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# Observing system needs for understanding carbon–climate feedbacks

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## Abstract

Carbon–climate (CC) feedbacks — arising from response of land and ocean carbon sinks to elevated $CO_2$ and climate warming — are critical yet highly uncertain drivers of Earth's climate trajectory. Processes such as permafrost thaw, tropical forest dieback, reduced ocean uptake, and intensifying climate extremes are already weakening natural carbon sinks, with potential to amplify warming and accelerate crossing of tipping points. Detecting and quantifying these dynamics requires sustained, high-resolution, spatially-comprehensive Earth Observations. Drawing on outcomes from a 2024 community workshop, we identify three core priorities for advancing CC feedback monitoring: (1) frequent, long-term measurements of carbon fluxes and stocks at sub-continental scales; (2) improved flux detectability using greenhouse gas partial columns; and (3) targeted monitoring of poorly-observed vulnerable regions, such as the tropics, high latitudes, and the Southern Ocean. We argue that a unified, multi-platform observing system, built on lower-cost, proven technologies and orbits and focused on high-risk observation gaps, would significantly reduce uncertainties in Earth System Models, provide early warnings of feedbacks and tipping points, inform climate mitigation strategies, and enhance transparency in carbon monitoring.

## 1. Need for observations targeting carbon–climate (CC)feedbacks

CC feedbacks arise from the responses of land and ocean carbon sources and sinks to changes in $CO_2$ concentration ($\beta$ feedback) and climate ($\gamma$ feedback). These feedbacks, summarized in figure 1 and table 1, can dramatically alter the global carbon budget and trajectory of climate stabilization, making their understanding crucial for developing robust climate policies and ensuring that mitigation efforts are effective. Increases in global land and ocean carbon sinks continue to be driven to first order by increases in atmospheric $CO_2$ concentration that drive terrestrial greening and enhanced ocean $CO_2$ dissolution ($\beta$ feedbacks; Schimel and Carroll 2024). $\beta$ feedbacks have the potential to slow or reverse land and ocean carbon sinks when $CO_2$ emissions and atmospheric concentrations begin to decline as decarbonization efforts ramp up (Lovenduski *et al* 2021). These sinks are also increasingly susceptible to $\gamma$ feedbacks as the Earth continues to warm. On land, thermal maximums for photosynthesis (greening, tropical forest dieback) and permafrost (thaw) are gradually breached as the Earth warms (Cox *et al* 2013, Armstrong Mckay *et al* 2022, Miner *et al* 2022), and carbon sinks are increasingly abruptly lost to climate extremes (fires, droughts, floods; Reichstein

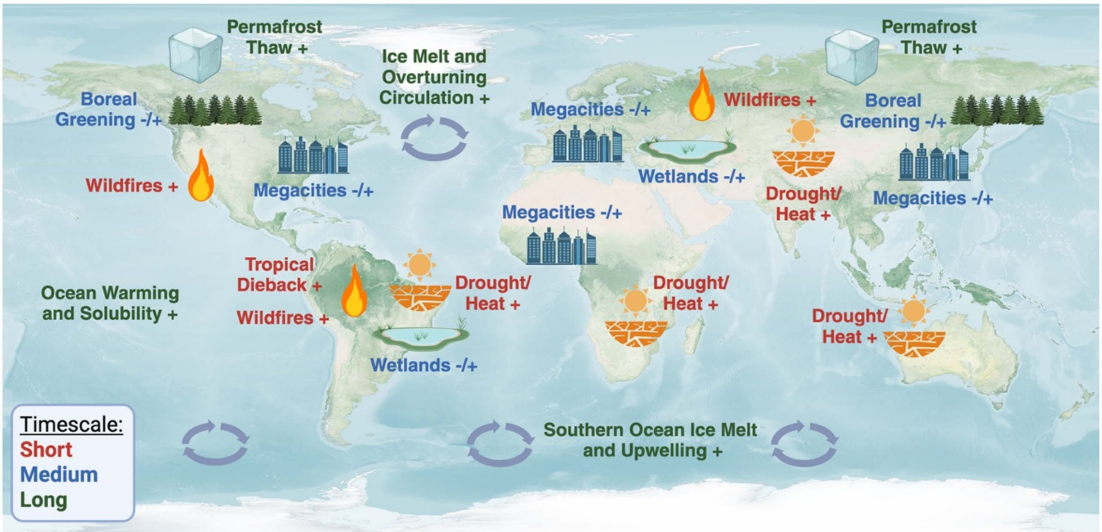


**Figure 1.** Map of key CC feedbacks/tipping points and associated sign of the feedback, color coded by timescale.

*et al* 2013). In the ocean, warming reduces the solubility of $CO_2$, while freshwater injection into the North Atlantic from melting land ice may slow the rate at which anthropogenic carbon emissions can be transported from the surface to the interior ocean (Gorte *et al* 2024)—both processes act to weaken the ocean carbon sink. In addition, population growth, the expansion of megacities (Duren and Miller 2012) and widespread deforestation, along with increasing demand for food, will have a direct influence on terrestrial carbon storage in the future. The speed and magnitude of these feedbacks vary depending on timescale and human intervention, with some feedbacks operating on short timescales (years to decades, e.g. climate extremes, thawing permafrost, expansion or contraction of wetlands) and others on longer timescales (decades to centuries, e.g. reverse $\beta$, ocean circulation). Even as emissions are reduced and carbon stocks are managed in collective efforts towards net zero, CC feedbacks will continue to shape humanity's future over long timescales (decades to centuries, Schimel and Carroll 2024).

The inevitability of CC feedbacks underscores the critical need to prioritize enhanced Earth observation (EO) and models to navigate the challenges of (i) relentless 21st century emissions, (ii) rapid changes in carbon stocks, and (iii) the detection of potential emissions reductions and $CO_2$ removals, should they occur. Observing CC feedbacks requires detectability of carbon flux and stock anomalies at the spatial scale of associated climate perturbations (Sellers *et al* 2018) in a manner that addresses multiple feedback challenges with a single, affordable EO system. A recent carbon cycle community workshop, held in September 2024 at the California Institute of Technology, discussed opportunities to leverage existing satellite and surface observations with new technologies to (1) address the multi-scale complexities of CC feedbacks and (2) provide long-term monitoring of carbon flux and stocks that benefit resource management.

In reflection of the workshop outcomes, it is clear that three observational shifts are needed to improve monitoring of CC feedbacks and tipping points: (i) sustained surface and satellite EO data to monitor fluxes and stocks at local and continental spatial scales; (ii) new observations of greenhouse gas (GHG) partial columns to bridge scales and improve monitoring and understanding of sub-continental feedbacks and tipping points, and (iii) renewed focus on undersampled regions in the tropics, high latitudes, and oceans.

## 2. Critical regions and tipping points

Sustained observational targeting of critical regions is a key step toward quantifying CC feedbacks. For example, tropical land sinks are experiencing two simultaneous feedbacks: $CO_2$ fertilization ($\beta$), and increasing droughts ($\gamma$; Gatti *et al* 2021). Similarly, the Northern Hemisphere terrestrial carbon sink may be weakened by drought and disturbance ($\gamma$; Guo *et al* 2025). Sustained monitoring in these regions using advanced spaceborne remote-sensing techniques is needed to better understand these transitions and identify tipping points.

By combining new observations of the land and ocean surface with airborne EO, we can better quantify CC feedbacks. *In-situ* observations are vital for calibrating and validating spaceborne measurements, improving precision, and studying

**Table 1.** List of key carbon–climate (CC) feedbacks, along with observations required for improved monitoring, primary technological advances, platform affordability, and overall priority score. *x*GHG = GHG partial columns; *f* = more-frequent GHG observations; EO = sustained long-term EO monitoring and harmonization of surface and satellite flux and/or biomass; and EO-Surf = expanded surface EO data. Priority score is calculated based on the average of scores (rounding up to the nearest integer) from observation gaps with greatest risk and affordability columns, where for each case low = 1, medium = 2, and high = 3.

| Feedback (sign) references | Observation gaps with greatest risk | Observations required | Primary technological advances | Platform | Affordability (technology + platform) | Score |
|---|---|---|---|---|---|---|
| | | | Short timescale (1–5 years) | | | |
| Drought/heat (+) Reichstein *et al* (2013) | High | $xCO_2$, *f* | Multi-spectral sounder | Multi-LEO | Med | 3 |
| | | | | Multi-GEO | Low | 2 |
| Disturbance (±) Xu *et al* (2021) | Med | $xCO_2$, EO | SAR + Lidar | LEO | High | 3 |
| Wildfires (+) Cunningham *et al* (2024) | Med | *f*, EO | Multi-spectral sounder | Multi-LEO | Med | 2 |
| | | | Medium timescale (5–20 years) | | | |
| Tropical dieback (+) Cox *et al* (2013) | Med | $xCO_2$, *f*, EO | Multi-spectral sounder | Multi-GEO | Low | 2 |
| | | | | Multi-LEO | Med | 2 |
| Megacities (±) Duren and Miller (2012) | Low | $xCO_2$, $xCH_4$, EO | Multi-spectral sounder | Multi- LEO | Med | 2 |
| | | | | Multi-GEO | Low | 1 |
| Wetlands (±) Zhang *et al* (2025) | High | $xCH_4$, EO | Point-source Imager | LEO | High | 3 |
| Boreal greening (±) Piao *et al* (2020) | Low | EO | SAR + Lidar | LEO | High | 2 |
| | | | Long timescale (20+ years) | | | |
| $CO_2$ fertilization (±) Schimel and Carroll (2024) | Med | $xCO_2$, EO | Multi-spectral sounder | LEO | High | 3 |
| Ice melt (+) Gorte *et al* (2024) | Med | EO-Surf | Lidar (IPDA) | LEO | Med | 2 |
| Permafrost thaw (+) Miner *et al* (2022) | High | $xCO_2$, $xCH_4$, *f*, EO | Multi-spectral Sounder | HEO | High | 3 |
| | | | Lidar (IPDA) | LEO | Low | 2 |
| Ocean warming and solubility (+) Goodwin and Lenton (2009) | Med | EO-Surf | Lidar (IPDA) | LEO | Low | 2 |

under-sampled ecosystems such as wetlands, which are significant sources of methane ($CH_4$)—a potent GHG with strong CC feedbacks. Ocean pH and sea level will continue to change long after atmospheric $CO_2$ and temperature stabilize, underscoring the need for sustained ocean coverage, such as the growing BGC-Argo fleet of ocean profilers to monitor changes in ocean carbon and improve fisheries management. Furthermore, improved monitoring across the Southern Ocean is critical, as this region plays a key role in anthropogenic $CO_2$ uptake (Long *et al* 2021) but its response to climate change is still poorly assessed and represented in models, with substantial differences in interannual variability and long-term trends between models and data-based products (Hauck *et al* 2023).

New observations targeting critical regions susceptible to tipping points can provide early warning and identification of potential thresholds in ecosystem carbon dynamics. Tipping elements are generally defined as components of the Earth system that span at least sub-continental scales (∼1000 km) and may cross a tipping point within this century; however, many tipping points can also occur at smaller, regional scales. We stress that the majority of EO *in-situ* data is from northern mid-latitude regions, yet key tipping points and potential CC feedbacks are often largest at low and high latitudes (Sellers *et al* 2018). While the timescales of many tipping elements/points are beyond the reach of the Decadal Survey lifetime, some may occur over decadal (Labrador-Irminger Seas/subpolar gyre convection collapse) and sub-decadal (boreal permafrost collapse) timescales and are beginning to be crossed (Armstrong Mckay *et al* 2022). Enhanced monitoring of these tipping elements/points and critical regions using both spaceborne assets and surface networks can provide earlier detection of critical transitions, such as the Amazon rainforest becoming a net carbon source (Gatti *et al* 2021), allowing for more timely interventions and adaptation strategies to minimize the adverse consequences for ecosystems and human societies.

## 3. Increasing carbon flux sensitivity with GHG partial columns

The ability to leverage atmospheric GHG observations with inverse models (e.g. Sellers *et al* 2018) to monitor carbon sources and sinks resulting from feedbacks (e.g. megacity emissions, wildfires, permafrost, ocean warming) within a single continent or ocean basin requires $CO_2$ and $CH_4$ flux resolutions of 100–500 km (NASEM, 2019). This capability continues to be limited by low sampling frequency (∼1–2 weeks revisit time) and low surface sensitivity of column-integrated concentrations from current and planned satellite GHG instruments. A key opportunity moving forward is the use of partial columns. By targeting separate signals of vertical information in the planetary boundary layer and overlying free troposphere, partial columns can better account for background influences, offer a factor of two improvements in flux resolution (figure 2), and provide increased sensitivity to land and air–sea $CO_2$ exchange (e.g. Gatti *et al* 2021, Long *et al* 2021). Partial columns can also mitigate the impacts of regional and global-scale transport errors in atmospheric $CO_2$ inversion uncertainties.

## 4. Harmonized mapping of carbon stock

The resilience of land carbon sinks to increasing anthropogenic pressures from climate extremes, disturbance, and poor management remains uncertain (Schimel and Carroll 2024). For example, increased frequency and/or intensity of fires, climate extremes, and pests are likely to make nature-based climate solutions (NbCSs, Buma *et al* 2024), such as afforestation and agroforestry, more challenging and less durable, highlighting the need for improved measurement, monitoring, reporting and verification to ensure that resource management efforts are effective. Above-ground biomass (AGB) is a key measure of ecosystem carbon stock and land sink resiliency, which stresses the need for near-continuous monitoring of AGB through the fusion of light detection and ranging (Lidar) and synthetic aperture radar (SAR) data. Accurate, low-latency and harmonized information on biomass change is essential for tracking carbon stocks in living vegetation pools across tropical, temperate, boreal, and polar landscapes. Lidar and SAR can aid understanding of forest resilience and support the timber economy. Furthermore, these platforms can be used to understand how forest carbon stocks are impacted by (1) disturbances such as wildfires, deforestation, pests, and storms (Xu *et al* 2021) and (2) CC feedbacks and tipping points (Guo *et al* 2025). By leveraging Lidar altimetry's vertical precision to accurately measure canopy height and volume under increasing carbon densities with SAR cloud and canopy penetration capabilities, biomass harmonization will greatly improve quantitative and qualitative understanding of vulnerabilities and resiliencies.

## 5. The way forward

Two key monitoring needs are required to better detect the CC feedbacks shown in figure 1: (1) frequent monitoring at sub-regional scales (<500 km) focused on process attribution and episodic events, and (2) long time series focused on timing, magnitude, and duration. The required observations to meet these monitoring needs are summarized in table 1. High-priority observational needs are identified using a scoring system (1–3), which considers

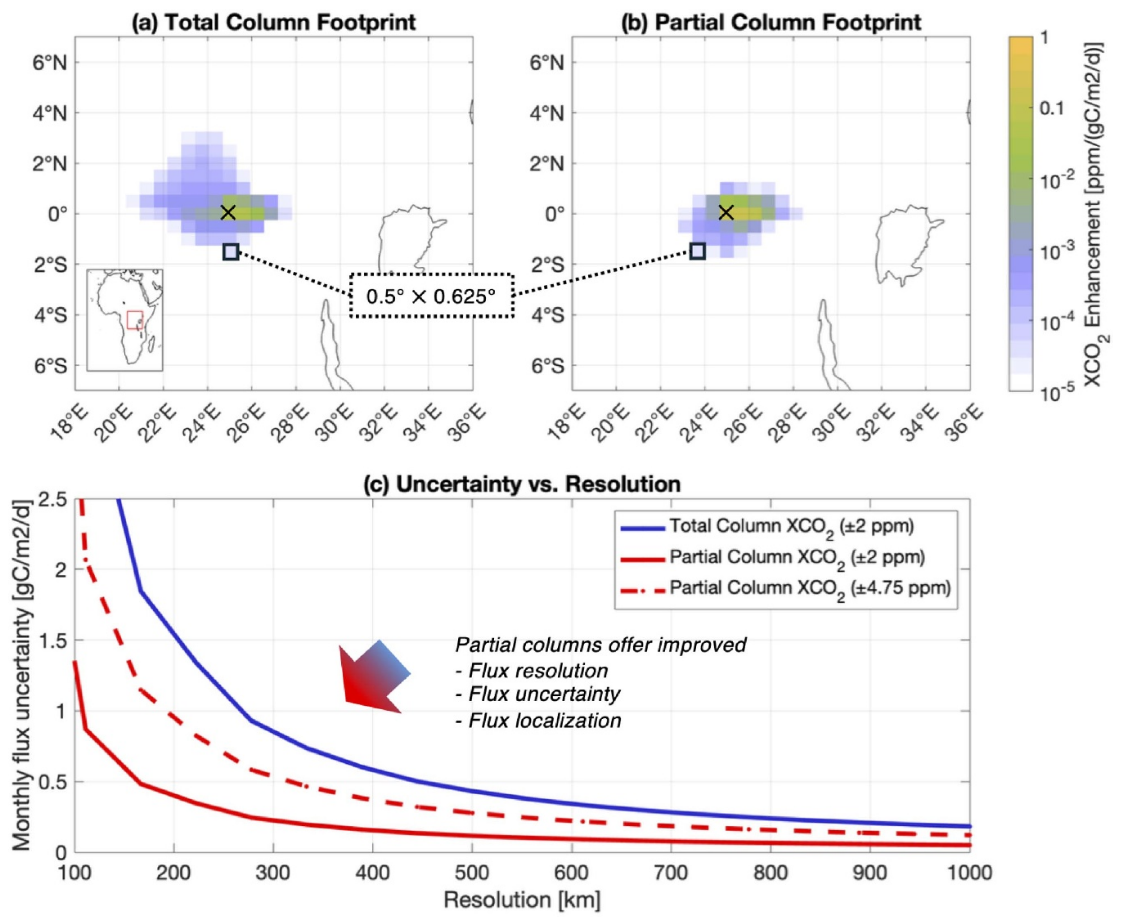


**Figure 2.** Demonstration of impact of GHG partial columns on $CO_2$ flux retrieval. Simple inversion observing system simulation experiment (OSSE) leveraging Jacobians of $CO_2$ fluxes over central Africa: panels (a) and (b) show the atmospheric footprint of a 1 gC $m^{-2}$ $d^{-1}$ flux (location marked by 'x' in both panels) as observed by total column and partial column $CO_2$ observations, respectively. Partial column $CO_2$ integrates over a smaller area compared to total column $CO_2$, resulting in better-resolved, less-diffuse flux footprints. The corresponding flux estimation uncertainty—across a range of spatial resolutions—is shown in panel (**c**): two partial column observing system scenarios (red lines) provide improved flux resolution and uncertainty relative to the existing total column observing system capabilities (blue line), thus making it easier to accurately detect and quantify small-scale fluxes. Additional benefits of partial-column data include the mitigation of transport errors in regional and global atmospheric $CO_2$ inversion systems. The OSSE configuration details are described in the supplementary material.

a balance of high-risk observational gaps and affordability based on technological maturity and platform cost/risk. Based on this analysis, feedbacks related to $CO_2$ fertilization, permafrost thaw, climate extremes, disturbance, and wetlands emerge as the highest priority due to insufficient sampling in the program of record and relatively high affordability. A unified, multi-tiered global spaceborne observing framework featuring frequent global vertical GHG profiles (∼daily), cloud-free sampling and harmonized AGB (∼weekly) will address all high priority observational needs.

Vertically-resolved GHG profiles combining high spatial resolution (<1 km) and measurement precision (∼0.25% for $CO_2$ and $CH_4$) will facilitate quantification of anomalous $CO_2$ sources and sinks associated with fertilization, permafrost, and climate extreme feedbacks, and improve the effective (cloud free) sampling rate. Two approaches under development to meet GHG partial column requirements include multi-channel passive systems and integrated path differential absorption (IPDA) Lidar methods. Multi-channel passive systems sample near- and thermal-infrared bands with sensitivity to lower and upper atmospheric layers, respectively (e.g. Kuze *et al* 2022). IPDA Lidar methods, such as cloud slicing (Mao *et al* 2023)—which is currently tested in airborne campaigns—retrieve full columns around clouds and partial columns to cloud tops, enabling near-surface estimates from cloud top to ground. Point-source imagers with sub-kilometer sampling can improve cloud-free monitoring of methane feedbacks in tropical wetlands (e.g. Frankenberg *et al* 2024). Integration of these approaches with expanded airborne and ground-based networks will be needed for calibration, validation, and detailed process-level insights, especially in under-sampled regions.

Continuity and integration of existing and planned Lidar (GEDI, ICESat-2) and SAR (ALOS-4, NISAR, BIOMASS) datasets, harmonized with reference biomass products (Hunka et al 2023), can significantly lengthen AGB time series while also improving high-resolution (0.1–1 km) monitoring of disturbance feedbacks in key boreal, temperate, and tropical regions.

Long-term operational monitoring of GHGs via low earth orbit (LEO) or geostationary orbit (GEO), similar to weather and environmental monitoring and weather programs at NOAA (NEON/GOES) and ESA (MSG), will be needed for continuity over decades to address long-time scale observational needs (permafrost and $CO_2$ fertilization). The minimum requirement to obtain the desired frequency and longevity and to ensure national resilience (e.g. to weather disasters) and maximize opportunities for action (given low-latency GHG information) will be a single instrument in GEO providing regionally-targeted monitoring capabilities. Global monitoring will require a constellation of two or more instruments, with consideration of affordability and risk factors such as orbit (GEO, HEO, LEO), technology (multi-spectral sounder vs IPDA Lidar), and single or multi-instrument payloads. Generally speaking, passive instruments in LEO cost less and pose less risk than active instruments in GEO.

## 6. Benefits to humanity

There are numerous long-term benefits of sustained and new EO data targeting CC feedbacks for humanity. First, the observations support improved climate change projections. Current Earth system model (ESM) predictions of CC feedbacks are uncertain and the EO data generated from improved observations of carbon flux and biomass should be assimilated into models to better constrain (1) long-term partitioning and trends in land and ocean carbon stocks and (2) associated CC feedbacks. By providing more comprehensive data on carbon fluxes and stocks, along with their responses to climate change, the new EO data will also enable more accurate benchmarking of ESMs and their estimated feedbacks and long-term climate trajectories. Reducing model uncertainty will lead to more reliable projections of future warming and allowable carbon emissions for remaining below temperature targets (Schimel and Carroll 2024). Integrated EO data from these new observations, combined with data–data and model–data fusion, will also provide a more complete, consistent picture of global carbon dynamics including unobserved processes (e.g. below-ground carbon), which will help to improve models and resolve existing uncertainties regarding the relative roles of different carbon cycle processes, the time evolution of the land and ocean sink partition, and CC feedbacks.

These observations can also support enhanced mitigation strategies. For example, if EO data reveal a weakening of natural carbon sinks due to climate stress, this may necessitate more aggressive emissions reductions or carbon capture to meet temperature targets. Additionally, improved monitoring of durability and leakage of NbCS (Buma et al 2024), such as afforestation at project scale for biomass (∼1 km) and sub-regional scale for carbon flux (<500 km), will help assess their effectiveness and potential to offset remaining emissions. Furthermore, by providing timely and policy-relevant information on carbon emissions, removals, and stocks, the new observations will enhance transparency and accountability in tracking progress towards emissions reductions and support progress towards international agreements (Jacquet and Jamieson 2016).

## 7. Concluding remarks

CC feedbacks—changes in land and ocean carbon sinks in response to rising $CO_2$ and climate change—will shape Earth's climate trajectory. Processes such as permafrost thaw, forest dieback, reduced ocean uptake, and increased respiration are weakening natural carbon sinks and amplifying warming. Detecting and quantifying these feedbacks requires long-term, high-resolution, and spatially-comprehensive EO data. We identify three core priorities: (1) sustained, frequent EOs of carbon fluxes and stocks; (2) improved flux accuracy at spatial resolutions finer than 500 km; and (3) targeted monitoring of vulnerable regions, including tropical forests, high latitudes, and the Southern Ocean. Key opportunities to address these needs include using GHG partial columns to improve sensitivity to surface fluxes, and integrating Lidar with SAR for harmonized biomass mapping—both essential for tracking forest resilience and evaluating NbCSs.

New multi-platform carbon observations that combine these capabilities represent a crucial investment in humanity's future. Such observations would enable: (i) quantification of carbon emission, removal, and storage; (ii) assessment of stock vulnerability to climate change, CC feedbacks, and disturbance recovery rates; and (iii) identification of critical thresholds where ecosystem vulnerability sharply increases. This information will directly inform active management strategies, including NbCSs, to maintain robust natural and managed carbon storage in the face of feedbacks, tipping points, and extreme events. Detailed carbon stock and flux data will also guide the design of forestry, agricultural, and coastal management practices that promote ecosystem resilience, protect biodiversity, and maximize carbon sequestration potential. By reducing uncertainties in ESMs and providing early warning signs of change, enhanced EOs will be critical for transparent emissions tracking, accountable climate action, and achieving global climate stabilization goals.

## Data availability statement

No new data were created or analysed in this study.

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