately 0.1 PgC yr–1 since the 1960s [18,29,32–35](https://www.zotero.org/google-docs/?2t6qRB).However, each of these methodologies is subject to various levels of uncertainty (Table 1).

Atmospheric inversion and DGVM model estimates depend on modeling assumptions and design, such as whether certain processes are represented and uncertainty in forcing datasets [2](https://www.zotero.org/google-docs/?J8Gym4). Satellite observations of biomass can be inaccurate in dense canopies [46](https://www.zotero.org/google-docs/?vZ7vW1) and generate spurious trends [106](https://www.zotero.org/google-docs/?loSpF3). Estimates of biomass and greening vary among the different satellite products owing to sensor degradation [50](https://www.zotero.org/google-docs/?ATMATc) and different methods to detect trends [47,51,107,108](https://www.zotero.org/google-docs/?DfeVNA). Divergences between LAI estimates are more pronounced in highly vegetated areas with dense canopies, resulting in larger uncertainty in areas with greater aboveground biomass (Fig. 2e). A further issue contributing to uncertainty is that widespread greening trends do not necessarily translate to increases in the net land sink. For example, Europe’s net land carbon sink has reportedly not benefited from long-term vegetation greening because increases have been offset by ecosystem respiration [109](https://www.zotero.org/google-docs/?o96sfz) and evapotranspiration [110](https://www.zotero.org/google-docs/?j3l5bB). The reverse is also true: increases in biomass and the land sink are possible without greening. For example, CO2 fertilization **[G]** can increase photosynthesis without concurrent increases in LAI or biomass [111,112](https://www.zotero.org/google-docs/?7Az7yc).

Inference about biomass growth from tree ring data is complicated by the fact that tree ring responses vary depending on local climate and background stress conditions. Furthermore, individual tree-ring measurements do not necessarily translate to an all-stand or ecosystem-level change in carbon stock and net sink. Conversely, higher stand density could lead to higher biomass even without a change in individual growth rates. Patchy distribution of in-situ sampling sites also complicates the estimation of broad-scale trends. For example, eddy-covariance flux towers are not evenly distributed around the globe and under-sample important biomes such as the tropics [113](https://www.zotero.org/google-docs/?GWIKt4). Their uneven distribution creates a barrier to capturing extreme climate and disturbance events and thus measuring long-term trends [114](https://www.zotero.org/google-docs/?NS6XzR).

### [H1] Key processes driving the land carbon sink

Multiple drivers contribute to changes in the land sink, including CO2 fertilization, warming effects on growth and growing season length, water limitation, nutrient fertilization, light availability, and land use change, which are now discussed (Fig. 3).

#### [H2] CO2 fertilization

CO2 fertilization is very likely the leading mechanism behind observed gains in the land carbon sink [8,30,31,104,115,116](https://www.zotero.org/google-docs/?tEj7AL) (Fig. 4). CO2 fertilization alone increased the land carbon sink by 60.4-81 TgC per ppm CO2 from 1995 to 2014 [115](https://www.zotero.org/google-docs/?PQQ8E6). Under increased atmospheric CO2, plants can take up more carbon without increased water loss via transpiration, resulting in increased water use efficiency and potential release from water stress [117](https://www.zotero.org/google-docs/?F493kO). Indeed, a global increase in water use efficiency is evident in atmospheric carbon isotopes, with an increase in isotopic discrimination of 0.66 ± 0.34‰ from 1975 to 2005 [38](https://www.zotero.org/google-docs/?x6BJ1y). Further evidence that rising CO2 increases water use efficiency comes from tree ring isotopes [118–120](https://www.zotero.org/google-docs/?ganyDy). For example, a global 40% increase in tree water use efficiency was attributed to rising CO2 [121](https://www.zotero.org/google-docs/?h1HReq). Increases in water efficiency are expected to result in increased growth [86,91,122](https://www.zotero.org/google-docs/?KHe3Db). Indeed, an increase of 75 ppm CO2 from 1970-2015 induced 12.3 and 28.8% increases in wood volume in 75- and 25-year-old temperate forest biomass plots, respectively [83](https://www.zotero.org/google-docs/?hbRA3m).

A useful approach to quantifying the CO2 fertilization effect is free air CO2 enrichment (FACE) experiments, which artificially increase ambient atmospheric CO2. FACE experiments indicate increases in photosynthesis, LAI, net primary productivity, water use efficiency and biomass growth for plants grown under elevated CO2 conditions [8,123–126](https://www.zotero.org/google-docs/?CCKn9x). A meta-analysis of FACE results estimated that each﻿ 100-ppm increase in CO2 increased total biomass by 11.7% [127](https://www.zotero.org/google-docs/?j4dszb). FACE experiments generally show a larger increase of belowground than aboveground biomass, increased soil respiration, and decreased nitrogen (N) concentration in leaves [128](https://www.zotero.org/google-docs/?P2VWe5).

The magnitude of the CO2 fertilization effect varies across plant type. For example, C3 plants are expected to be more sensitive to CO2 fertilization than C4 plants; across 186 independent studies, an increase of 200 ppm CO2 resulted in a 18% increase in yield in C3 crops in unstressed conditions [129](https://www.zotero.org/google-docs/?bfsdNu). The magnitude of the CO2 fertilization effect also depends on nutrient availability, which can be a limiting factor to growth [129,130](https://www.zotero.org/google-docs/?u4V8Ek), along with mycorrhizal association [131](https://www.zotero.org/google-docs/?FOu7PY) and differences in below-ground allocation [132,133](https://www.zotero.org/google-docs/?QUr2rN). Finally, differences in vegetation age, climate, and nutrient and water availability can diminish or enhance CO2 fertilization effect [134–137](https://www.zotero.org/google-docs/?6cYqVS).

Widespread global greening has been attributed to CO2 fertilization [47,138](https://www.zotero.org/google-docs/?EpF4K0). Estimates of the effect of CO2 fertilization vary; the impact of elevated CO2 ranges from 40% [138](https://www.zotero.org/google-docs/?SHIhAk) to 70% [47](https://www.zotero.org/google-docs/?0TxL77) of the observed greening trend. In semi-arid lands, increases in vegetation cover were attributable to increased plant water use efficiency from elevated CO2 [69](https://www.zotero.org/google-docs/?j71Eub). For example, in Australia’s semi-arid regions, approximately 90% of increases in green vegetation cover was directly attributable to increasing atmospheric CO2 as the same amount of precipitation led to larger greening over time [70](https://www.zotero.org/google-docs/?qQN1jM).

Field experiments measuring the CO2 fertilization effect on plant productivity are used to parameterize global DGVMs, which then estimate the percentage of the total carbon land sink that is attributed to elevated CO2 [30,31,116,139](https://www.zotero.org/google-docs/?Jfr40A). Indeed, DGVMs suggest that 60 [30](https://www.zotero.org/google-docs/?eQxesr) to 85% [31](https://www.zotero.org/google-docs/?fy7hvL) of the increase in the land carbon sink since the 1960s could be due to atmospheric CO2. In DGVMs, the simulated land sink is very sensitive to CO2 fertilization; one DGVM predicted that even a 20 ppm increase in CO2 resulted in a detectable increase in carbon assimilation rates [140](https://www.zotero.org/google-docs/?yPpGgO). However, estimates vary considerably among models.

#### [H2] Increasing temperature

Rising temperatures have divergent effects on the land carbon sink across the globe (Fig. 5a and 5b). In warm regions, several factors might cause the carbon land sink to diminish under warming. Higher temperatures increase respiration, which wholly or partially offsets productivity [141](https://www.zotero.org/google-docs/?gqU0Mf). Tropical forests might already be at optimal temperatures for photosynthesis, which would indicate that canopy photosynthesis could decline under additional warming [142](https://www.zotero.org/google-docs/?33TvKD). Increased temperatures in tropical biomes could also increase heterotrophic respiration, resulting in large releases of CO2 from soil carbon stocks [143](https://www.zotero.org/google-docs/?Be0Ne6). Indeed, maximum temperature was found to be the most important control on aboveground biomass across the tropics, with a loss of 9.1 MgC ha-1 ˚C-1 [144](https://www.zotero.org/google-docs/?wSwvBW), underscoring the vulnerability of tropical carbon stocks to further warming. Globally, DGVM model output suggests climate change alone, dominated by near surface warming, reduced the land sink by 15% or 0.45 ± 0.39 GtC yr-1 from 2011 to 2020 [2](https://www.zotero.org/google-docs/?WkyPxy).

Conversely, in cold, wet climates (for example, alpine and boreal systems), longer growing seasons could increase the land carbon sink [25,145](https://www.zotero.org/google-docs/?ZITujY). High-latitude systems are thought to be greening because of temperature increases (Fig. 5b). 16.4% of high-latitude land area was released from temperature limitation during 1982-2012 [146](https://www.zotero.org/google-docs/?ry4t4O). Further, 60% of springtime respiration in the eastern United States has been offset by increasing gross primary productivity [147](https://www.zotero.org/google-docs/?Oy4p7g). Longer growing seasons accounted for 40-50% of increases in net ecosystem productivity over 10 years in a deciduous temperate forest [99](https://www.zotero.org/google-docs/?JsQRX3). However, earlier leaf-out dates might dampen summer [110,148](https://www.zotero.org/google-docs/?LPDz1J) and autumn photosynthesis [149,150](https://www.zotero.org/google-docs/?OsyorZ), so that growing seasons might not be as productive as previously projected, with fall respiration offsetting up to 90% of increases in spring gross primary productivity [149,151](https://www.zotero.org/google-docs/?NuON7b).

#### [H2] Water availability

Changes in water availability have the potential to reduce the land carbon sink. Water limitation decreases plant productivity, the net land sink, and ecosystem carbon stocks [152–156](https://www.zotero.org/google-docs/?eU22WX) in many cases, though not all [157](https://www.zotero.org/google-docs/?yN8Eip). Strong continental wetting or drying trends have been detected [158–160](https://www.zotero.org/google-docs/?XKKd1J), driving higher interannual variability in the land carbon sink [161,162](https://www.zotero.org/google-docs/?se8Em4) on the order of 2 PgC yr-1, which at times counteract the mean sink [163](https://www.zotero.org/google-docs/?OM9dSW). Significant drying trends have been detected in the western United States, mid-altitudes, European peatland, and global islands, limiting the carbon sink [158,164–167](https://www.zotero.org/google-docs/?aN7wU3).

Semi-arid biomes have been greening [50,156,168](https://www.zotero.org/google-docs/?QXl16f) while simultaneously drying after accounting for the CO2 fertilization effect on plant water dynamics [166,168–171](https://www.zotero.org/google-docs/?SqllSW). However, many ecosystems are becoming more sensitive, in terms of productivity and greenness, to changes in water availability [172–174](https://www.zotero.org/google-docs/?e6ccc1), with dry region sensitivity to precipitation increasing at a rate of 0.624% yr-1 from 1981 to 2015 [175](https://www.zotero.org/google-docs/?8n8lJR). If vegetation productivity becomes more sensitive to water availability, droughts and dry anomalies could result in large losses to the carbon land sink [176,177](https://www.zotero.org/google-docs/?TLsX2K). In high-latitude systems, potential increases in the land carbon sink from longer growing seasons could be limited by increasingly severe and frequent seasonal water deficits [110,178](https://www.zotero.org/google-docs/?YVFOZn).

#### [H2] Nutrient availability

N deposition – which has increased globally owing to agricultural N-fertilizer application and NOx emissions from fossil fuel combustion [179](https://www.zotero.org/google-docs/?BEmu3O) – is an important but localized potential driver of an enhanced sink [115](https://www.zotero.org/google-docs/?CPsJkd). Soil N affects photosynthetic capacity; a meta-analysis of 138 experiments found that soil carbon:N ratio was the best predictor of carbon fertilization effects [130](https://www.zotero.org/google-docs/?VxSpZk). N fertilization has the potential to generate sizable and lasting carbon sinks in ecosystems [180,181](https://www.zotero.org/google-docs/?0eIRuv), particularly if turnover times of long-lived carbon pools are N dependent. However, DGVMs suggest only a modest N-driven increase in the land carbon sink globally, reaching about 0.3 PgC yr-1 (Fig. 4a) [9,130,181,182](https://www.zotero.org/google-docs/?te40Yh).

Phosphorus (P) limitation can also have an important role for below-ground biomass [183](https://www.zotero.org/google-docs/?EVDt5I), especially in tropical biomes, where gains via CO2 fertilization may be substantially offset by nutrient limitation [184–186](https://www.zotero.org/google-docs/?3fHECi). However, this effect is still poorly constrained because P-poor soils are under-studied and few DGVM models incorporate the P cycle.

#### [H2] Light availability

Changes in the characteristics of light, such as the degree to which radiation is diffuse rather than direct, also contribute to changes in the land carbon sink[16](https://www.zotero.org/google-docs/?172G4k). Aerosol loading and increased cloudiness throughout the mid-20th century have led to less direct but more diffuse light [187](https://www.zotero.org/google-docs/?ECUNsk), or a global ‘dimming’ [16](https://www.zotero.org/google-docs/?phkcWW) . Anthropogenic aerosols have been reported to increase the global land sink by 0.14 PgC yr−1, or cumulatively 22.6 PgC, since 1850 [16](https://www.zotero.org/google-docs/?xzQinn). Including a diffuse light effect in a land surface model caused an increase in the net land carbon sink of ~0.4 PgC yr-1 because photosynthetic efficiency is higher in more diffuse light (Fig. 4a) [188,189](https://www.zotero.org/google-docs/?2kdh8t). Aerosol-induced cooling effects can also reduce respiration, especially in the tropics, and thereby increase the net land sink [190](https://www.zotero.org/google-docs/?XxCePM).

#### [H2] Land cover change and disturbance

Since 2000, global land use change is estimated to have decreased the net land sink by 1.2 PgC yr-1 (Fig. 4a) [191](https://www.zotero.org/google-docs/?ZpPPXY). Land use change emissions may have remained relatively flat [18](https://www.zotero.org/google-docs/?C5OKNh), declined [37](https://www.zotero.org/google-docs/?7z4BUl) or increased [53](https://www.zotero.org/google-docs/?82FKFj), depending on detection methodology, and thereby increasing or decreasing the net land carbon sink. Agricultural intensification and afforestation strongly contribute to greening trends in many parts of the world, particularly in India and China, which alone accounts for 25% of the global increase in LAI (Fig. 3) [49](https://www.zotero.org/google-docs/?23C67D). Afforestation in the United States increased soil organic carbon in mineral soils by 21% on average, with increases primarily reported in formerly industrial and wild lands [192](https://www.zotero.org/google-docs/?DtLQUf).

Disturbance events such as droughts and fires can both increase and decrease the land carbon sink. Initial declines in aboveground biomass following a disturbance, such as fire [193](https://www.zotero.org/google-docs/?IQMLCo), forest pathogen outbreaks [194](https://www.zotero.org/google-docs/?kkcSMP), or land clearing [195](https://www.zotero.org/google-docs/?mnGGnl), can lead to long-term gains in the net land carbon sink as systems regenerate [196](https://www.zotero.org/google-docs/?ZvsVax). These disturbances could also reverse the historic sink enhancement trend and result in net carbon releases to the atmosphere [14](https://www.zotero.org/google-docs/?19b5Bh), especially if extreme events recur faster than recovery times [197](https://www.zotero.org/google-docs/?etXJo8).

In regions where fire activity and fire-related emissions have been declining [198,199](https://www.zotero.org/google-docs/?yEdhGu), the carbon sink has increased, and vice versa [53,200](https://www.zotero.org/google-docs/?j49mf3). For example, fire suppression in the United States has resulted in an increased land carbon sink [201,202](https://www.zotero.org/google-docs/?JNpuYw). In Alaskan boreal forests, increased fire activity has counterintuitively led to an increased land carbon sink when burned stands are replaced with fast-growing and deciduous species [203,204](https://www.zotero.org/google-docs/?757BAo). Patterns like this could continue as fire increases in the future [204](https://www.zotero.org/google-docs/?PQzCbr), but the trend could also reverse toward increased carbon emissions with more severe and frequent burning [205,206](https://www.zotero.org/google-docs/?vVtIiU). Indeed, boreal forest fires emitted a record-breaking 0.48 PgC in 2021 (or 23% of global fire carbon emissions), concurrent with a major drought [207](https://www.zotero.org/google-docs/?SHQuo2). The unprecedented bushfires in Australia in 2019-2020 [208](https://www.zotero.org/google-docs/?b2LlUQ) released an estimated 0.715 PgC to the atmosphere. Recent increases in Australian forest megafires [209](https://www.zotero.org/google-docs/?KsI1EE) are part of a multi-decadal upward trend in burned area and frequency of fires driven by long-term warming [210](https://www.zotero.org/google-docs/?x9lvRw) , which have the potential to substantially diminish the land carbon sink.

#### [H2] Complex, coupled responses

CO2 fertilization and longer growing seasons under warming are increasing the land carbon sink (Figures 4 and 5) [2](https://www.zotero.org/google-docs/?jKc6J2). However, whether gains in plant growth will translate into an increased land carbon sink in the future remains debated for multiple reasons. First, enhanced growth in early life stages could cause trees to die sooner and be less resilient to disturbance events [94,211–213](https://www.zotero.org/google-docs/?Idz2XO). For example, a 50% increase in early growth was associated with a concurrent 23% decrease in lifespan for trees across the world [214](https://www.zotero.org/google-docs/?mRSy5j). Shorter tree lifespans could cause faster carbon turnover and reduced carbon pools in the soil. Second, observed enhancement of carbon fixation is potentially unrelated to carbon sink rates [111](https://www.zotero.org/google-docs/?rPK3oA), suggesting a mismatch between carbon fixation and long-term storage in woody tissue.

Several limiting factors can reduce the CO2 fertilization effect. Elevated CO2 can increase turnover rates of newly-assimilated soil carbon [215,216](https://www.zotero.org/google-docs/?zhhyLb), which can release CO2 and therefore offset any gains in the land carbon sink. Further, the increases in net ecosystem exchange resulting from CO2 fertilization [217](https://www.zotero.org/google-docs/?3E2M2o) are reduced by drought and other factors, particularly in the eastern Amazon, south Africa, and western Australia (Figures 4 and 5f).Low nutrient supply also can limit the CO2 fertilization effect [130,134,185,186,218–220](https://www.zotero.org/google-docs/?F0MYgd) because stoichiometric requirements constrain tissue formation and function. However, evidence also suggests increased belowground allocation and mycorrhizal associations under elevated CO2 [127,221](https://www.zotero.org/google-docs/?koX1fo), both of which can increase nutrient availability to plants [131,222](https://www.zotero.org/google-docs/?XfhqAV). Indeed, ectomycorrhizal-associated plant N uptake increased by 24% under elevated CO2 [223](https://www.zotero.org/google-docs/?TkvW4f). Finally, tradeoffs between above and belowground carbon storage under elevated CO2 could result in stable biomass with CO2 fertilization [133](https://www.zotero.org/google-docs/?Soaj4u). Unfortunately, many of these mechanisms are not represented in the current generation of DGVMs, due in part to a lack of robust empirical and theoretical understanding of these mechanisms [185](https://www.zotero.org/google-docs/?q7Zs3z).

Global change drivers influence plant growth in interactive ways. For example, N deposition can increase biomass [224](https://www.zotero.org/google-docs/?ieEAxm) while warming-induced droughts simultaneously cause increased mortality [94,211](https://www.zotero.org/google-docs/?Sio7QA). Elevated CO2 and water use efficiency can accelerate woody encroachment in semi-arid systems [69,225](https://www.zotero.org/google-docs/?i06iLP), yet growth can be constrained by water availability. Therefore, detecting ecosystem responses to these drivers is challenging, as many changes occur concurrently.

In addition, some processes can be counterintuitive. For example, lengthening of the growing season leads to a net release of carbon during autumn in high latitude ecosystems [226](https://www.zotero.org/google-docs/?16rhHB), but an increase in the net land carbon sink during autumn for mid-latitude ecosystems [99,147](https://www.zotero.org/google-docs/?89vf1d) owing to variation in the extent of temperature limitations on respiration in autumn. Positive impacts of warming on plant growth are expected in temperature-limited biomes, but negative impacts are expected where water is limiting [127](https://www.zotero.org/google-docs/?1Zhtsa). Coupled responses and confounding factors (such as the uncertainty regarding land use change emissions) make attribution and detection of an enhanced sink challenging, especially at the ecosystem scale. DGVMs are therefore helpful tools in delineating effects of individual drivers on the land carbon sink.

### [H1] Land carbon sink projections

The Coupled Climate Intercomparison Project (CMIP6) predicts an increasing sink under various emissions scenarios, albeit at a slower pace and reaching saturation in the second half of this century at high CO2 levels (Fig. 6). Low emissions scenarios such as Shared Socioeconomic Pathway (SSP) 2-4.5 predict declining land carbon sinks during the second half of the century in response to declining atmospheric CO2.This projected decline suggests that land carbon sink enhancement will only persist in response to high emissions, with warming offsetting some of the sink.

Predictions of the land carbon sink from DGVMs remain uncertain [227](https://www.zotero.org/google-docs/?o5kXn0), ranging from positive to negative trends depending on which processes are included [19,20](https://www.zotero.org/google-docs/?ydY62j). DGVMs often exclude important processes such as land cover change and fire disturbance [209,228](https://www.zotero.org/google-docs/?G03ojm) and misrepresent carbon allocation [133](https://www.zotero.org/google-docs/?qscumQ), which could dampen positive gains from the CO2 fertilization effect. Other factors omitted from some DGVMs include management, tree demographics, and nutrient cycling [213](https://www.zotero.org/google-docs/?3HAR3H). Including basic parameters related to N-cycling in DGVMs suggests a 50% smaller land carbon sink [20](https://www.zotero.org/google-docs/?E8EySd) relative to models that do not include N-cycling. However, there is insufficient information to accurately include processes such as nutrient mineralization, immobilization, fixation, and leaching in models. Together, these omissions together with differences in process implementation lead to a divergence in predictive performance between simulations of the historic period and future projections [229](https://www.zotero.org/google-docs/?yhZxFh).

The absolute effect of CO2 fertilization on long-term carbon sequestration[8](https://www.zotero.org/google-docs/?BaoUuA) and whether the enhanced CO2 sink will continue into the future as the climate changes [19](https://www.zotero.org/google-docs/?vdUPdi) (Fig. 6) remain uncertain [85,87](https://www.zotero.org/google-docs/?E8MHRG). Biomass accumulation can be decoupled from carbon source dynamics [111,112](https://www.zotero.org/google-docs/?p6AikT) and thus can have lower sensitivity to rising CO2 than that of photosynthesis. Even decade-long FACE experiments still do not confirm the longevity of responses to CO2 fertilization [230](https://www.zotero.org/google-docs/?FG9X6W). Some suggest a sustained enhancement of the plot-level carbon sink by 20-30% [231](https://www.zotero.org/google-docs/?3Mcx3d) while others show a diminishing or negligible response over time, particularly in grassland or arid sites [232–234](https://www.zotero.org/google-docs/?QoAm3x)[.](https://www.zotero.org/google-docs/?broken=N0yhZ2)

Increasing temperature could continue to enhance the land carbon sink in cold climates, but this effect is still uncertain and depends on the extent of offsets by concurrent carbon release. Warming of soils and permafrost will likely result in sizable carbon releases over the next century [235,236](https://www.zotero.org/google-docs/?ARAH0N), with a wide range of 3.1–41 PgC release per ˚C of warming by 2100 [4](https://www.zotero.org/google-docs/?DHbsTy). However, concurrent increases in carbon storage in plants could offset some or all of these releases [237](https://www.zotero.org/google-docs/?ZrwqDq). Even if warming increases the net land carbon sink in cold regions, the response could tip toward net releases if warming leads to higher vapor pressure deficits, drier soil, and more frequent extreme events and disturbances [160,162,238](https://www.zotero.org/google-docs/?IHTwm6). In tropical ecosystems, warming temperatures could exceed the optimum for, and therefore decrease, photosynthesis [142](https://www.zotero.org/google-docs/?oAudte). That said, resilience to future warming in tropical ecosystems has also been predicted [144,239–242](https://www.zotero.org/google-docs/?LkuO3j).

Future water availability remains uncertain globally [163,243–247](https://www.zotero.org/google-docs/?dvRAT6). A drier global future is expected at the continental scale, such as the western United States [169,248,249](https://www.zotero.org/google-docs/?fofz6s). However, other evidence suggests there will not be substantial decreases in water availability in the future [170,250](https://www.zotero.org/google-docs/?nHTSCC). The disagreement stems in part from alternate ways of quantifying drought severity [170,251](https://www.zotero.org/google-docs/?hakZ4R), as well as different methods for incorporating warming-induced elevation of atmospheric vapor pressure deficit and its effects on plant stress and mortality [160,252–254](https://www.zotero.org/google-docs/?vHuqJ9). In particular, the degree to which plant stomata close in response to elevated CO2, and thereby reduce evapotranspiration, is uncertain [156,255](https://www.zotero.org/google-docs/?QdEEjk), potentially leading to an overestimation of future ecosystem water demand [168](https://www.zotero.org/google-docs/?A2yzzq).

### [H1] Implications for natural climate solutions

Two-thirds of the Paris Agreement signatories pledged to use both natural and managed lands to offset CO2 emissions as a means of meeting climate agreements [256,257](https://www.zotero.org/google-docs/?91mOnt). Nature-based climate solutions (NbCS) represent a growing suite of strategies to increase land carbon storage and avoid greenhouse gas emissions through natural ecosystem management [258](https://www.zotero.org/google-docs/?IHq8VC). Examples of NbCS include reforestation, afforestation, ecological restoration, climate-smart commodity certification, and agricultural land management [259,260](https://www.zotero.org/google-docs/?I3t92q). NbCS can be designed to provide multiple co-benefits such as improved soil health, nutrient retention, biodiversity and drought resilience [261](https://www.zotero.org/google-docs/?8vQrsp). Generally, NbCS are likely to be the most beneficial in high productivity land like the tropics because they have high carbon density per unit area.

Estimates that take cost into account suggest that reforestation could increase the land sink by up to 8-13.8 Pg CO2 equivalents yr-1 (2.3-3.7 PgC yr-1) globally from 2020 to 2050 [260](https://www.zotero.org/google-docs/?4ih7tV). This value could even be underestimated if CO2 and climate effects continue to enhance the land sink (for example, ref. [22](https://www.zotero.org/google-docs/?oV4zu4)). However, the value could be overestimated if the impacts of disturbances or cost become large.

Reforestation, agroforestry, and reducing deforestation together have the potential to mitigate up to 20 Pg CO2 equivalents yr-1 (Fig. 7a)[260](https://www.zotero.org/google-docs/?7KFtMf). The major policy tool aimed at reforestation and reduced deforestation is carbon credits [22](https://www.zotero.org/google-docs/?njZSWu), which assign monetary value to carbon captured from, or emissions prevented to, the atmosphere. The general consensus is that protecting old-growth forests is optimal for carbon storage because existing forests, even when old, continue to act as net land carbon sinks and represent large stores of avoided emissions [78,81](https://www.zotero.org/google-docs/?spcffg).

However, there are potential downsides of NbCS projects, despite their potential to store carbon. First, the carbon sink in planted forests could be less persistent than primary forests owing to wind throw events and fire regimes [212,262–265](https://www.zotero.org/google-docs/?AdwRYk). Second, afforestation, reforestation and forest protection programs have been critiqued for worsening inequality in the Global South [266](https://www.zotero.org/google-docs/?1yLzdy), and carbon credit programs are liable to abet greenwashing. Gains from NbCS projects are also modest relative to current anthropogenic emissions of fossil carbon. On the whole, however, NbCS projects, when appropriately implemented at scale, are expected to increase the land carbon sink and slow the growth of atmospheric CO2.

As NbCS become more common, it is important to monitor and quantify their efficacy, especially in terms of carbon storage, as some interventions fail to increase the land carbon sink or decrease emissions long term (Fig. 7b). Current monitoring, measurement, reporting and verification methods, which rely primarily on extensive field measurements of biomass, do not fully leverage the wealth of ecological observations available for improved and scalable estimates, such as remote sensing or eddy covariance flux tower data [261](https://www.zotero.org/google-docs/?wm17kw). Projections of NbCS strategies also often do not adequately quantify the risks posed by climate change or the potential benefit due to CO2 fertilization [258](https://www.zotero.org/google-docs/?aBekM2) . The incorporation of forecasts from process-based models,which better estimate future carbon sequestration and suitability of proposed NbCS because they can simulate future scenarios of CO2, climate and nutrient availability, may overcome the limitations of current approaches. Beyond the efficacy in terms of carbon storage, NbCS must be cost-effective. Finally, stakeholder engagement throughout project development and deployment is essential to ensuring NbCS projects’ longevity and equity [267](https://www.zotero.org/google-docs/?zlazv9).

### [H1] Summary and future perspectives

There is strong support for an increased land carbon sink globally. Multiple lines of evidence indicate that the land biosphere sequesters roughly one third of the CO2 emitted annually by human activities, with a rate that has doubled from 1.2 ± 0.5 PgC yr-1 in the 1960s to 3.1 ± 0.6 PgC yr-1 in the 2010s [2](https://www.zotero.org/google-docs/?QMuVRw). Understanding the causes of the enhanced land sink is essential for evaluating the longevity of this important ecosystem service. Synthesis of the diverse lines of evidence presented here offers compelling, collective support for the existence of an enhanced land sink driven substantially by CO2 fertilization and, at high latitudes, reduced cold-limitation under elevated temperatures. However, uncertainties in monitoring and predicting the land carbon sink persist. Long-term ecosystem responses to changing climate, disturbance regimes, land use change, and nutrient cycling, for example, have large uncertainties at the global scale.

Major opportunities exist to advance understanding of whether the historic enhancement of the land sink will continue into the future and which processes will limit land sink enhancement [160,238](https://www.zotero.org/google-docs/?kvyHox).

A research priority is to determine the fate of the additional carbon being taken up by photosynthesis [137](https://www.zotero.org/google-docs/?NhLy3Q). To address this question, we advocate for a new generation of large-scale model-guided ecosystem manipulation experiments, similar to FACE experiments; these experiments should measure long-term ecosystem responses to elevated CO2 in combination with temperature, nutrient, and disturbance manipulations [246,268](https://www.zotero.org/google-docs/?TbsiWt). These approaches should be complemented by less expensive, simpler experiments regarding leaf-level photosynthesis and plant-level carbon allocation in controlled environments.

The role of nutrient limitation in constraining ecosystem responses to elevated CO2 is another area in critical need of investigation, particularly in the tropics (for example, NGEE-Tropics and Amazon-FACE) [185,186](https://www.zotero.org/google-docs/?MEplep). Ecosystem-level manipulation studies are recommended to address key unknowns, including the role of interactions with microbial communities and fungal associations [131,221](https://www.zotero.org/google-docs/?HxoNOC), flexibility in stoichiometry in phosphorus cycling [185](https://www.zotero.org/google-docs/?ZZ9KLl), and ability to alleviate phosphorous limitations [269](https://www.zotero.org/google-docs/?MaICae), especially in the context of elevated CO2 [130,131](https://www.zotero.org/google-docs/?wYPj2b). These experiments should also measure the effect of warming temperatures and nutrient availability on belowground carbon release [236,270](https://www.zotero.org/google-docs/?27e3B6).

Although DGVMs are currently an important means of modeling the land carbon sink, they have several known deficiencies which must be improved.In particular, they should be updated to account for altered competitive and successional dynamics driven by global environmental changes. Demographic models, such as the Functionally Assembled Terrestrial Ecosystem Simulator, are being developed to replicate competitive interactions of individuals at a global scale and better encapsulate changing disturbance regimes [239,271](https://www.zotero.org/google-docs/?SldThy). These efforts aim to improve predictive ability, although information with which to constrain important processes such as competition for light [272](https://www.zotero.org/google-docs/?pcO4sI), recruitment, and mortality is lacking at a global scale, undermining the reliability of model projections [273](https://www.zotero.org/google-docs/?o5zbFD). Initiatives focused on model benchmarking and functional response analyses, such as the ILAMB project [274,275](https://www.zotero.org/google-docs/?Tc46Dc), provide a rigorous system for assessing model efficacy, but efforts that use observations to directly inform predictive models within a data-assimilation framework [276](https://www.zotero.org/google-docs/?yC3xOl) are still needed. Such efforts would benefit from broader integration of the growing suite of satellite remote sensing observations relevant to the carbon cycle [45,277](https://www.zotero.org/google-docs/?HpqVcV).

Going forward, it is also important to sustain and expand several in-situ and remote observation networks, such as FLUXNET, Integrated Carbon Observation System (ICOS), Earth Observing Satellites, biometric inventories, and global CO2 station networks. These networks are essential for detecting and attributing changes in the land carbon sink and carbon stocks, with new insights with each additional year and decade of observations. The networks should be expanded to better represent under-sampled biomes and regions. Expanding the networks will allow for improved monitoring of disturbance events. Although it can be difficult to secure funding for these long-term investments, many of the most valuable insights have come from expensive, large-scale, coordinated activities. Comprehensive data integration efforts present fruitful opportunities [30](https://www.zotero.org/google-docs/?wkppTc), as do combinations of observations and models to interrogate hypotheses and develop holistic, predictive understanding [127,278,279](https://www.zotero.org/google-docs/?7BYgM3). Research using remote sensing advances, including in solar-induced fluorescence and vegetation optical depth, and increased temporal and spatial resolution, also will advance understanding of the carbon cycle at the global scale [45](https://www.zotero.org/google-docs/?0tFONq).

By improving on previous experimental designs, using advances in model-experiment integration, and leveraging novel technologies, we expect major advances will narrow the gap between theory and observation. These steps are crucial for understanding the magnitude and causes of an increasing land carbon sink and for projecting the future evolution of the Earth System.

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### Acknowledgements

SR acknowledges support from NASA FINESST grant No. 80NSSC22K1448. TFK acknowledges support from the RUBISCO SFA, which is sponsored by the Regional and Global Model Analysis (RGMA) Program in the Climate and Environmental Sciences Division (CESD) of the Office of Biological and Environmental Research (BER) in the U.S. Department of Energy (DOE) Office of Science, a DOE Early Career Research Program award #DE-SC0021023, a NASA Carbon Cycle Science Awards 80NSSC21K1705 and 80NSSC20K1801, and the LEMONTREE (Land Ecosystem Models based On New Theory, obseRvations and ExperimEnts) project, funded through the generosity of Eric and Wendy Schmidt through the Schmidt Futures programme. JGC thanks the support of the Australian National Environmental Science Program - Climate Systems Hub. AB was funded by the European Union (ERC StG, ForExD, grant agreement No. 101039567). Views and opinions expressed are, however, those of the authors only and do not necessarily reflect those of the European Union or the ERC; neither the European Union nor the granting authority can be held responsible.

**Author contributions**: TK and CW conceived of the review and wrote the first draft. SR developed the manuscript with input from TK and CW. SR generated the figures. YZ and XL contributed figure data. AB, JGC, ICP, SS, and CT contributed to writing and made substantial contributions to the discussion of content.

**Competing interests**: The authors declare no conflicts of interest.

**Data Availability**

Global Carbon Project data can be accessed at <https://www.globalcarbonproject.org/carbonbudget/>. Data for atmospheric inversion modeling (RECCAP-2) is available at [https://climate.esa.int/en/projects/reccap-2](https://climate.esa.int/en/projects/reccap-2/about/)**.** CMIP-6 data is available at <https://esgf-node.llnl.gov/projects/cmip6/>. CRU temperature and precipitation data are available at https://crudata.uea.ac.uk/cru/data/hrg/.

**Peer review information**

***Nature Reviews Earth & Environment* thanks [Referee#1 name], [Referee#2 name] and the other, anonymous, reviewer(s) for their contribution to the peer review of this work.**

**Publisher's note**

**Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.**

**Supplementary information**

**Supplementary information is available for this paper at https://doi.org/10.1038/s415XX-XXX-XXXX-X**

### Table 1: | Evidence of an enhanced land carbon sink from multiple methods.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Method** | **Spatial scale** | **Time scale** | **Observed trend** | **Estimate** | **Certainty \* (1-10)** | **Citations** |
| Yearly atmospheric observations | Global | 1960s-present | Increasing | 25-30% of anthropogenic CO2 emissions | 10 | [4,24,25](https://www.zotero.org/google-docs/?K6CpA8) |
| Atmospheric inversions | Global | 1990s-present | Increasing | 0.1-0.2 PgC yr-1 increase from 1992-2013\* | 5 | 35,44,45 |
| DGVM output | Global | 1800s-present | Increasing | 1.2 ± 0.5 GtC yr-1 (1960s) to 3.1 ± 0.6 GtC yr-1 (2010s)\*\* | 5 | [2](https://www.zotero.org/google-docs/?OyPVsA) |
| Satellite observations | Global,continental, biome | 1981-present | Widespread greening | Global 0.8% mean LAI increase yr-1; increasing across 52-59% of global vegetated lands | 6 | [47,50,107](https://www.zotero.org/google-docs/?xOtv1C) |
| Seasonal atmospheric observations | Zonal | 1960s-present | Increased seasonal cycle in northern hemisphere | 30-50% increase in the seasonal cycle since 1960s, with a 0.6 ± 0.5 PgC yr-1 (2000s) summer uptake | 8 | [25,67,68](https://www.zotero.org/google-docs/?QuMqS9) |
| Biomass plots | Ecosystem | 1960s-present | Increased growth and mortality | 0.45 ± 0.12 MgC ha-1 yr-1 in the tropics | 9 | [77,78,82](https://www.zotero.org/google-docs/?Dkh1vm) |
| Eddy covariance flux towers | Ecosystem | 1990-present | Increased C uptake | Global LUE model suggests 0.46 ± 0.09 PgC yr-1 trend (1982-2016) | 7 | [103,104](https://www.zotero.org/google-docs/?MgwZbE) |
| Tree rings | Individual | 1600s-present | Increased growth rates | Up to 0.7% yr-1 increase since 1935 | 8 | [84](https://www.zotero.org/google-docs/?XAnupr) |

\* Certainty scores represent ranking from 1 (low certainty) to 10 (high certainty) of land carbon sink estimates, based on the rigor and establishment of the method used.

\*\*Atmospheric inversion models include fire and land use change in estimating the land carbon sink. DGVM output depends on the modeling protocol and how land use change and disturbance are parameterized.

### Figure legends

**Figure 1 | Historic enhancement of the land carbon sink and effects on atmospheric CO2.**

Estimates of global annual land carbon sink using various observational and modelling approaches: the ensemble mean of 6 atmospheric inversion models [280](https://www.zotero.org/google-docs/?ytHMzr) (thin blue line); the ensemble mean of 13 Dynamic Global Vegetation Models (DGVMs) [2](https://www.zotero.org/google-docs/?wyVnd2) (thin red line); estimates from atmospheric CO2 and δ13C [34](https://www.zotero.org/google-docs/?6sTbtT) (thin brown line), calculated by adding net land sink estimates to historic land use emissions estimates from the Global Carbon Project [2](https://www.zotero.org/google-docs/?NpnOlV); and the average of these approaches with a loess regression line (thick black line). Shading represents ± 1 standard deviation across the models, and thick blue, red and brown lines the loess regression line for atmospheric inversion, DGVM and δ13C approaches, respectively. Historical terrestrial sink from CMIP6 [281](https://www.zotero.org/google-docs/?zUzq4V) are depicted as black dots. The two grey lines and the right y-axis demonstrate the relative impact of these land carbon sink estimates on atmospheric CO2 concentration; theoretical atmospheric CO2 concentrations in the absence of the land carbon sink (dashed grey line) are calculated by detrending the mean land sink estimates (black line) and adding the residual carbon to the observed atmospheric CO2 concentrations (solid grey line). Observed atmospheric CO2 concentration in 2020 is approximately 100 ppm lower than would be expected given historic anthropogenic emissions.

**Figure 2 | Global changes in vegetation cover.** **a**| Percent change in annual maximum leaf area index (LAI) [107](https://www.zotero.org/google-docs/?oLxDjc) over 1982-2016 from Global Land Surface Satellite (GLASS) [282](https://www.zotero.org/google-docs/?ic0lBd). **b**| As in a, but for Leaf Area Index (third generation) (LAI3g) [283](https://www.zotero.org/google-docs/?qjbIpY). **c**| as in a, but for**]** terrestrial climate data record (TCDR) [284](https://www.zotero.org/google-docs/?8EDt1G). **d**| The mean of LAI changes from GLASS, LAI3g and TCDR. **e**| the standard deviation of LAI changes across the 3 products. Significant increases in LAI have been observed globally, particularly in the northern latitudes, with higher uncertainty in the tropics.

**Figure 3 | Changes to the land carbon sink. a|** schematic representation of the processes enhancing the land carbon sink by stimulating biomass growth and supporting either larger trees or more individuals. **b**| the processes limiting the net land carbon sink by supporting fewer, smaller individuals. The past, present and future of the land carbon sink is determined by the combined result of enhancing and limiting processes.

**Figure 4 |** **Global and continental carbon flux responses over the 21st century**. **a|** DGVM-derived [285](https://www.zotero.org/google-docs/?imzRCZ) published estimates of the change in net ecosystem exchange flux aggregated to the continental and global scale between 1901-1920 and 2001-2019 related to different forcings: CO2 [285](https://www.zotero.org/google-docs/?Z4FsEs), light (PAR, photosynthetically active radiation, both diffuse and direct) [188](https://www.zotero.org/google-docs/?ks1cCF), nitrogen addition and deposition (N) [286](https://www.zotero.org/google-docs/?RgKXip), ozone (O3) [287](https://www.zotero.org/google-docs/?y3T5O7), climate [285](https://www.zotero.org/google-docs/?pOYmJr), land use change (LUC) [191](https://www.zotero.org/google-docs/?WsHoQ8), and their sum (total). Boxes show interquartile range and median, with whiskers representing the range of values from all model simulations. . **b|** as in a, but for Africa. **c|** as in a, but for Asia. **d|** as in a, but for Europe. **e|** as in a, but for North America. **f|** as in a, but for Oceania. **g|** as in a, but for South America.The CO2 fertilization effect has been the primary driver increasing land carbon sink at the global and continental scales.

**Figure 5 |** **Spatial patterns in** **carbon flux responses to CO2 and climate change.** a| DGVM-derived[285](https://www.zotero.org/google-docs/?WVjzC2) estimates of the extent of climate forcing of net ecosystem exchange. b| Per-grid cell climate forcing as a function of mean annual temperature and precipitation [288](https://www.zotero.org/google-docs/?4uHbs8). c| and d | as in a and b, but for CO2 forcing. e| and f| as in a and b, but for the additive forcing of climate and CO2. The land carbon sink has increased globally, with climate forcings offsetting some of the gains from the CO2 fertilization effect.

**Figure 6 | Historical and future projections of the land carbon sink.** Multi-model mean changes in net biome productivity **[G]**, which represents net ecosystem exchange aggregated over a large spatial and temporal extent and includes disturbance and land use change, of terrestrial ecosystems from 8 Coupled Model Intercomparison Project (CMIP6) models under historical (black) and shared socioeconomic pathways (SSP; coloured) scenarios. CMIP6 models include NorESM2-MM, MPI-ESM1-2-LR, IPSL-CM6A-LR, INM-CM5-0, ESM1-2-LR, CESM2, CanESM5, and MIROC-ES2L [289](https://www.zotero.org/google-docs/?ttDLUv). Thin lines indicate yearly average between all model simulations, with shading representing ± 1 standard deviation across models. Thick lines represent loess smooths of mean yearly values. The vertical dashed line represents the transition from historical observations to future projections. The land carbon sink is projected to continue to increase until at least 2040, with different emission scenarios determining when a saturating point will be reached.

**Figure 7 | Carbon emission mitigation potential on land. a**| Carbon mitigation potential of nature-based climate solutions (NbCS) by geographic area. Y-axis labels denote various strategies, grouped into broader categories of (for example, protecting existing carbon resources vs. restoring previously degraded resources) [260](https://www.zotero.org/google-docs/?yHZGtV). **b**| Theoretical projections of NbCS. Enhanced carbon storage relative to baseline situations (red) may enhance the land carbon sink (blue) or reduce carbon emissions (brown) via non-saturating, saturating or non-additional NbCS. The amount of additional carbon captured (thick blue arrows) or emissions avoided (thick brown arrows) relative to baseline conditions (thick red arrows) by the enhanced land carbon sink varies over time, with non-additional NbCS potentially resulting in little or no long-term land carbon sink gains.NbCS could substantially increase the land carbon sink, although their longevity remains in question; NbCS will require careful study and diligent oversight to offset anthropogenic CO2 emissions long term.

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### Glossary

|  |  |
| --- | --- |
| CO2 atmospheric growth rate | The difference in atmospheric CO2 concentration between the start and end of each year, representing the sum of all CO2 fluxes into and out of the atmosphere by both natural and human processes |
| Carbon flux | The quantity of carbon exchanged between carbon stocks (on land or in the ocean) and the atmosphere over a specific area and time period. Here, carbon flux is positive when uptake occurs in the land or ocean carbon sinks |
| Land carbon sink | This term is used when applicable to both the net and natural land carbon sinks |
| Net land carbon sink | The balance of carbon leaving and entering the terrestrial biosphere through all pathways |
| Natural land carbon sink | Net carbon sequestered by terrestrial ecosystems independent of direct anthropogenic interventions such as land use and land use change (or net primary productivity minus heterotrophic respiration and other natural C losses to the atmosphere like fire, VOCs, and others.) |
| Airborne fraction | The long-term fate of anthropogenic CO2 emissions that remain in the atmosphere (not taken up by the land or oceanic sinks)  |
| Residual land sink | The calculated global land carbon sink after accounting for atmospheric growth rate, ocean sink, and land use change emissions  |
| CO2 fertilization | The stimulation of both photosynthetic light and water use efficiency by rising atmospheric CO2 concentrations, the response to which can be an increase in photosynthesis and/or a decrease in leaf-level water use |
| Net ecosystem exchange | Gross primary productivity – ecosystem respiration. This quantity can be positive or negative. |
| Net biome productivity | Net ecosystem exchange over a large spatial and temporal extent, including disturbance and management effects |

### Table of Contents summary

The terrestrial biosphere stores carbon in a land carbon sink, offsetting emissions of carbon into the atmosphere. This Review demonstrates that the magnitude of the land carbon sink has increased over time, but that its stability in the future is less clear and depends on effective implementation of nature-based solutions.

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