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Emerging climate impact on carbon sinks in a consolidated carbon budget

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Abstract

Despite the adoption of the Paris Agreement ten years ago, fossil CO_2 emissions continue to rise, pushing atmospheric CO_2 levels to 423 ppm in 2024 and driving human-induced warming to 1.36°C, within years of breaching the 1.5°C limit [1,2]. Accurate reporting of anthropogenic and natural CO_2 sources and sinks is a prerequisite to tracking the effectiveness of climate policy and detecting carbon sink responses to climate change. Yet notable mismatches between reported emissions and sinks have so far prevented confident interpretation of their trends and drivers [1]. Here, we present and integrate recent advances in observations and process understanding to address some long-standing issues in the global carbon budget estimates. We show that the magnitude of the natural land sink is substantially smaller than previously estimated, while net emissions from anthropogenic land-use change are revised upwards [1]. The ocean sink is 15% larger than the land sink, consistent with new evidence from oceanic and atmospheric observations [3,4]. Climate change reduces the efficiency of the sinks, particularly on land, contributing 8.3 ± 1.4 ppm to the atmospheric CO_2 increase since 1960. The combined effects of climate change and deforestation turn Southeast Asian and large parts of South American tropical forests from CO_2 sinks to sources. This underscores the need to halt deforestation and limit warming to prevent further loss of carbon stored on land. Improved confidence in assessments of CO_2 sources and sinks is fundamental for effective climate policy.

The increase in atmospheric CO_2 concentration has been systematically monitored since the late 1950s, marking the beginning of comprehensive research into the global carbon cycle[5]. It soon became evident that the observed increase in atmospheric CO_2 was smaller than the CO_2 emissions from burning fossil fuels, indicating that terrestrial ecosystems and/or the ocean acted as carbon sinks [6]. Until the late 1980s, it was believed that the ocean was the main sink of carbon, while the role of land ecosystems was unclear and was often referred to as the "missing sink" [7]. The presence of a large CO_2 sink on land was confirmed later on, supported by field studies [8], biomass inventories [9] or vegetation modelling [10]. Over the last 20 years, our understanding of the global carbon cycle has rapidly improved, supported by the annual assessments of the global carbon budget (GCB) activity of the Global Carbon Project. This activity has enabled continuous community review of the anthropogenic perturbation on the global carbon cycle [1,11]. The GCB assessments are widely used in science and policy, including in the latest assessment of the Intergovernmental Panel on Climate Change (IPCC)[12].

The carbon balance among individual components of the global carbon cycle provides a rigorous test of our understanding of the carbon cycle: mass conservation implies that estimated net emissions from fossil (E_{FOS}) and land-use change (E_{LUC}) and uptake by the ocean and land sinks (S_{OCEAN} and S_{LAND}) must balance the observation-based atmospheric CO_2 growth rate G_{ATM} perfectly. This has not been the case throughout the history of the GCB reports, including in the latest 2024 update[13] (hereafter GCB2024). GCB2024 reported a budget imbalance (B_{IM}; $B_{IM} = E_{FOS} + E_{LUC} - S_{LAND} - S_{OCEAN} - G_{ATM}$) over the last decade of -0.4 ± 1.4 GtC/yr, which is about 10% of the observation-based atmospheric CO_2 growth rate. Despite its large uncertainty, the negative B_{IM} implies that estimated sources were too low and/or estimated sinks too large. Over the last 65 years, the B_{IM} also showed a negative trend of -0.14 ± 0.04 GtC/yr per decade, statistically significant at the 1% level (p-value=0.003), with a positive B_{IM} in the early part of the record and a negative B_{IM} in the most recent years (Extended Data Fig. 1).

A statistically significant trend in the B_{IM} impedes robust interpretation of trends in individual components of the global carbon budget. Hence, reducing the magnitude and trend of the B_{IM} is a prerequisite to reliably assessing temporal changes in the strength of the carbon sinks. Here, we present and integrate recent advances in observations and process understanding to improve our estimates of components of the global carbon budget, with direct impact on the magnitude and trend of the B_{IM}. These improvements allow a more robust assessment of the human interference on the global carbon cycle over the past 65 years, and of the emerging impacts of climate change on the evolution of the carbon sinks.

Introducing the latest evidence

The net land-use change CO_2 emissions (E_{LUC}) assessed in the GCB are derived from bookkeeping models forced by reported changes in land use. Most bookkeeping models assume that land-cover types, such as forest or pasture, have distinct but static equilibrium carbon densities (i.e., amount of carbon per unit area of a full-grown ecosystem) [13]. This assumption allows to isolate the direct land-use impact (e.g., due to deforestation, afforestation) from indirect human-induced effects on vegetation [14,15] such as higher global biomass and higher soil carbon densities due to environmental effects (e.g., due to atmospheric CO_2 increase) [16]. However, neglecting the effects of environmental changes in E_{LUC} estimates results in an underestimation of the historical E_{LUC} trend [16,17]. To address this issue, we replaced the static carbon densities used in bookkeeping models by transient values informed by dynamic global vegetation models (DGVMs) derived carbon dynamics [17,18] (see Methods). Accounting for transient carbon densities leads to an increase in net E_{LUC} of 0.11 ± 0.04 GtC/yr over the last decade, and additional emissions of 3.0 ± 1.0 GtC since 1960 (Fig. 1a and Extended Data Fig. 2b).

The land CO_2 sink (S_{LAND}) is estimated in GCB from DGVMs using historical simulations that assume a constant pre-industrial land cover. In doing so, the models do not double account for CO_2 fluxes associated with land-cover changes from anthropogenic land use, which are already included in E_{LUC}. However, given the historical reduction in forest cover and expansion of agriculture, assuming a pre-industrial land cover leads to an overestimation of the land sink [17–20]. This is a known bias now referred to as the Replaced Sinks and Sources (RSS) [17,19,21]. To address this issue, we developed a new correction method using outputs from the DGVMs that resolve net land-atmosphere carbon fluxes at the plant functional type level (see Methods). Accounting for evolving land-cover change leads to a decrease of the mean S_{LAND} by 0.5 ± 0.3 GtC/yr over the last decade, and a decrease of 21 GtC since 1960 (Fig. 1b and Extended Data Fig. 3d).

The land and ocean CO_2 sinks in the GCB account for the lateral carbon export (LCE) from land ecosystems to inland waters, coastal environments, and the open ocean using natural (pre-industrial) estimates of 0.65 ± 0.30 GtC/yr [22,23] but neglecting its anthropogenic perturbation. Recent advances in understanding aquatic carbon cycle processes indicate an increase in carbon exported from terrestrial ecosystems to the aquatic environment, with an increased outgassing of CO_2 from these aquatic systems to the atmosphere, increased carbon storage in aquatic sediments and export to the ocean [24,25] (see Methods). Accounting for the anthropogenic perturbation of LCE leads to a decrease of the mean S_{LAND} by 0.07 ± 0.06 GtC/yr over the last decade (Fig. 1b and Extended Data Fig. 3).

The ocean CO_2 sink in the GCB combines independent estimates from data products based on observations (fCO_2-products) [26,27] as well as global ocean biogeochemical models (GOBMs). fCO_2-products and GOBMs broadly agree on ocean sink trends and variability, with remaining differences mostly explained by limited data and seasonal biased sampling causing overestimation in decadal trends of fCO_2-products, and possible GOBM underestimation of decadal variability [28], especially in the Southern Ocean [29–31]. However, fCO_2-products suggest a substantially larger ocean sink than GOBMs (3.1 ± 0.3 GtC/yr versus 2.6 ± 0.4 GtC/yr, respectively, over 2014-2023), which is also supported by independent constraints derived from atmospheric CO_2 and oxygen observations [3] as well as ocean interior observations [4]. Multiple model evaluation efforts have now shown that GOBMs underestimate the mean oceanic sink in the order of 10%, based on evidence of too weak overturning circulation [32], ocean interior constraints [33], and biases arising from spin-up strategies [34]. In parallel, estimates from fCO_2-products could also be biased low because they do not account for temperature gradients between the measurement depth, usually several meters below surface, and the surface skin layer where the gas exchange takes place [35–37]. Accounting for the GOBMs bias and for skin temperatures and warm layer in fCO_2-products leads to an increased S_{OCEAN} of 0.2 ± 0.23 GtC/yr over the last decade, and an increase of 11 ± 14 GtC since 1960 (Fig. 1c and Extended Data Fig. 2c).

Fossil CO_2 emissions (E_{FOS}) include the oxidation of fossil fuels from combustion, chemical reactions, decomposition of fossil carbonates, and the CO_2 uptake from the cement carbonation [1]. The GCB estimate of E_{FOS} (9.7 ± 0.5 GtC/yr for the 2014-2023 period) is a composite of different datasets, aimed to give the best emission estimate and reduce biases. The differences between independent datasets are well understood, with the range between different datasets around 5% and with all showing similar trends [38]. E_{FOS} misses minor emission sources in some developing countries for decomposition of some carbonates, estimated to be <0.5% of the global total. The cement carbonation sink is probably the most poorly constrained element of E_{FOS}, but at 0.2 GtC/yr in recent years, the contribution to E_{FOS} uncertainty is small. Hence, we do not have any compelling reason to suspect a substantial bias in global E_{FOS} mean or trend that would require a correction in this study.

The atmospheric CO_2 growth rate (G_{ATM}) in GCB is based on marine boundary layer CO_2 mole fraction observations (in ppm/yr), which have only a small measurement uncertainty [39]. These measurements are subsequently converted to mass growth rates in GtC/yr using a conversion factor (CF), which so far has been assumed to be a constant value of 2.124 GtC/ppm, without associated uncertainty [40]. However, the surface fluxes that lead to changes in atmospheric mole fractions are not instantaneously observed at the surface stations, given that atmospheric mixing takes time. The surface network is also not fully representative of the whole atmosphere [41]. Any variability and uncertainty in CF would propagate into the estimated annual CO_2 growth rate (G_{ATM}) and its uncertainty. Here we quantify the annual CF values and their uncertainties using the atmospheric inversions from the GCB (see Methods). In Extended Data Fig. 4, we show these CFs and the resulting uncertainty on G_{ATM} and the B_{IM}. Including annually varying CFs would mainly reduce the variability of the B_{IM} (up to 40%) but has no effect on its mean or trend. This interannual effect of CF will be further evaluated and considered for inclusion in future GCB assessments.

Consolidating the global carbon budget

The inclusion of known missing processes and the associated corrections on E_{LUC}, S_{LAND} and S_{OCEAN} in the GCB2024 estimate [1] results in a consolidated global carbon budget (Table 1, see also Extended Data Table 1 and 2). The revised estimate of E_{LUC}, when accounting for transient carbon densities, is 1.2 ± 0.7 GtC/yr for the last decade (2014-2023). Although the correction increases land-use change emissions with time, the statistically significant decline in E_{LUC} of 0.2GtC/decade since the late 1990s, as identified in GCB2024, remains (p-value<0.001). About

75% of the 0.11 ± 0.04 GtC/yr increase in E_{LUC} is due to larger net land-use change emissions in South America, Southeast Asia, and Africa. Note that while the net effect of anthropogenic land-use change is a source of CO_2 to the atmosphere, parts of the world including North America, Europe, and China are currently net carbon sinks from land-use change. Total global anthropogenic net CO_2 emissions (E_{FOS}+E_{LUC}) increased until the 2000s but remained relatively constant after 2010 at around 11 GtC/yr.

S_{LAND} is substantially reduced when accounting for evolving land-cover change and for the increase in terrestrial carbon outgassed by inland waters. The revised mean land sink is 2.7 ± 0.9 GtC/yr over 2014-2023 (Fig. 1b, Table 1). As a result, the revised net land CO_2 flux (S_{LAND} - E_{LUC}) is reduced by 31% from a sink of 2.1 ± 1.1 GtC/yr to a sink of 1.4 ± 1.1 GtC/yr (Table 1). Conversely, the revised ocean CO_2 sink is increased by 8% when accounting for the effect of warm layer and cool skin on ocean fCO_2 products and correcting for the known GOBMs bias, reaching 3.1 ± 0.5 GtC/yr over the past decade (Fig. 1c, Table 1). As a result of these revisions, the ocean sink is about 15% larger than the land sink while it was 10% lower in GCB2024 (Table 1), although these differences remain within the uncertainty bounds of both fluxes.

The corrections applied to E_{LUC}, S_{LAND} and S_{OCEAN} are each within the uncertainty of the initial estimates, hence the revised estimates are not statistically significantly different from the GCB2024 estimates (Table 1). However, the corrections applied here are based on known biogeochemical processes, which have not been considered in the GCB estimates so far. Furthermore, high confidence can be placed on the sign of each of these corrections: assuming constant vegetation densities leads to an underestimation of E_{LUC}, assuming pre-industrial land cover leads to an overestimation of S_{LAND}, ignoring historical increase in lateral carbon export also leads to an overestimation of S_{LAND}, and neglecting the ocean cool skin effect leads to an underestimation of S_{OCEAN}. Hence the revised estimate of E_{LUC}, S_{LAND} and S_{OCEAN} represents an improvement in their representation in the global carbon budget. Furthermore, the revised budget, with a smaller net land CO_2 (1.4 ± 1.2 GtC/yr) and a larger ocean sink (3.1 ± 0.5 GtC/yr), is fully consistent with the estimates from atmospheric inversions (1.4 ± 0.5 GtC/yr and 3.1 ± 0.5 GtC/yr for the net land flux and the ocean sink, respectively), and with estimates derived from atmospheric O_2 observations (1.0 ± 0.8 GtC/yr and 3.4 ± 0.5 GtC/yr, respectively)

(Table 1) [1,3,42]. The convergence of these independent estimates gives stronger confidence that this revised budget provides more robust estimates compared to GCB2024.

The budget imbalance, which was -0.4 ± 1.3 GtC/yr over 2014-2023 in GCB2024, is reduced to near zero (-0.1 ± 1.3 GtC/yr) (Fig. 1d, Table 1), although it is not statistically significantly different from the GCB2024 estimate. Finally, the statistically significant negative trend in the B_{IM} over the last 65 years of -0.14 ± 0.04 GtC/decade (p-value= 0.003) in the GCB2024 estimate is now reduced to a non-significant trend of -0.06 ± 0.04 GtC/decade (p-value= 0.14), adding confidence in the revised estimate of the global carbon budget presented here (Extended Data Fig. 2f).

Influence of climate change

With virtually no imbalance, the consolidated global carbon budget provides a basis for analysing the long-term evolution of the land and ocean sinks and their role in mitigating the atmospheric CO_2 increase due to anthropogenic CO_2 emissions. Climate change is widely expected to cause a reduction of CO_2-induced land and ocean carbon sinks (relative to a theoretical case with the same atmospheric CO_2 increase but no climate change) [12,43,44]. Using additional historical simulations of GOBMs and DGVMs driven by the observed atmospheric CO_2 increase but under a constant climate forcing (see Methods), we estimate that the effect of climate change has reduced the land and ocean sinks by 0.8 ± 0.9 GtC/yr (-23%) and 0.18 ± 0.1 GtC/yr (-6%), respectively over the last decade (Fig. 2a,b and Fig. 3), with tropical regions accounting for the largest effect on land (Fig. 4). The cumulative reduction in the land and ocean sinks combined amounts to 30 ± 6 GtC (29 ± 6 GtC and 2 ± 1 GtC, respectively) since 1960, implying that the carbon-climate feedback has already contributed 8.3 ± 1.4 ppm (8%) to the rise in atmospheric CO_2 concentration (Fig. 2c).

The net land CO_2 flux can be decomposed in three contributions: the response to atmospheric CO_2 increase, the response to climate change (e.g., temperature, rainfall), and land-use change (Extended Data Fig. 5). Over the decade of 2014-2023, the atmospheric CO_2 increase induced a 3.6 ± 1 GtC/yr sink, while the effect of climate and land-use change led to a source of 0.9 ± 0.6 GtC/yr and 1.2 ± 0.7 GtC/yr, respectively, bringing the net land CO_2 flux to a sink of 1.4 ± 1.2

GtC/yr. The combined effect of climate change and land-use change is largest in the tropics. While deforestation is the main driver of carbon losses in Africa and South-East Asia, climate impacts on ecosystems are the dominant causes of carbon losses in South America (Fig. 4), in line with observational evidence [45,46]. Our findings reinforce the need to halt deforestation and to mitigate climate change to prevent an increasingly larger fraction of the terrestrial biosphere from becoming a source of CO_2.

Implications

Recent advances in observations and understanding implemented here within the GCB have contributed to addressing some of the long-standing issues and improving coherence between bottom-up estimates from DGVMs and GOBMs and top-down estimates based on atmospheric CO_2 inversions and O_2 observations. Important uncertainties remain, as reflected by the large interannual variability still present in the B_{IM}, and global agreement between bottom-up and top-down estimates could still be due to compensating errors in critical processes in components of the global carbon budget. Further improvements are required in several areas, including on the estimates of carbon losses from land degradation; the understanding of the long-term impact of fires on carbon storage; the representation of small-scale physical processes in GOBMs; the understanding of the variability of the biological ocean carbon pump; the Southern Ocean observational coverage for better fCO_2-product representation; and the reconciliation of bottom-up and top-down estimates at the regional level. Delivering on those issues hinges on continued monitoring of atmospheric and surface ocean CO_2 levels, which are fundamental to carbon cycle research. Maintaining regular assessments of the sources and sinks of CO_2 and integrating the latest understanding will facilitate monitoring changes in the natural carbon cycle and lead to more informed and effective decisions.

Methods

Land-use change emissions. Transient carbon densities correction (δL)

In the GCB, E_{LUC} is estimated based on four bookkeeping models driven by historical land-use change data. All but one of the bookkeeping models (OSCAR, see below) use static equilibrium carbon density values for vegetation and soil from various sources, representative of "present-day" carbon densities. The OSCAR bookkeeping model does not require any adjustment as it already endogenously simulates changes in biome carbon densities under environmental changes, in parallel to the bookkeeping calculation of E_{LUC} [18,47]. Although not used in GCB2024, the BLUE bookkeeping model also offers alternative E_{LUC} estimates based on transient carbon densities [17]. To adjust for δL in BLUE, the static equilibrium carbon densities are converted into transient densities based on the carbon density evolution from DGVMs from the GCB (under simulations with transient environmental changes but constant land cover, termed S2, see below). Transient biomass carbon densities are derived based on twelve DGVMs and transient soil carbon densities based on seven DGVMs providing the necessary providing the necessary plant functional type (PFT)-level output.

For the other two bookkeeping models that use static carbon densities in GCB2024 (H&C23 and LUCE), the E_{LUC} estimates under transient carbon densities are derived by scaling their E_{LUC} values with the average ratio of ELUC with transient densities to E_{LUC} with static densities estimated from OSCAR and from BLUE. Scaling is done individually for each of the following E_{LUC} sub-components: total deforestation, total forest (re-)growth, gross sources from wood harvest, gross sinks from wood harvest, and other transitions. The resulting component-wise E_{LUC} with transient densities estimates are then summed to obtain the net E_{LUC} estimate for H&C23 and for LUCE. The uncertainty on δL is estimated based on uncertainty estimates from BLUE and OSCAR. For BLUE, we estimate the δL uncertainty (one standard deviation) across the estimates from the seven DGVMs providing PFT-level output for soil and vegetation carbon [17]. For OSCAR, the δL uncertainty is estimated as weighted standard deviation [18]. The δL uncertainty for H&C23 and LUCE is derived as the average relative uncertainty of BLUE and OSCAR. The final δL uncertainty is estimated using a random-effects model considering both the uncertainty estimates of each model and the variability of δL estimates across bookkeeping models. The transient carbon densities correction (δL) leads to an increase in E_{LUC} of 0.11 ± 0.04 GtC/yr for the last decade.

Land sink. Replaced sinks and sources correction (RSS)

In the GCB, the natural land sink (S_{LAND}) is estimated using simulations from an ensemble of DGVMs that follow a common experimental protocol. Each model performs several simulations in order to isolate drivers of changes in land carbon fluxes. S_{LAND} is estimated with the "S2" simulation, where atmospheric CO_2 and climate vary over time, but land cover is held at pre-industrial (year 1700) levels. This setup is designed to isolate the direct effects of rising CO_2, climate change, and nitrogen deposition on land carbon uptake, while excluding effects of direct human-driven land-use change. These latter are calculated separately in the E_{LUC} flux estimated with the bookkeeping models. Because land cover is fixed at pre-industrial levels, these S2 simulations represent the response of the land surface to rising atmospheric CO_2, nitrogen deposition, and changes in climate with too much forest cover globally (as forest area has decreased by about 20% since 1700). As carbon sinks in forests are typically larger than in other ecosystems, the S_{LAND} term is overestimated. This issue is known as the replaced sinks and sources (RSS) [17,19] (in some publications also called the loss of sink capacity [21]). To address this issue, a recent study [48] developed a correction method that adjusts the S_{LAND} estimate to reflect the actual historical land cover distribution while still excluding carbon fluxes associated with direct human influences on land cover (e.g., from deforestation, af/reforestation). The method uses a subset of seven DGVMs that simulate net biome production (NBP) at the PFT level and include separate soil and litter carbon pools for each PFT. These models provide outputs from both the S2 simulation and the S3 simulation (varying CO_2, climate, and land use/cover). We extract the PFT-level NBP from the S2 simulation and combine it with the time-varying land cover fractions from S3. This allows us to reconstruct a corrected NBP flux that reflects how the land system would respond to CO_2 and climate under the actual, changing land cover, while excluding anthropogenic land-use change emissions and sinks. We then compute the bias as the difference between the original S_{LAND} (from the S2 simulation) and the reconstructed, land-cover-corrected S_{LAND}. The global correction is derived by summing grid cell-level biases across the models, and the uncertainty is estimated from the inter-model standard deviation. This correction leads to a decrease of S_{LAND} by 0.5 ± 0.3 GtC/yr for the 2014-2023 period.

Land sink. Lateral carbon export correction (LCE)

In the GCB, the impact of human-induced changes in lateral carbon transfers on the land and ocean carbon sinks and G_{ATM} have so far been excluded. Here, we account for anthropogenic impacts on these lateral fluxes by taking the average of two recently published estimates: a data-ensemble method [24] and a process-based model which includes land-aquatic lateral exchanges and CO2 fluxes with the atmosphere [25]. The two estimates are quantitatively consistent, are supported by a recent global assessment using another land surface model enabled for land-aquatic lateral exchanges (H. Zhang, pers. com.), and are very close (within 10 %), for their present-day carbon export estimate, to a recent global assessment relying on process-based models, observations and machine learning [49]. Extended Data Fig. 3 provides an overview about the different components of the carbon export correction. The anthropogenic perturbation (2014-2023 minus pre-industrial) on the lateral land-to-inland water carbon flux (F'_{LI}) amounts to 0.54 ± 0.44 GtC/yr and is partitioned into increased aquatic CO_2 evasion (F'_{IA}, 0.34 ± 0.26 GtC/yr), aquatic carbon storage (F'_{IS}, 0.09 ± 0.03 GtC/yr), and carbon exports to the ocean (F'_{IE}, 0.11 ± 0.08 GtC/yr).

To estimate the impact of this enhanced lateral carbon export on S_{LAND}, we use the process-based estimate [25] which allows to separate the lateral land-to-inland water carbon flux (F'_{LI}) depending on the origin of the exported carbon. Incidentally, one half (0.27 ± 0.31 GtC/yr) results from the transfer of dissolved CO_2 from the soil water column to the aquatic system, and the other half (0.27 ± 0.31 GtC/yr) results from the transfer of terrestrial organic carbon to the aquatic system. The former (numbers in orange in Extended Data Fig. 3) represents a lateral displacement of CO_2 produced by soil heterotrophic respiration to the aquatic system (F'_{IA}, orange values), with no impact on the combined terrestrial+aquatic CO_2 flux to the atmosphere, and hence no impact on S_{LAND}. The latter (numbers in red in Extended Data Fig. 4) represents an additional loss from terrestrial ecosystems carbon reservoirs to the aquatic system, which can impact S_{LAND}. Indeed, out of the 0.27 ± 0.22 GtC/yr of organic carbon lost from the terrestrial reservoirs, about one quarter, 0.07 ± 0.06 GtC/yr, is transferred to inland waters, decomposed and released back to the atmosphere as CO_2, hence impacting S_{LAND} (F'_{IA}, red values), while the remaining three quarters are stored in other reservoirs (0.09 ± 0.03 GtC/yr buried in aquatic systems, F'_{IS} and 0.11 ± 0.08 GtC/yr exported to the open ocean, F'_{IE}), with no impact on S_{LAND}.

We do not correct the GCB estimate of the ocean sink (S_{OCEAN}), i.e., we assume that the terrestrial carbon exported to the ocean (F'_{IE}, 0.11 ± 0.08 GtC/yr GtC/yr) remains stored in the ocean, as the fate of the land-derived carbon in the coastal and open ocean remains too uncertain to be quantified with confidence [24].

In summary, the lateral carbon export (LCE) correction leads to a 0.07 ± 0.06 GtC/yr reduction of S_{LAND}, with the uncertainty estimated by combining the uncertainties reported in the original studies for enhanced CO_2 outgassing [24,25]. No LCE correction on S_{OCEAN} was applied here.

Ocean sink bias correction

In the GCB, the ocean carbon sink (S_{OCEAN}) is calculated as the mean of the ensemble average of global ocean biogeochemical models (GOBMs) and the ensemble average of observation-based estimates (fCO_2-products). Both approaches are subject to known biases that are quantified here.

The evidence for the underestimation of the ocean CO_2 sink using GOBMs, already mentioned in GCB2024 [1] comes from a number of studies, which all suggest an underestimation of around 10%. Comparison with interior ocean estimates of anthropogenic carbon accumulation suggests an underestimation of 8% [4] to 17% [33] for the periods 1994-2007 and 2004-2014, respectively. GOBMs produce a lower ocean sink compared to atmospheric inversions (by 16%) and atmospheric oxygen-based estimates (by 24%), for the decade 2014-2023 [1], although uncertainty ranges overlap. Process-based evaluation of the Earth System Models (ESMs) also suggests a 9-11% underestimation of the ocean sink due to biases in simulated Atlantic Meridional Overturning Circulation, Southern Ocean ventilation, and surface ocean Revelle factor [50], also qualitatively supported by regional studies [51–53]. A composite analysis of GOBMs and ESMs suggest that GOBMs underestimate the ocean sink by 10% due to inadequate spin up strategies [34]. Regionally, eddy-covariance CO_2 flux data suggest a substantial underestimation of the Southern Ocean sink by the GOBMs [54]. All in all, while all lines of evidence have their own uncertainties, they consistently support that GOBMs underestimate the ocean sink. We thus have high confidence (90% confident) that the correction on the GOBMs estimate is positive. Hence, we propose a correction of +10% ± 8% based on the evidence provided above, with the uncertainty consistent with a 90% chance the correction is positive (Z-score =-1.28). The upward scaling of the GOBMs by 10% results in an increase of the GOBM sink estimate by 0.26 ± 0.21GtC/yr for the 2014-2023 period.

Observation-based estimates (fCO_2-products) are built on direct measurements of the fugacity of CO_2 (fCO_2, which equals pCO_2 corrected for the non-ideal behaviour of the gas) from the Surface Ocean CO_2 Atlas (SOCAT)[26] that are gap filled using various statistical, regression and machine learning approaches. The air-sea CO_2 exchange is then calculated from the air-sea partial pressure difference of CO_2 and a wind dependent bulk gas transfer formulation. These calculations do not consider temperature gradients arising from the surface warm layer and cool skin effect (the less than 1 mm thick surface micro-layer that cools through ocean heat loss to the atmosphere), which are mechanistically well understood but have historically been difficult to quantify. A recent study based on field study of direct air–sea CO_2 fluxes suggests that the measurements need to be adjusted to consider a cool skin effect (0.42 GtC/yr, increasing sink), which is in part offset by the effect of temperature differences between the measurement depth and the ocean surface (0.24 GtC/yr, decreasing sink), resulting in an upward adjustment of the sink of 0.18 GtC/yr [37]. This is broadly consistent in magnitude with a GOBM model study that implemented the cool skin effect[55]. For the cool skin and warm layer corrections of the fCO_2-products, the field study estimate comes without uncertainty[37]. However, based on the uncertainty estimate of the modelling study[55] and our expert judgement, we have medium confidence (66% confidence) that the correction is positive. Uncertainties remain, e.g. due to the lack of dedicated field campaigns and choice of rapid or equilibration model for the cool skin correction [36,56], and should be resolved in the future to increase confidence. Hence, we propose a correction of 0.18 ± 0.4 GtC/yr, with the uncertainty consistent with a 66% chance the correction is positive (Z-score =-0.45). Additional warm bias leading to potential enhanced underestimation of the ocean sink has been identified also from variable sample depth and potential artificial warming in the ship environment, but these factors are less well understood and constrained [35,36] and thus not further considered here.

In our revised assessment, we increase the GOBMs estimate by 10 ± 8% and the fCO_2-products estimate by 0.18 ± 0.4 GtC/yr. These two corrections combined lead to an increase of S_{OCEAN} by 0.22 ± 0.23 GtC/yr for the 2014-2023 period.

We note that the adjustment of both GOBM and fCO2-product estimates does not resolve the discrepancy between them, but it does align the GCB mean ocean sink closer to independent estimates based on observations of the ocean interior and of atmospheric oxygen [3,4]

Atmospheric CO_2 growth rate estimate

In the GCB, the global atmospheric CO_2 annual growth rate is derived from CO_2 mole fraction observations at the surface (in ppm/yr) which are converted to mass growth rates (G_{ATM}, in GtC/yr) using a conversion factor (CF) with a constant value of 2.124 GtC/ppm 46. Here, we estimate the uncertainty in CF and hence G_{ATM}, using the 14 atmospheric inversions included in GCB2024, following the method by van der Woude et al. [57]. We use the model-sampled mole fractions at the surface stations to calculate the annual CO_2 growth rate (in ppm/yr), following the same calculation for the observations as developed by [41], similar to the method used by the National Oceanic and Atmospheric Administration (NOAA) [39]. We calculate the annual net input of CO_2 in the atmosphere (in GtC/yr) as the sum of the annual fossil fuel emissions and the inverse-derived net land and ocean sinks. The annual ratio of this net annual input of CO_2 divided by the annual growth rate gives the CF (in GtC/ppm). This is repeated for each inverse model and results in annual estimates of the CF (Extended Data Fig. 4a), with their standard deviation. Note that not all inversions are available over the complete period, and we therefore focus the analysis on the period covered by most inversions (2001-2023). CF shows statistically significant interannual variability that is larger than the standard deviation of the 14 inverse models (Extended Data Fig. 4a). We subsequently propagate the uncertainty in CF resulting from 1) the annual uncertainty in the observation-based growth rate, 2) the mean interannual variability over the 2001-2023 period and 3) the mean standard deviation of the inversions over 2001-2023, to estimate the resulting uncertainty on G_{ATM} (in GtC/yr) (Extended Data Fig. 4b). Finally, we propagate this combined uncertainty to the GCB B_{IM}, where the uncertainty band represents the uncertainty in the B_{IM} explained by the GATM uncertainty (Extended Data Fig. 4c). Years within this uncertainty band therefore do not have a statistically significant B_{IM}. No adjustment on G_{ATM} itself is made here as the year-to-year changes in CF need further evaluation.

Climate change impact on the global carbon budget

The land and ocean sinks in the GCB account for both the effect of increasing atmospheric CO_2 and climate change over the historical period. As described in GCB2024, the DGVMs and GOBMs performed two simulations: one accounting for changes in atmospheric CO_2 and climate, and one with the same prescribed increase in atmospheric CO_2, but with a constant climate forcing, representative of a natural climate (1900-1910 for the DGVMs, late 1950s for the GOBMs). The difference between these two simulations is the effect of climate change on the land and ocean sinks (S_{LAND}^{clim}, S_{OCEAN}^{clim}), as simulated by the DGVMs and GOBMs (Fig. 2, Extended Data Fig. 5). We add these climate change effects on the revised estimates of S_{LAND} and S_{OCEAN} to estimate the land and ocean sinks in the absence of climate change. The impact on atmospheric CO_2 (Fig. 2c) is estimated as $G_{ATM}^{clim} = AF \times (S_{LAND}^{clim} + S_{OCEAN}^{clim})$, where AF is the airborne fraction. The theoretical atmospheric CO_2 growth rate, in the absence of climate change, is then estimated as G_{ATM}-G_{ATM}^{clim}.

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Author contributions

PF and CLQ designed the study and drafted the manuscript. JP, CS and TG provided the revised land-use emission estimate, MOS, SS, PR, and HT provided the revised land sink estimate, JH, PL, DCEB, AO and CLQ provided the revised ocean sink estimate. ITL, WP, AvdW, XL, EM and HL assessed the variability and uncertainty in the atmospheric concentration growth rate. RMA and GPP assessed the fossil emissions estimate. MWJ, JGC, PC commented on the draft. All authors contributed to the writing of the manuscript.

Supplementary Information is available for this paper.

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Data availability

All data presented in this manuscript are available on Zenodo (https://zenodo.org/records/16367993).

Code availability

No new code was generated for this study. Figures with maps were done using the R statistical environment.

The authors declare no competing interests

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Figures legend

Figure 1. Revised components of the global carbon budget. Top left panel: net land-use emissions (E_{LUC}). Top right panel: land sink (S_{LAND}). Bottom left panel: ocean sink (S_{OCEAN}). Bottom right panel: budget imbalance (B_{IM}). Grey bars on the left show the GCB2024 estimate, intermediate bars show the incremental corrections from this study, and colour bars on the right show the consolidated estimates. Units are GtC/yr. Components are averaged over the last decade (2014-2023). δL, RSS and LCE respectively refer to the transient carbon densities correction, the replaced sinks and sources correction, and the lateral carbon export correction, see Methods.

Figure 2. Impact of climate change on carbon sinks and atmospheric CO_2 increase Impact of climate change on (a) the ocean sink (S_{OCEAN}) as simulated by GOBMs (GtC/yr), (b) the land sink (S_{LAND}) as simulated by DGVMs (GtC/yr), and (c) their cumulative effect on the atmospheric CO_2 concentration increase since 1960 (ppm).

Figure 3. Consolidated global carbon budget. Fossil CO_2 emissions (E_{FOS}), the revised net land-use change emissions (E_{LUC}), the revised land sink and ocean sink (S_{LAND} and S_{OCEAN}) both separated into their response to CO_2 and response to climate, the atmospheric CO_2 growth rate (G_{ATM}) and the residual budget imbalance (B_{IM}). Units are GtC/yr. Components are averaged over the last decade (2014-2023). Dashed outlines indicate a new update in this study compared to GCB2024.

Figure 4. Land CO_2 fluxes and attribution effects. Decadal mean (2014-2023) of the net land CO_2 flux (S_{LAND}-E_{LUC}) (central map and grey bars for each land RECCAP region) and attribution to the effects of atmospheric CO_2 increase (CO_2 fertilization; green bars), climate impact (red bars), and land-use change (orange bars). Units are $gC/m^2/yr$ for the spatial map and MtC/yr for the integrals over the RECCAP regions. CO_2 and climate flux uncertainties calculated as the 1 sigma spread among DGVMs from GCB2024. E_{LUC} uncertainty is calculated as the 1 sigma spread among Bookkeeping models from GCB2024. The uncertainty on the net flux is the square root of the sum of squares of the three component fluxes.

Table 1. Global carbon budget as in GCB2024 and consolidated budget from this study. Annual CO_2 fluxes averaged over the 2014-2023 decade. Units are GtC/yr.

	G_{ATM}	E_{FOS}	E_{LUC}	S_{LAND}	Net Land	S_{OCEAN}	B_{IM}
GCB2024	5.2±0.02	9.7±0.5	1.1±0.7	3.2±0.9	2.1±1.1	2.9±0.4	-0.4±1.3
This study	**5.2±0.02**	**9.7±0.5**	**1.2±0.7**	**2.7±0.9**	**1.4±1.1**	**3.1±0.5**	**-0.02±1.3**
Difference	*0*	*0*	*+0.1*	*-0.5*	*-0.6*	*+0.2*	*+0.4*
Atmospheric inversions	5.2±0.0	9.7±0.5	N/A	N/A	1.4±0.5	3.1±0.5	0
Atmospheric oxygen	5.2±0.0	9.7±0.5	N/A	N/A	1.0±0.8	3.4±0.5	0

* Net land is the net land CO_2 flux, calculated as S_{LAND} - E_{LUC}. Atmospheric inversions and atmospheric oxygen do provide Net Land but do not separate E_{LUC} from S_{LAND}. The budget imbalance (B_{IM}) is the difference between anthropogenic net emissions (E_{FOS}+E_{LUC}) and accumulation of carbon in the atmosphere, land and ocean (G_{ATM}+S_{LAND}+S_{OCEAN}). By design, atmospheric inversions and atmospheric oxygen budget imbalance is null. The uncertainty represents ± 1 standard deviation as in ref. [1].

Extended Data Figures legend

Extended Data Figure 1 | Budget imbalance (B_{IM}) as reported in the GCB2024, as reported in the GCB2024, showing a statistically significant negative trend (dotted line) of -0.14 ± 0.04 GtC/yr per decade (p-value=0.003). Units are GtC/yr.

Extended Data Figure 2 | Consolidated global carbon budget. Revision (in red) compared to the GCB2024 estimate (in black) of (b) net land-use emissions, (c) ocean sink, (d) land sink, and (f) budget imbalance. Panels (a) fossil CO2 emissions and (e) atmospheric CO2 growth rate are unchanged. All fluxes are in GtC/yr.

Extented Data Figure 3 | Impact of lateral carbon flux correction on SLAND Global carbon budget (2014-2023) without (a) and with (b) historical changes in lateral carbon fluxes. Units are GtC/yr. The additional green/blue box represents inland waters, and the surrounding green open rectangle represents the whole land system (terrestrial ecosystems and inland waters combined). The perturbations on inland water fluxes follow the nomenclature of ref. [24] and represent land-to-inland water flux (F'_{LI}), aquatic CO_2 outgassing (F'_{IA}), aquatic carbon storage (F'_{IS}) and lateral carbon exports to ocean (F'_{IE}). All fluxes were quantified as the mean of values reported by refs.[24,25] and Zhang, pers com. F'_{IA} is subdivided into contributions from soil-derived CO_2 (in orange) and CO_2 from soil organic carbon (in red) respired in inland waters. The Δ represents changes in carbon storage in the different reservoirs. The net effect on S_{LAND} is a decrease of 0.07 ± 0.06 GtC/yr. See methods for further details.

Extended Data Figure 4 | Atmospheric growth rate. Annual conversion factors (CF, in GtC/ppm) for converting the observation-based atmospheric growth rate [ppm/yr] to atmospheric mass growth rates [GtC/yr] derived from the 14 atmospheric inversions included in GCB2024 (orange) in comparison to the fixed value currently used in GCB2024 (blue), open symbols represent years in which less than 4 atmospheric inversions are available; (b) atmospheric growth rate (G_{ATM}) with propagated uncertainty from: 1) uncertainty in the annual observation-based growth rate [ppm/yr], shown in blue shading, 2) mean interannual variability in the CF over 2001-2023, and 3) mean standard deviation of the inverse CFs over 2001-2023 (total combined uncertainty shown in orange shading); and (c) the GCB2024 budget imbalance (B_{IM}) [GtC/yr] with the propagated uncertainty in G_{ATM} (orange shading).

Extended Data Figure 5 | Land CO_2 fluxes. (a) Land carbon sink due to atmospheric CO_2 increase (CO_2 fertilization) only, (b) effect of climate change on the land carbon flux, (c) land carbon flux due to land-use change, (d) net land CO_2 flux (a+b+c). Positive values indicate sinks, negative values indicate sources. Units are $gC/m^2/yr$.

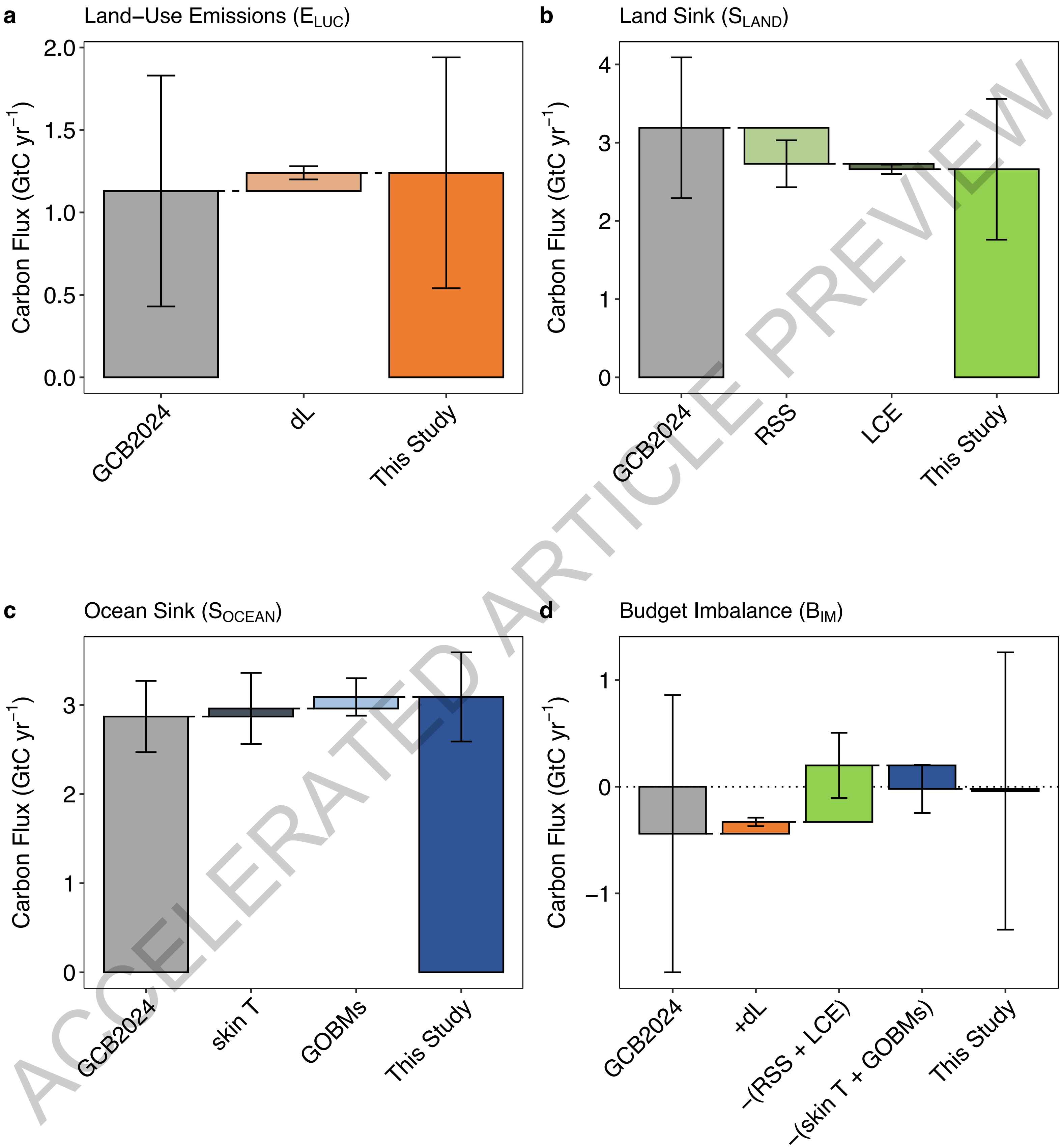
Extended Data Tables Title and legend

Extended Data Table 1

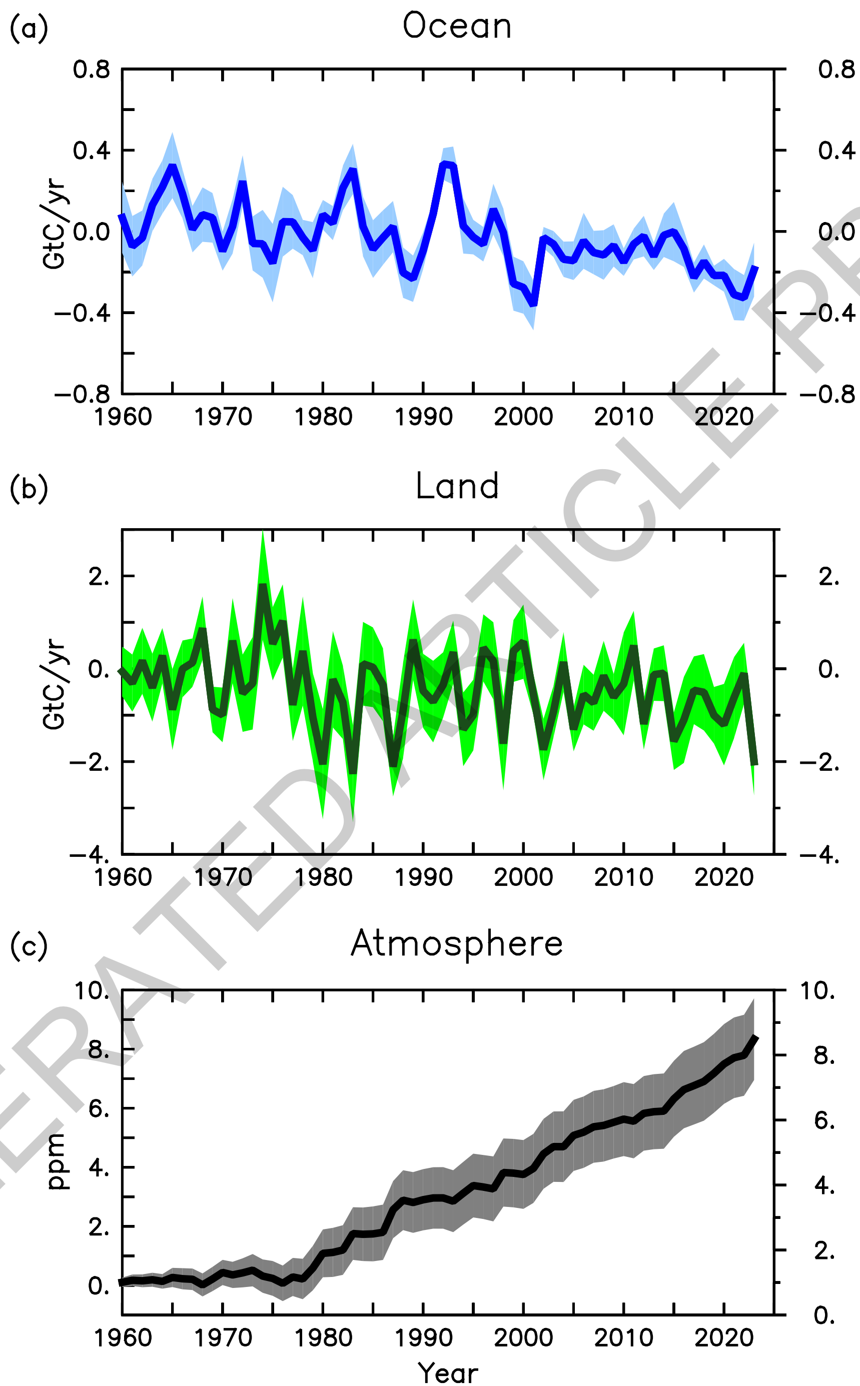
Title:
Extended Data Table 1 | Decadal average of all components of the consolidated global carbon budget (GtC/yr)

Legend:
Net Land is the net land CO_2 flux, calculated as S_{LAND} - E_{LUC}. Atmospheric inversions and atmospheric oxygen do provide *Net Land* but do not separate E_{LUC} from S_{LAND}. The budget imbalance (B_{IM}) is the difference between anthropogenic net emissions (E_{FOS}+E_{LUC}) and accumulation of carbon in the atmosphere, land and ocean (G_{ATM}+S_{LAND}+S_{OCEAN}). By design, atmospheric inversions and atmospheric oxygen budget imbalance is null.

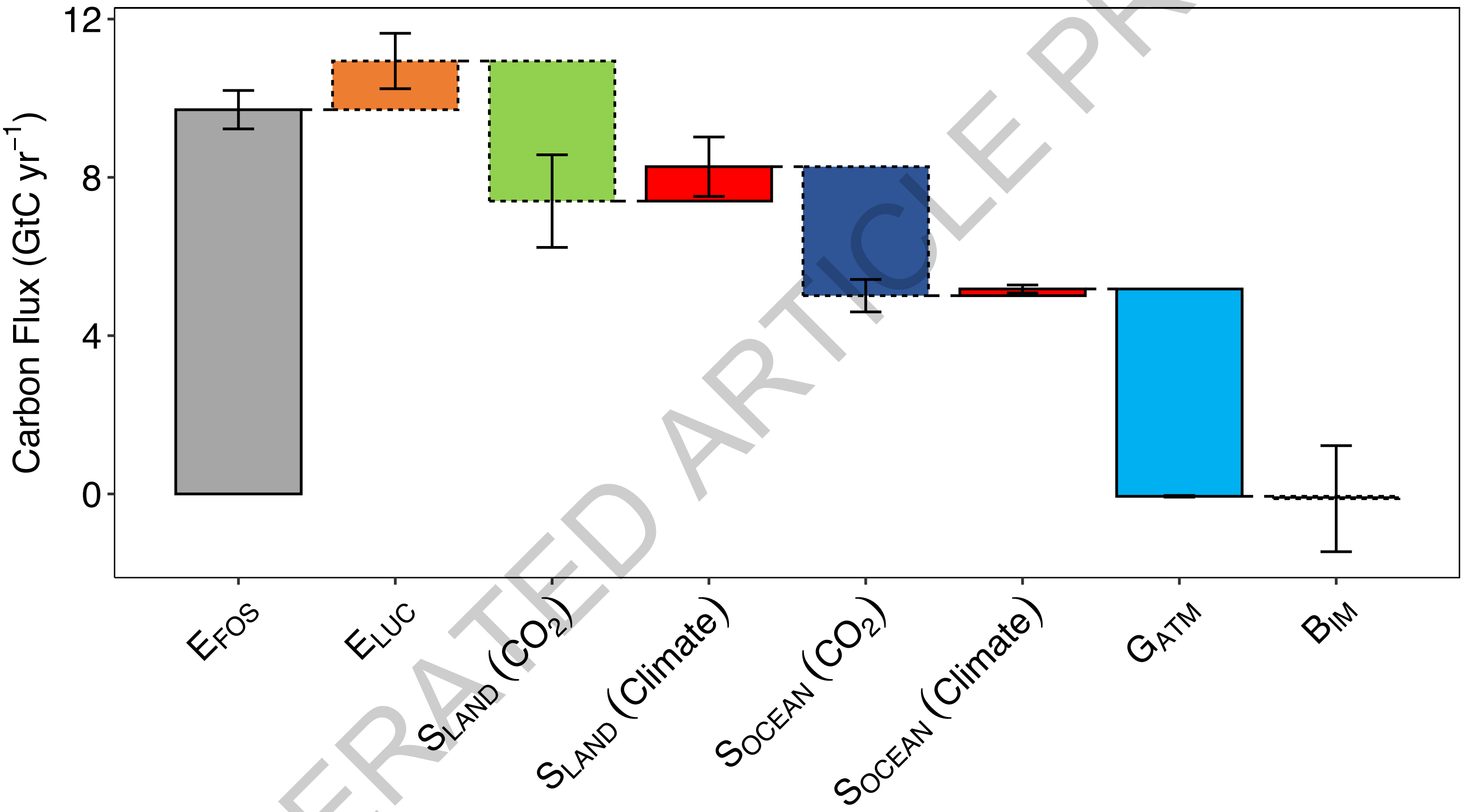
Extended Data Table 2
Title:
Extended Data Table 2 | Decadal average of all components of the consolidated global carbon budget (GtC/yr)



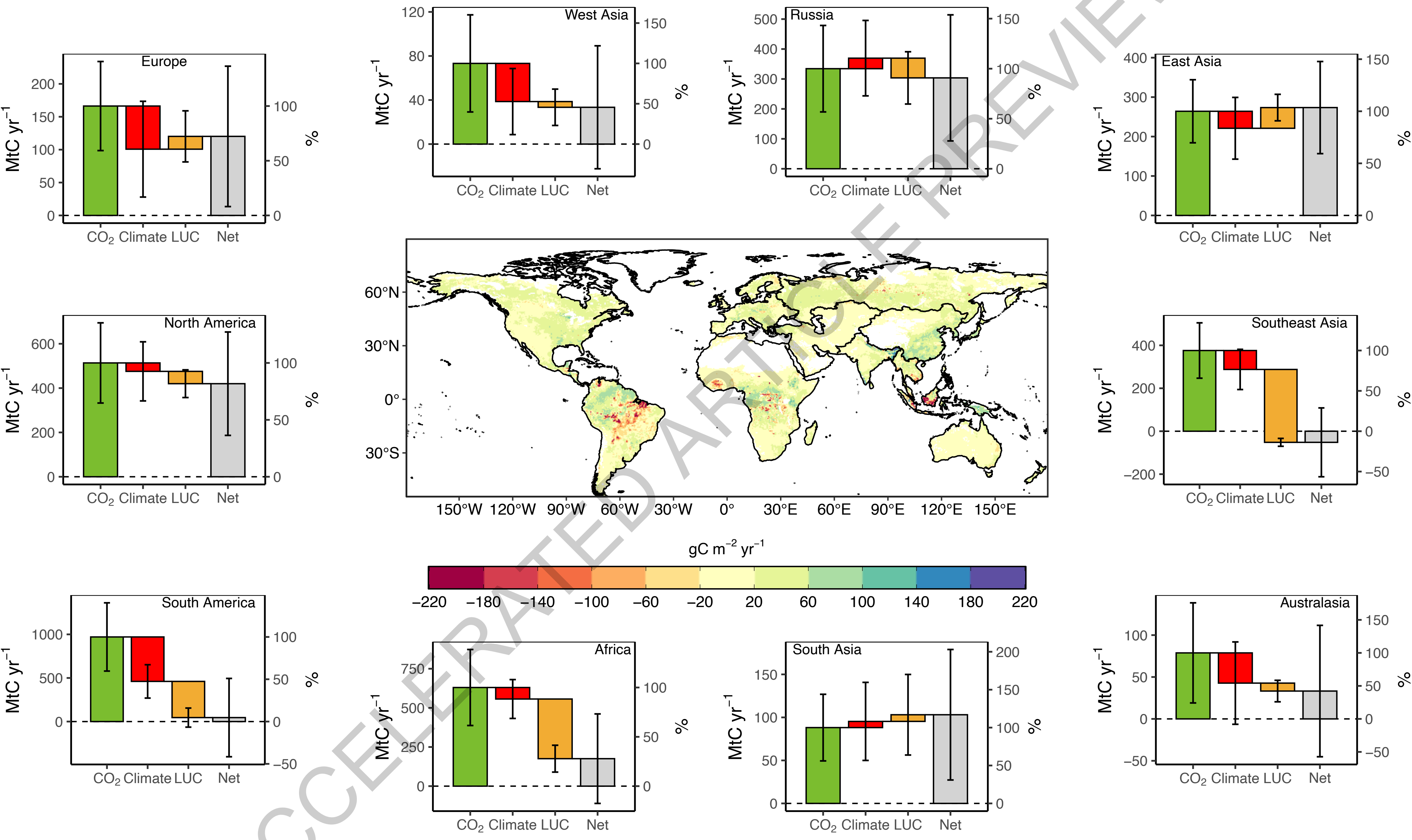
a
Land−Use Emissions (E_{LUC})
Carbon Flux (GtC yr^{-1})
2.0
1.5
1.0
0.5
0.0
GCB2024
dL
This Study
b
Land Sink (S_{LAND})
Carbon Flux (GtC yr^{-1})
4
3
2
1
0
GCB2024
RSS
LCE
This Study
c
Ocean Sink (S_{OCEAN})
Carbon Flux (GtC yr^{-1})
3
2
1
0
GCB2024
skin T
GOBMs
This Study
d
Budget Imbalance (B_{IM})
Carbon Flux (GtC yr^{-1})
1
0
−1
GCB2024
+dL
−(RSS + LCE)
−(skin T + GOBMs)
This Study



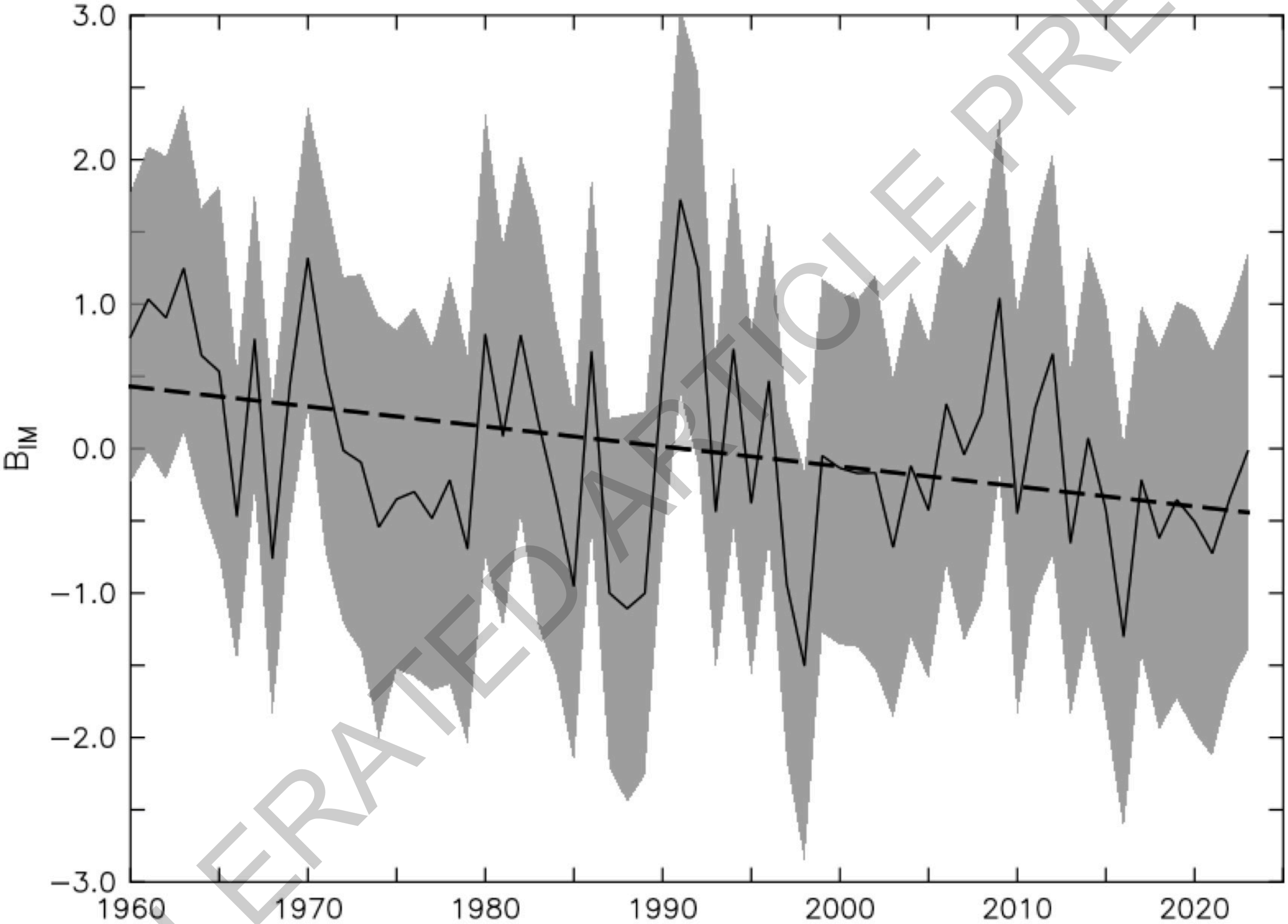
(a)
Ocean
0.8
0.4
0.0
−0.4
−0.8
GtC/yr
1960
1970
1980
1990
2000
2010
2020
(b)
Land
2.
0.
−2.
−4.
GtC/yr
(c)
Atmosphere
10.
8.
6.
4.
2.
0.
ppm
Year



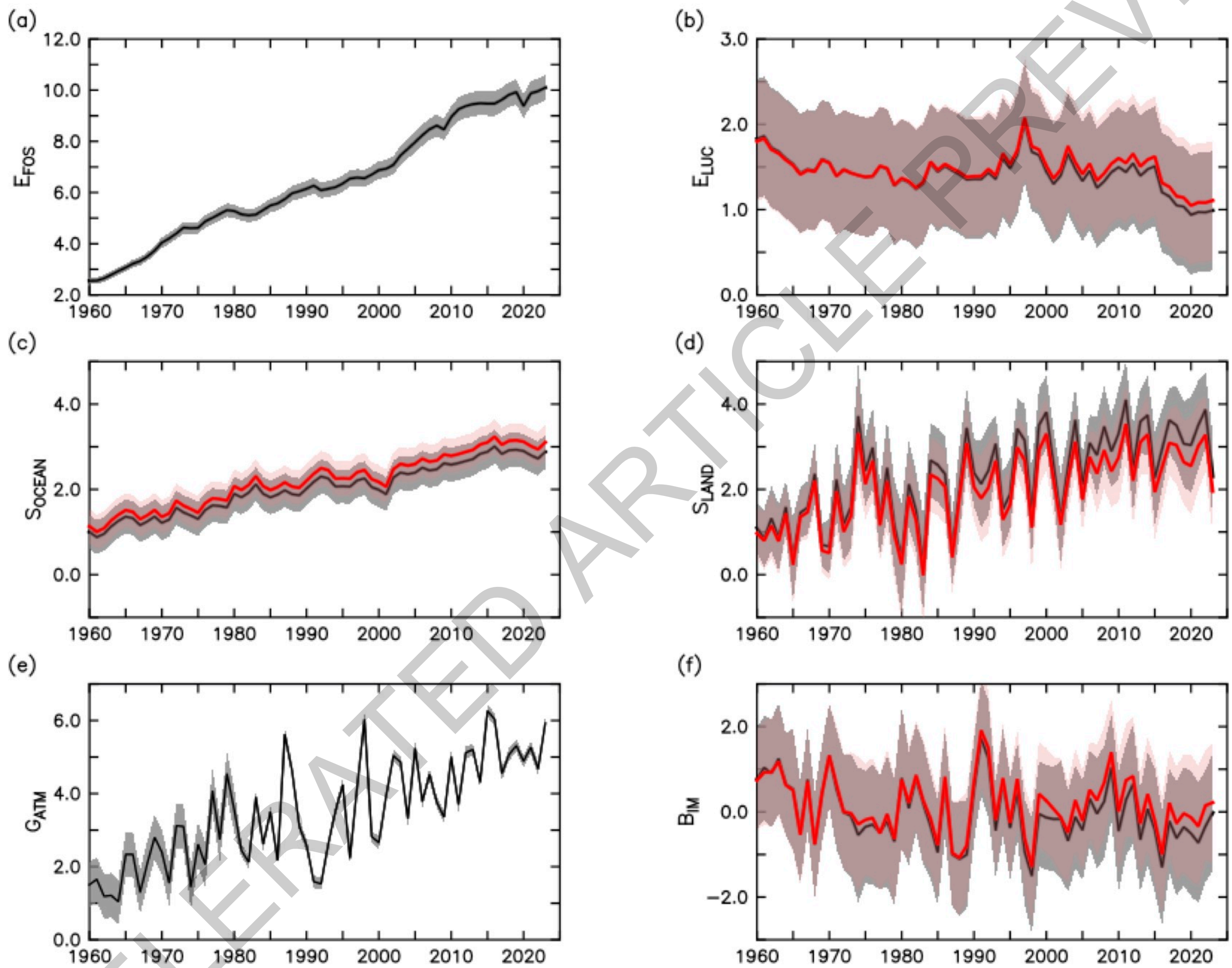
Carbon Flux (GtC yr-1)
12
8
4
0
EFOS
ELUC
SLAND (CO2)
SLAND (Climate)
SOCEAN (CO2)
SOCEAN (Climate)
GATM
BIM



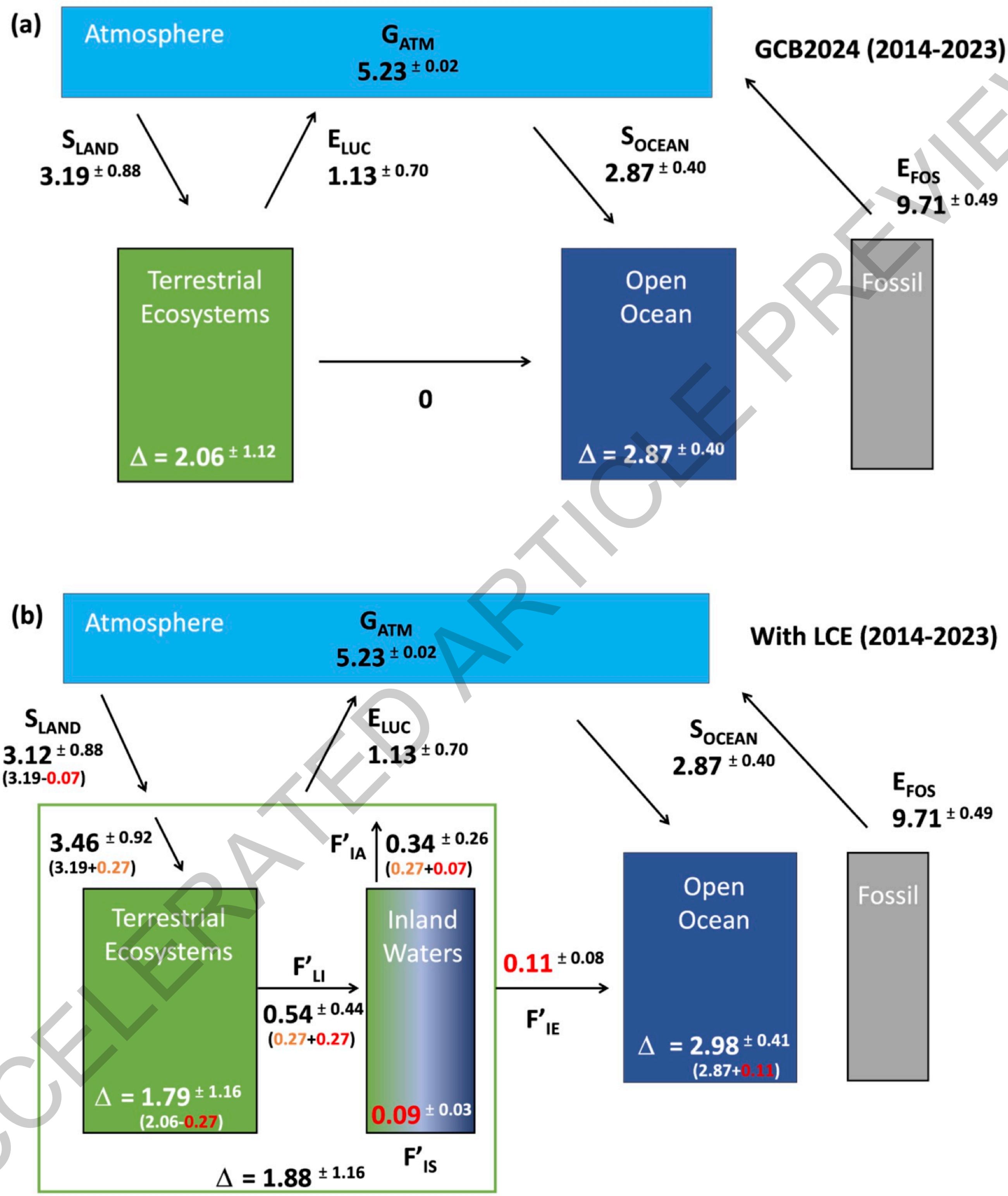
Europe
West Asia
Russia
East Asia
North America
Southeast Asia
South America
Africa
South Asia
Australasia
MtC yr−1
%
CO2 Climate LUC Net
gC m−2 yr−1
−220 −180 −140 −100 −60 −20 20 60 100 140 180 220
60°N
30°N
0°
30°S
150°W 120°W 90°W 60°W 30°W 0° 30°E 60°E 90°E 120°E 150°E



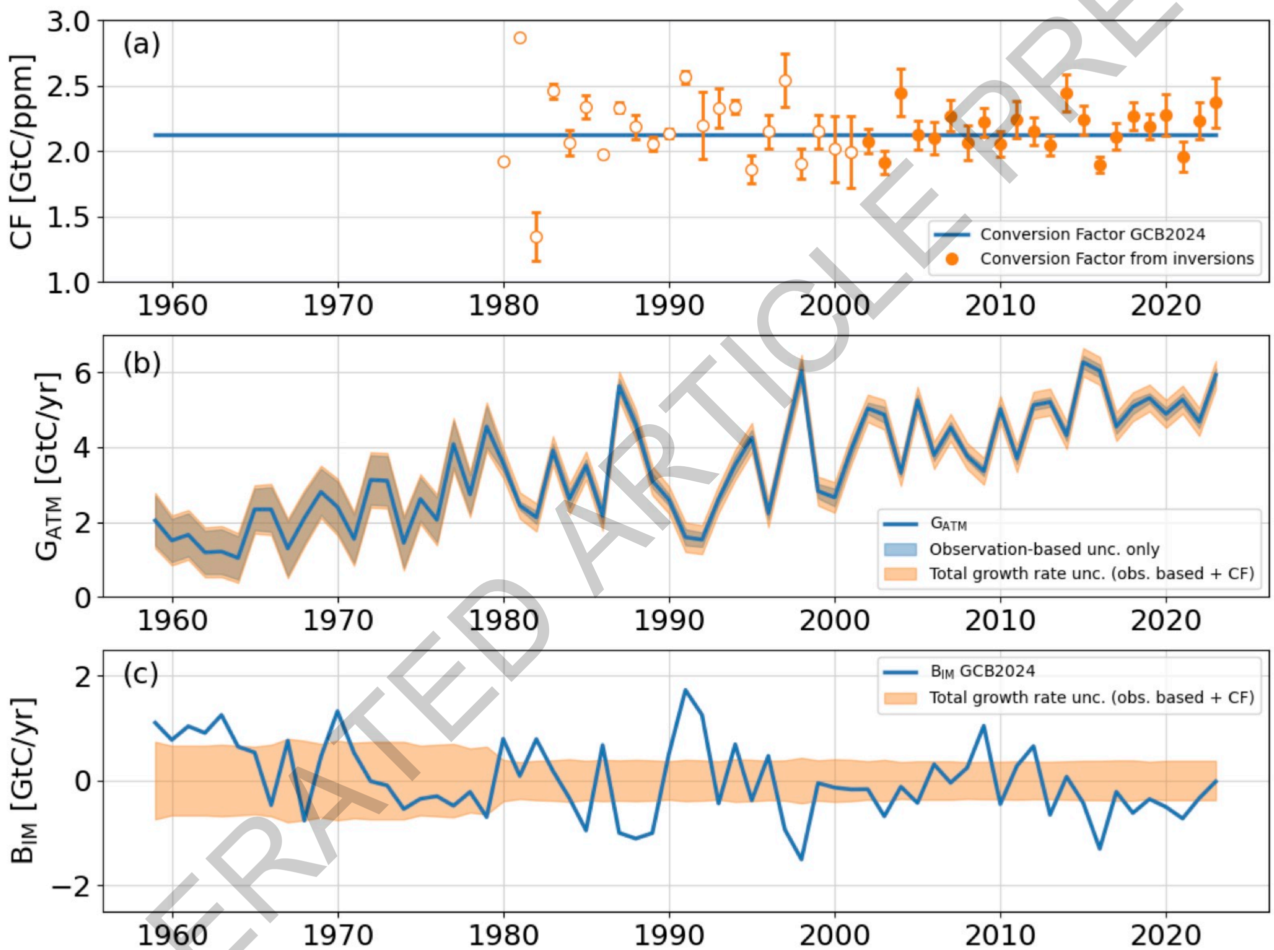
Extended Data Fig. 1



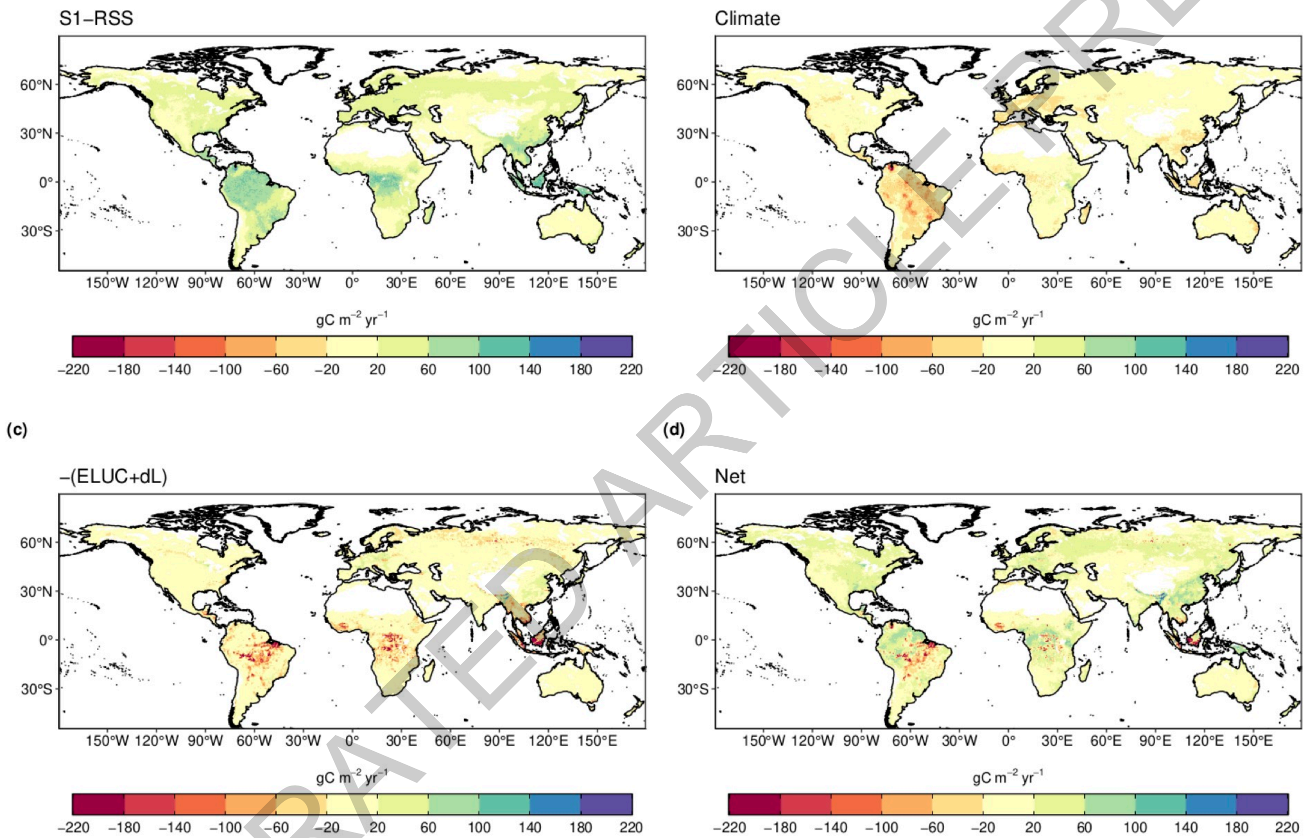
Extended Data Fig. 2



Extended Data Fig. 3



Extended Data Fig. 4



Extended Data Fig. 5

	G_{ATM}	E_{FOS}	E_{LUC}	S_{LAND}	Net Land	S_{OCEAN}	B_{IM}
GCB2024	5.2±0.02	9.7±0.5	1.1±0.7	3.2±0.9	2.1±1.1	2.9±0.4	-0.4±1.3
Revised E_{LUC} δL			1.2±0.7 (+0.1±0.04)	3.2±0.9	2.0±1.1		-0.3±1.3
Revised S_{LAND} RSS				2.75±0.9 (-0.46±0.3)	1.5±1.1		0.1±1.3
Revised S_{LAND} LCE				2.7±0.9 (-0.07±0.06)	1.4±1.1		0.2±1.3
Revised S_{OCEAN}						3.1±0.5 (+0.22±0.23)	-0.02±1.3
This Study	**5.2±0.02**	**9.7±0.5**	**1.2±0.7**	**2.7±0.9**	**1.4±1.1**	**3.1±0.5**	**-0.02±1.3**
Atmospheric inversions	5.2±0.0	9.7±0.5	N/A	N/A	1.4±0.5	3.1±0.5	0
Atmospheric oxygen	5.2±0.0	9.7±0.5	N/A	N/A	1.0±0.8	3.4±0.5	0

Extended Data Table 1

		1960s	1970s	1980s	1990s	2000s	2014-2023
Net emissions	E_{FOS}	3.0±0.2	4.7±0.2	5.5±0.3	6.4±0.3	7.8±0.4	9.7±0.5
	E_{LUC}	1.6±0.7	1.4±0.7	1.4±0.7	1.6±0.7	1.5±0.7	1.2±0.7
Partitioning	G_{ATM}	1.7±0.07	2.8±0.07	3.4±0.02	3.1±0.02	4.0±0.02	5.2±0.02
	S_{OCEAN}	1.3±0.5	1.6±0.5	2.1±0.5	2.3±0.5	2.5±0.5	3.1±0.5
	S_{LAND}	1.0±0.5	1.7±0.8	1.5±0.8	2.0±0.6	2.4±0.7	2.7±0.9
	B_{IM}	0.5±1.0	0.1±1.2	-0.02±1.2	0.4±1.2	0.3±1.1	-0.1±1.3

Extended Data Table 2