

Supplementary Information for “Atmospheric CO₂ reversals do not diagnose land-carbon recovery”

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Supplementary text

S1. Annual record: year-to-year structure and event subsets

These analyses support the annual comparison in Figure 1: the year-to-year structure of the record, the reference used for the recovery years and the strong El Niño subsets. Table S1 lists the ten events and their recovery years.

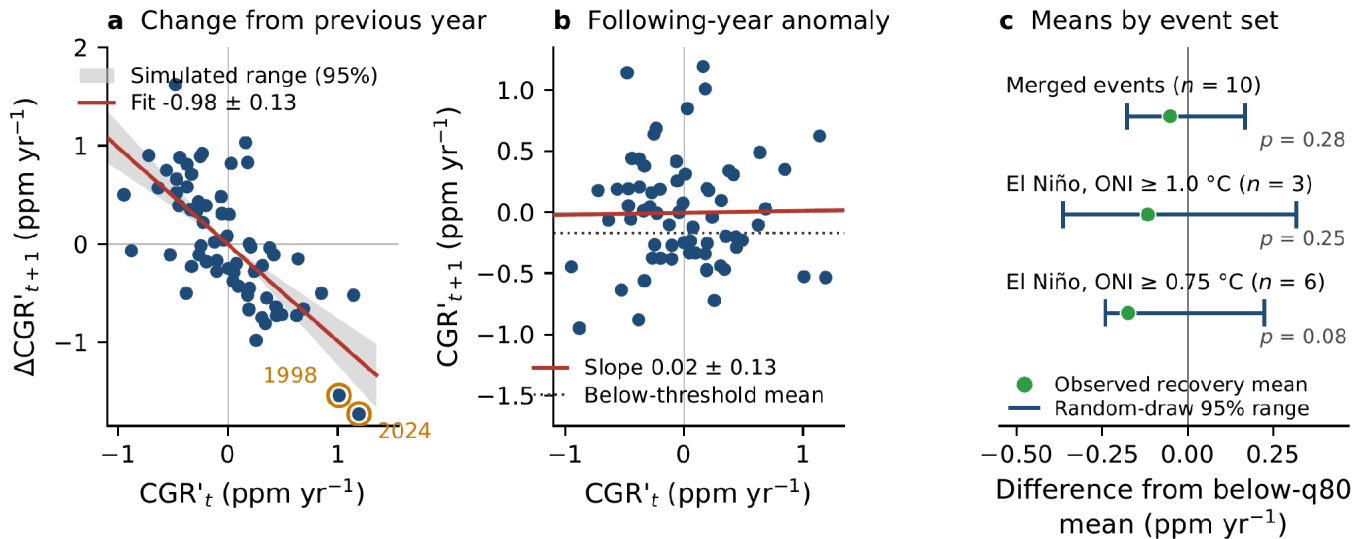
Table S1 | The 10 merged events and their recovery years. Consecutive high years merge into one event labelled by its onset year; the recovery year is the year after the last high year of the run, which is below q80 by construction. All growth rates and anomalies are in ppm yr⁻¹; the composite uncertainty is a standard error across events. The last column gives the calendar-year mean ONI of the recovery year, quoted to one decimal place because several values fall exactly halfway between hundredths.

Event	High years	Largest anomaly (ppm yr ⁻¹)	Recovery year	CGR (ppm yr ⁻¹)	Recovery anomaly (ppm yr ⁻¹)	Recovery-year ONI (°C)
1972	1972, 1973	+0.38	1974	0.68	-0.47	-0.9
1977	1977	+0.69	1978	1.29	+0.03	-0.1
1979	1979, 1980	+0.85	1981	1.15	-0.20	-0.3
1983	1983	+0.44	1984	1.23	-0.20	-0.5
1987	1987, 1988	+1.14	1989	1.47	-0.10	-0.6
1998	1998	+1.01	1999	1.33	-0.53	-1.2
2002	2002	+0.42	2003	2.28	+0.31	+0.3
2005	2005	+0.44	2006	1.77	-0.29	+0.1
2015	2015, 2016	+0.64	2017	2.14	-0.23	-0.1
2024	2024	+1.19	2025	2.06	-0.54	-0.3
Composite					-0.22 ± 0.08	

Annual changes and following-year anomalies

A large decline after a high-CGR year can occur when growth simply returns to its usual range. We therefore examined both the size of the decline and whether a high anomaly predicts a low anomaly in the following year. Across 66 year pairs, the fitted slopes are -0.98 ± 0.13 for the change and 0.02 ± 0.13 for the following-year anomaly (Fig. S1a, b; uncertainties are standard errors). The near-zero following-year slope indicates little linear association between successive annual anomalies. The two slopes are linked: the change is the following-year anomaly minus the preceding anomaly. When both relationships use the same year pairs and include an intercept, the slope for the change is exactly one less than the following-year slope. The negative change slope therefore supplies no separate evidence for a recovery sink.

To show the range of slopes expected from random annual fluctuations, we generated 10,000 series matching the 67-year record. Each simulated anomaly combined a small contribution from the preceding year with an independent, normally distributed random contribution. The preceding-year contribution was multiplied by the observed correlation between successive anomalies (0.016); the random contribution had zero mean and a size chosen to reproduce the observed variance. We discarded the first 50 simulated years before retaining 67 years, then fitted the change against the preceding anomaly. Figure S1a shows the central 95% of these slopes as lines through zero; the shading is not a prediction range for individual observations.



Supplementary Figure S1 | Annual CGR changes and following-year anomalies. a, Change against the preceding anomaly; orange circles mark 1998 and 2024. b, Following-year against preceding anomaly. Panels a and b show the same data: the change in a is the following-year anomaly in b minus the preceding anomaly, so the slope in a is the slope in b less one. Fitted-slope uncertainties are standard errors. Shading in a spans the central 95% of simulated regression slopes, drawn as lines through zero; the simulations match the annual anomaly variance and correlation between successive years. The dotted line in b marks the below-q80 mean. c, Recovery means (green) as differences from the below-q80 mean for the ten merged events and for the strong El Niño cases selected by calendar-year mean ONI ≥ 1.0 °C ($n = 3$) and ≥ 0.75 °C ($n = 6$). Bars span the central 95% range of means of the same number of years drawn at random from the below-q80 years; p values are one-sided. All panels use the NOAA global CGR record.

Recovery-year reference and strong El Niño cases

Recovery years fall below q80 because a further high year would otherwise belong to the same event. Random draws from below-threshold years therefore provide the appropriate comparison and give $p = 0.28$ (Fig. S1c). Drawing instead from all years would give $p = 0.042$: that reference includes high positive anomalies that cannot occur in the recovery-year sample. The lower p value would consequently reflect a difference in how the samples were selected.

Calendar-year mean ONI ≥ 1.0 °C identifies 1987, 1997 and 2015. Each lies within or immediately precedes a merged high-CGR event (1987–1988, 1998 and 2015–2016). Taking the year immediately after the ONI year would select 1988, 1998 and 2016, which still have high CGR. We instead identify recovery after the final high-CGR year, giving 1989, 1999 and 2017. Lowering the ONI threshold to 0.75 °C adds 1965, 1972, 1982 and 2023. The 1965 case has no corresponding high-CGR event; the six recovery years are therefore 1974, 1984, 1989, 1999, 2017 and 2025. Their mean anomaly is -0.34 ± 0.08 ppm yr $^{-1}$ ($p = 0.077$; Fig. S1c). Historical ERSSTv5 ONI was retained for consistent dating, although NOAA changed its official monitoring index in February 2026 (National Weather Service, 2026).

What distinguishes the largest recoveries

The two most negative recovery years of the record, 2025 (-0.54 ppm yr $^{-1}$) and 1999 (-0.53 ppm yr $^{-1}$), follow the largest event (2024, $+1.19$ ppm yr $^{-1}$) and the third largest (1998, $+1.01$; Table S1). An overshoot sink predicts that larger losses leave larger deficits to refill, but the ordering already breaks at the second-largest event: 1987–1988 ($+1.14$) has the third-weakest recovery (-0.10). Recovery-year climate predicts the two strongest recoveries as well, because the largest high-CGR events are El Niño events and are typically followed by La Niña conditions.

Across the ten events, the recovery anomaly is more closely related to the recovery-year ONI ($r = 0.66$, $p = 0.04$) than to the size of the preceding loss, taken as the largest anomaly within the event ($r = -0.35$, $p = 0.32$). After removing what ONI explains from both series, the relationship with loss size falls to $r = -0.19$ ($p = 0.63$). These correlations use unrounded ONI, which Table S1 reports to one decimal place. The 1987–1988 event makes the same point individually: it has the second-largest anomaly of any event ($+1.14$ ppm yr⁻¹) but the third-weakest recovery (-0.10 ppm yr⁻¹). The 1998–1999 transition is the case where the alternatives are strongest, with the most negative recovery-year ONI of the record (-1.2 °C) and the largest fire contribution of any transition (Supplementary Text S4).

With ten events these are weak tests, and they do not exclude a contribution from pool replenishment. They show that the ordering of recovery years does not by itself separate replenishment from recovery-year climate.

S2. Alternative atmospheric growth-rate records

We repeated the Figure 1 analysis using growth-rate estimates from the GCB2025 inversion ensemble and the GRESO satellite method (Pandey et al., 2024). These estimate changes throughout the atmosphere and test whether the result depends on how well the marine boundary layer record represents those changes (Pandey et al., 2025). The surface-only inversions share surface CO₂ observations with the NOAA network, so they are alternative estimates rather than independent observations.

The inversion growth-rate record takes the per-system atmospheric accumulation from the “Atmospheric Growth” sheet of the GCB2025 workbook, divided by 2.124 to express ppm yr⁻¹ (Friedlingstein et al., 2026). The retained local workbook snapshot has modification date 28 March 2026 and SHA-256 ef7a68cb8f7d140abfe44a2d7aad2dba5eaadbaf6b128494e2111adff10a5358; no internal release version is recorded. The cited version 1.1 cannot be confirmed from this file. We took the median of the same six surface-only inversions used for monthly fluxes, requiring at least three available systems, for 2000–2024. The two satellite records use GRESO GOSAT for 2010–2025 and GRESO OCO-2 for 2015–2025. Annual growth is the sum of monthly boundary increments; the five-month smoothing applies only to the exported monthly series. Because their standalone records contain few completed events, we extended them backwards with the inversion median for 2000–2009 and 2000–2014, respectively. Each combined record was detrended and assigned its own q80 over its available coverage.

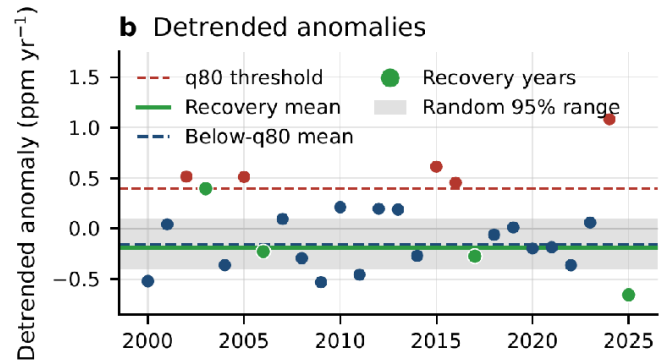
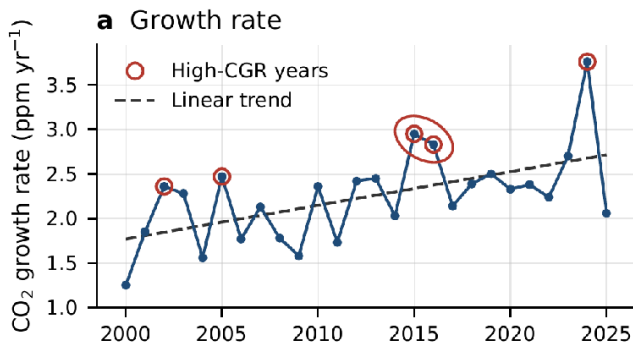
The inversion record and the two combined records (the inversion median extended with GRESO GOSAT, and with GRESO OCO-2) begin in 2000, so we also repeated the NOAA analysis for 2000–2025 (Fig. S2a, b). Over 2000–2024 the inversion median and NOAA record differ by 0.004 ppm yr⁻¹ on average (standard deviation of the difference 0.15 ppm yr⁻¹; correlation 0.96). GOSAT and OCO-2 growth rates differ from the inversion median by 0.00 and 0.01 ppm yr⁻¹ over their overlaps (correlations 0.98 and 0.99). We therefore joined the records without an offset adjustment.

None of these recent-period comparisons shows clear additional recovery uptake (Table S2). Event dates differ because each record has its own trend and threshold. In particular, 2016 is a high year in the NOAA record but a recovery year with a positive anomaly in the inversion and combined satellite records. This changes the sign of the small recovery difference. Table S2 gives each event set, mean and comparison. The inversion record ends before the 2025 recovery, and the satellite records alone contain only one or two recovery years. With three or four completed events in the longer records, the comparisons provide limited evidence about the recent period while remaining consistent with the full NOAA result.

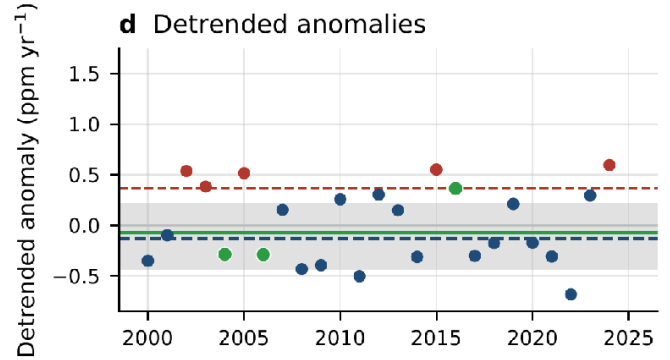
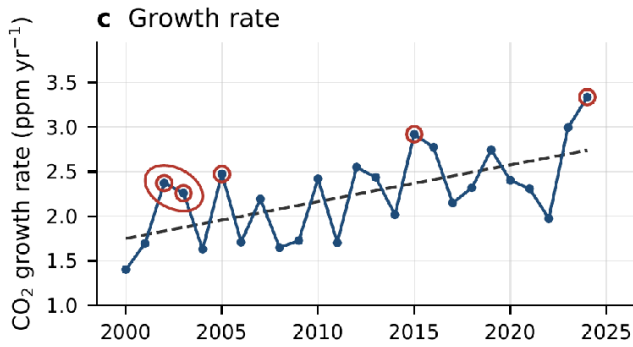
Table S2 | Event analysis repeated on alternative growth-rate records, 2000 onwards. Each record is linearly detrended and thresholded over its own coverage; the reference is the record's own below-q80 years. Values are ppm yr⁻¹. The one-sided p compares the recovery mean with 200,000 random draws of the same number of below-q80 years. SE is the standard error across events.

Record	Coverage	High years (merged events)	Recovery years	Recovery mean $\pm$ SE	Below-q80 mean	One-sided p
NOAA global	2000–2025	2002; 2005; 2015–2016 ; 2024	2003, 2006, 2017, 2025	–0.19 $\pm$ 0.22	–0.15 (n = 21)	0.39
GCB2025 inversion median	2000–2024	2002–2003 ; 2005; 2015; 2024	2004, 2006, 2016	–0.07 $\pm$ 0.22	–0.13 (n = 20)	0.66
Inversion + GRESO GOSAT	2000–2025	2002; 2005; 2015; 2023–2024	2003, 2006, 2016, 2025	–0.07 $\pm$ 0.26	–0.13 (n = 21)	0.65
Inversion + GRESO OCO-2	2000–2014 + 2015–2025	2002; 2005; 2015; 2023–2024	2003, 2006, 2016, 2025	–0.08 $\pm$ 0.26	–0.14 (n = 21)	0.64
GRESO GOSAT alone	2010–2025	2015; 2023–2024	2016, 2025	–0.17 $\pm$ 0.49	–0.14 (n = 13)	0.46
GRESO OCO-2 alone	2015–2025	2023–2024	2025	–0.55 (n = 1)	–0.16 (n = 9)	0.22

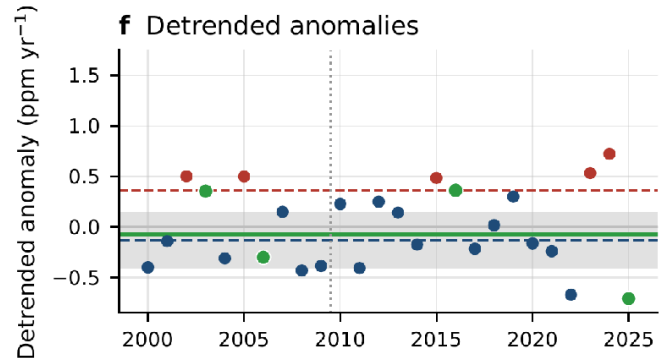
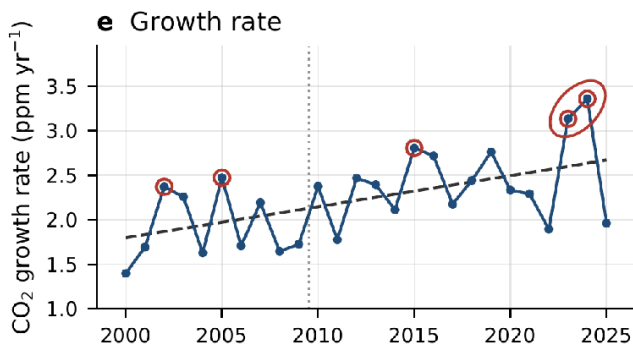
NOAA global, 2000-2025



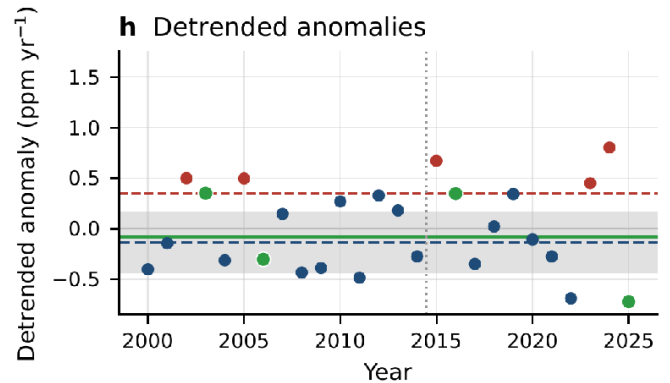
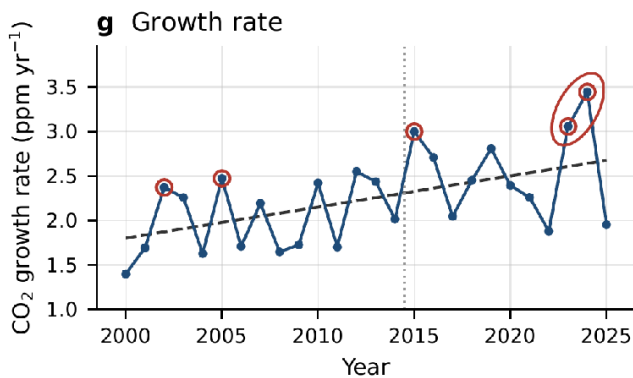
GCB2025 inversion median, 2000-2024



Inversion 2000-2009 + GRESO GOSAT 2010-2025



Inversion 2000-2014 + GRESO OCO-2 2015-2025



Supplementary Figure S2 | Event analysis on alternative growth-rate records, 2000 onwards. Rows show the NOAA global record over 2000–2025 (a, b), the GCB2025 six-system surface-only inversion median over 2000–2024 (c, d), the inversion median extended with GRESO GOSAT growth rates from 2010 (e, f), and the inversion median extended with GRESO OCO-2 growth rates from 2015 (g, h). Left panels: annual growth rate with the fitted linear trend (dashed); red circles mark years above the record's own q80 and ellipses join consecutive high years. Right panels: detrended anomalies (blue and red dots), the q80 threshold (red dashed), recovery years (green dots), the recovery mean (green line), the mean of

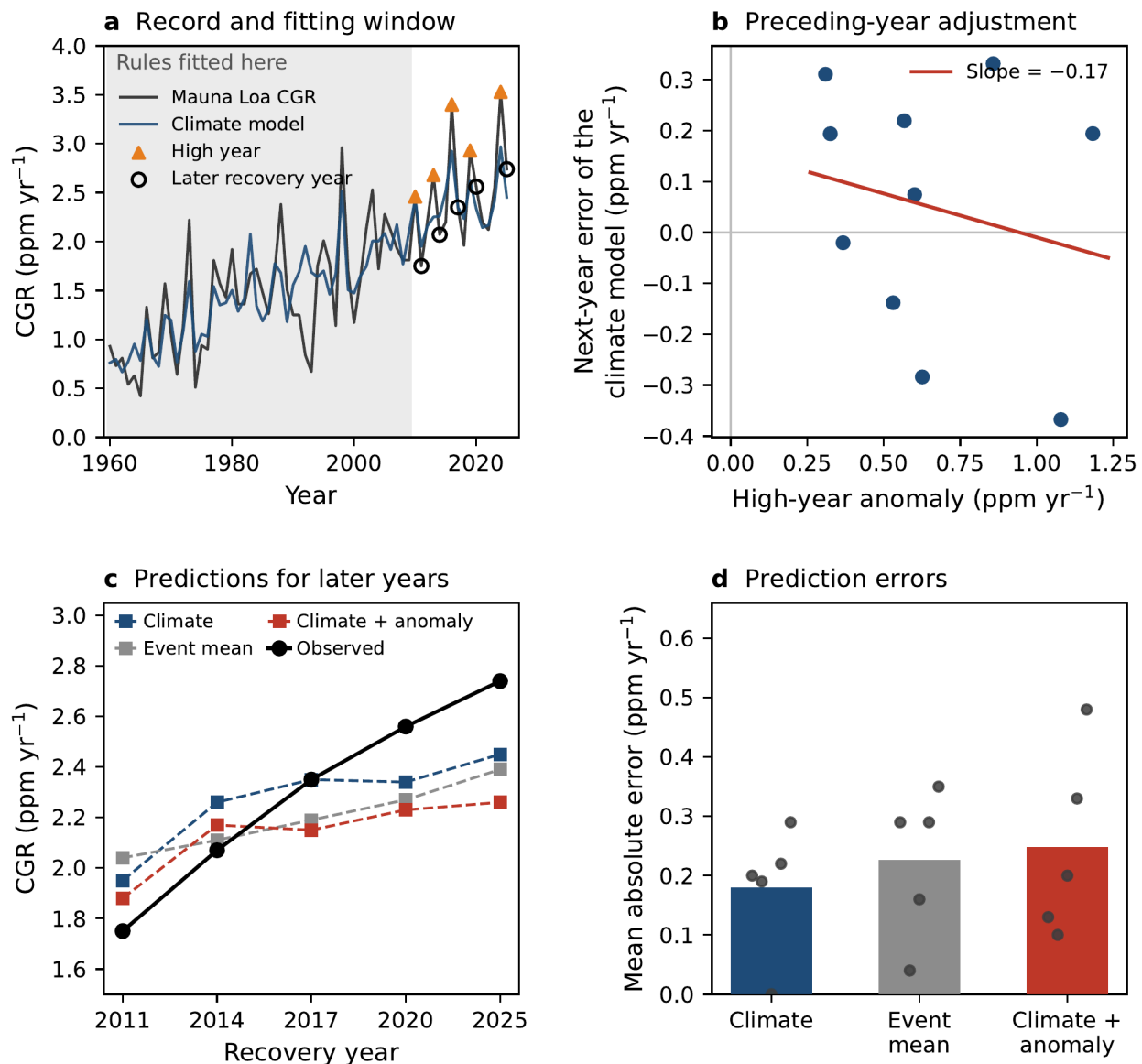
the record's below-q80 years (blue dashed) and the central 95% range of means of the same number of below-q80 years drawn at random (grey band). Vertical dotted lines mark the first satellite year in the spliced records. Layout and symbols follow Figure 1.

S3. Climate-based prediction test

If preceding carbon loss affects recovery-year uptake, the preceding CGR anomaly might improve predictions beyond climate and emissions alone. We tested this using Mauna Loa growth rates calculated as the difference between successive calendar-year mean concentrations. We fitted the relationships, straight-line trend and q80 threshold using 1960–2009, then kept them unchanged when identifying later events and predicting their recovery years: 2011, 2014, 2017, 2020 and 2025. Consecutive later high years were merged. These dates differ from the primary global event dates because the atmospheric record and annual growth-rate definition differ.

We compared three predictions. The first used annual fossil emissions and Niño3 averaged from July of the preceding year through June of the recovery year (Huang et al., 2025; NOAA Physical Sciences Laboratory, 2026), with a fitted constant. The second added the preceding CGR anomaly multiplied by a factor fitted from ten historical high years and the errors of the first prediction in their following years (Fig. S3b). Only the fitted slope supplied this adjustment; no additional constant was added. The third used the earlier average following-year anomaly added to the extrapolated growth-rate trend. Fossil emissions come from Global Carbon Budget 2025 (Global Carbon Project, 2026), exclude cement carbonation, and use the 2024 value for 2025 because the budget record ends in 2024.

We measured error as the average size of the difference between predicted and observed growth, regardless of sign. This mean absolute error was 0.18 ppm yr⁻¹ for climate plus emissions, 0.23 for the earlier average recovery anomaly, and 0.25 when the preceding anomaly was added to climate and emissions (Fig. S3c, d). Adding the preceding anomaly did not improve these five predictions. Five years are too few to rank the approaches with confidence, and this comparison cannot separate pool replenishment from climate effects that occur together.



Supplementary Figure S3 | Predictions for five recovery years using relationships fitted before 2010. a, Mauna Loa growth rates and the climate-and-emissions fit; shading marks 1960–2009, triangles the later high years and open circles their recovery years. b, Following-year prediction error against the preceding high-year anomaly for ten historical cases. The slope of this fitted line supplies the preceding-anomaly adjustment. c, Observed growth and three predictions using relationships kept unchanged after 2009. “Event mean” uses the earlier mean following-year anomaly added to the fitted trend. d, Mean absolute prediction error; grey dots show individual years. Growth rates are differences between calendar-year mean concentrations, so event dates differ from the primary NOAA global record.

S4. Fire emissions after high-CGR years

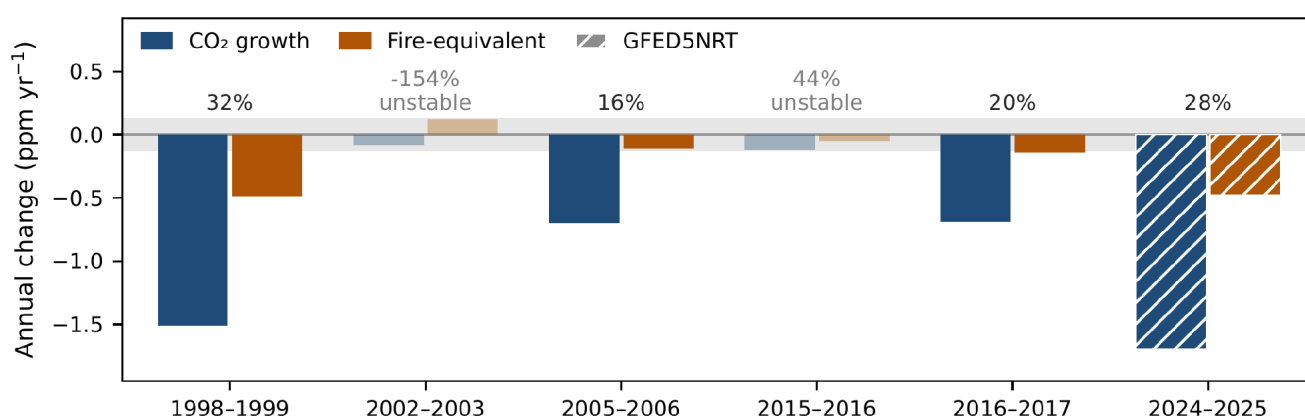
A decline in CGR can arise from increased carbon uptake or reduced emissions. We compared annual NOAA growth rates with GFED5.1 fire emissions (van der Werf et al., 2025a, 2025b) to assess how much of the decline after high-CGR years can be explained by reduced burning.

Fire emissions reduce net land uptake, so a drop in burning after an extreme fire year can appear as a stronger sink without vegetation absorbing extra carbon. Each transition follows a high-CGR year. GFED5.1 covers five individual high-year transitions. For each, we divided the decline in fire emissions by the decline in atmospheric accumulation, expressing both in the same carbon units. The atmospheric changes in 2002–2003 and 2015–2016 were no larger than 0.13 ppm yr^{-1} in magnitude. Such small denominators make the calculated percentages highly sensitive to small differences, so these transitions are greyed in Figure S4 and are not interpreted. Declining fire emissions account for 32% of the

1998–1999 decline, 16% in 2005–2006 and 20% in 2016–2017. These contributions reflect reduced emissions rather than uptake by the refill of depleted pools.

The regions in which burning changed differ between transitions, and no single region dominates any of them. We used annual emissions on the 14 GFED basis regions, from GFED5.1 through 2022 extended with GFED5NRT to 2024. In 1998–1999 the decline was spread across Southern Hemisphere Africa (−0.28 PgC), Boreal Asia (−0.22), Central America (−0.20), Northern Hemisphere Africa (−0.16) and Equatorial Asia (−0.15), partly offset by an increase in Australia (+0.14). In 2005–2006 it came mainly from Southern Hemisphere South America (−0.20), Southern Hemisphere Africa (−0.15) and Northern Hemisphere Africa (−0.13), against an increase in Equatorial Asia (+0.20). In 2016–2017 it came mainly from Boreal Asia (−0.18), Southeast Asia (−0.13) and Northern Hemisphere Africa (−0.12). Each transition therefore combines declines in several regions with increases in others, so the global fire contribution does not correspond to a single regional fire episode. Regional GFED5NRT grids are available through December 2025; the regional analysis reported here used a cutoff of December 2024, while the 2024–2025 comparison below is global.

GFED5.1 ends in 2022, so we used the near-real-time extension GFED5NRT, which covers 2023–2025, to include the 2024–2025 transition (Chen et al., 2026a, 2026b). Global fire carbon emissions fell from 4.03 PgC in 2024 to 3.02 PgC in 2025, a decline of 1.01 PgC or 0.48 ppm, against a CGR decline of 1.70 ppm. Reduced burning therefore accounts for 28% of the 2024–2025 decline (Fig. S4, hatched), within the 16–32% range of the three transitions above. The 2025 total is a full calendar year of the near-real-time product and is treated as preliminary. GFED5NRT does not overlap GFED5.1, so the two products cannot be compared against each other here; the 2024–2025 calculation uses GFED5NRT for both years, which limits the effect of any systematic difference between them.



Supplementary Figure S4 | Fire-emission changes after high-CGR years. Change in NOAA CGR (blue) and the matching change in fire emissions expressed in the same units ("fire-equivalent", orange; converted using 2.124 PgC per ppm), from each covered high year to the following year. Negative values are declines. Labels give the fraction of the CGR change matched by the fire change; a negative fraction means the two changed in opposite directions. Grey shading spans ± 0.13 ppm yr⁻¹, the range within which the denominator is too small for a stable fraction: the faded 2002–2003 and 2015–2016 transitions fall inside it and are not interpreted. GFED5.1 covers 1997–2022, so the 2024–2025 pair is taken from the GFED5NRT extension and is hatched to mark the change of product.

S5. Monthly records, event comparisons and flux persistence

Monthly records allow us to examine uptake that an annual average could conceal. This section describes the records used in Figure 2, the effect of changing the recovery-window length, and a separate check of regional responses after large loss months.

Records and preparation

The six surface-only inversions are Jena CarboScope r76nbetEXToc_v2025, NISMON-CO2 v2025.1, CT-NOAA CT2025, CTE2025, MIROC-ACTM v2025 and UoE v2025. The eight satellite-assimilating inversions are NISMON-CO2_GOSAT v2025.1 and NTFVAR v2025 (GOSAT; from January 2010), and CAMS-Satellite FT25r1, GCASv2 v2025, GONGGA v2025, THU v2025, CMS-Flux and COLA v2025 (OCO-2; from January 2015). NTFVAR, CMS-Flux and COLA also assimilate surface observations. Membership follows Supplementary Table S4 of Friedlingstein et al. (2026).¹ All members end in December 2024. The gridded file's observing-system flags for UoE and NISMON-CO2_GOSAT are transposed. UoE belongs to the surface-only group and NISMON-CO2_GOSAT to the satellite-assimilating group; the flux arrays remain attached to the correct model names.

Inversion fluxes use the GCB2025 gridded product, version 1_0_20251031, at 1° resolution (Luijkx et al., 2025). For Figure 2 and the latitude-band comparisons, we multiplied flux per unit area by grid-cell area and summed each inversion's fluxes before taking the median. Months outside a member's coverage contain declared fill values (1×10^{20}), which were masked before integration; missing or invalid months were excluded. Medians require at least three surface-only members from January 2000 or two satellite-assimilating members from January 2010. Two GOSAT systems cover 2010–2014; eight satellite-assimilating systems are available from January 2015. The continental-box calculation uses a different order, described below.

We removed the long-term change and repeating seasonal cycle from each area-integrated inversion flux series (global, latitude band or continental box) rather than from individual 1° grid cells, allowing the seasonal cycle to change gradually. The joint fit contains a quadratic trend and sine and cosine terms with periods of 12, 6, 4 and 3 months; the coefficients of the 12- and 6-month terms can change linearly with time. The harmonics were evaluated on elapsed time in years from 1 January 2000 (365.25-day years), with the inversion fractional-year coordinate rounded to four decimals. Subtracting the fit gives the anomalies. GRESO uses OCO-2 growth rates from January 2015, preceded by GOSAT for 2010–2014 (Pandey et al., 2024). Their mean difference during overlap is less than 0.003 ppm yr⁻¹, so no offset is applied at the join. GRESO anomalies subtract a straight-line trend evaluated on the supplied fractional-year coordinates rounded to three decimals and are multiplied by 2.124 to express PgC yr⁻¹. All three Figure 2 records are then averaged over each month and its two neighbours, with positive anomalies indicating net release from land to the atmosphere for the inversion records and faster atmospheric growth for GRESO.

Recovery windows and their comparison

The Figure 2 reference uses actual twelve-month stretches of each record, retaining the variation between neighbouring months. We drew 10,000 sets with the same number of windows as observed recoveries; repeating the comparison with independent draws changes the one-sided p values by less than 0.02. Starting months must fall below q80 and have sufficient subsequent coverage, including the last complete window. Random draws use NumPy PCG64 with seed 20260918. Starts differ within each set, although the windows can overlap. The one-sided p value is the fraction of set means at or below the observed recovery mean. Grey bands contain the central 95% of these means. The gap from their average to their

¹ The gridded file's observing-system flags for UoE and NISMON-CO2_GOSAT are transposed. UoE belongs to the surface-only group and NISMON-CO2_GOSAT to the satellite-assimilating group; the flux arrays remain attached to the correct model names.

5th percentile gives the additional uptake needed to place a recovery mean below 95% of the random means. This is a comparison threshold, not an upper bound on the true recovery sink or a measure of the probability of detecting it.

Short recovery windows can still contain the declining tail of a loss episode, whereas longer windows include more subsequent climate variation. We therefore repeated the comparison for 3–24 months (Table S3), keeping the event definition in Methods. The share of La Niña months varies with record and window length. ONI is joined by explicit calendar month, with DJF assigned to January through NDJ assigned to December. In twelve-month windows the La Niña share is 31% for surface-only inversions, 38% for satellite-assimilating inversions and 10% for GRESO. The table uses a common climate reference of 30% over 2000–2025; this is not a separate reference matched to each record's coverage.

The GRESO recovery window from December 2024 to November 2025 averages $-1.24 \text{ PgC yr}^{-1}$. Only 4.3% of eligible random twelve-month windows are as low, and it ranks sixth of all 179 twelve-month stretches in that record. This describes one unusually low recovery window, without identifying the cause of the decline.

Table S3 | Effect of recovery-window length in the monthly records. Each cell gives the recovery mean minus the mean of random windows of the same length (PgC yr^{-1}), its one-sided p value, the number of complete events (n), and the percentage of recovery months with $\text{ONI} \leq -0.5^\circ\text{C}$ (La Niña). Negative differences indicate lower release or greater uptake. The common La Niña reference is 30% over 2000–2025.

Window (months)	Surface-only inversions	Satellite-assimilating inversions	GRESO growth rate
3	+0.37 (p = 0.97; n = 16; La Niña 31%)	+0.58 (p = 0.94; n = 6; La Niña 33%)	+0.84 (p = 0.99; n = 5; La Niña 0%)
6	+0.30 (p = 0.93; n = 15; La Niña 33%)	+0.31 (p = 0.80; n = 6; La Niña 39%)	+0.31 (p = 0.83; n = 5; La Niña 10%)
9	+0.22 (p = 0.87; n = 15; La Niña 34%)	+0.13 (p = 0.66; n = 6; La Niña 37%)	+0.07 (p = 0.60; n = 5; La Niña 9%)
12	-0.02 (p = 0.47; n = 14; La Niña 31%)	-0.29 (p = 0.21; n = 5; La Niña 38%)	-0.09 (p = 0.42; n = 5; La Niña 10%)
18	-0.16 (p = 0.17; n = 14; La Niña 28%)	-0.44 (p = 0.08; n = 5; La Niña 43%)	-0.16 (p = 0.36; n = 4; La Niña 14%)
24	-0.11 (p = 0.19; n = 14; La Niña 28%)	-0.38 (p = 0.08; n = 5; La Niña 44%)	-0.33 (p = 0.14; n = 4; La Niña 20%)

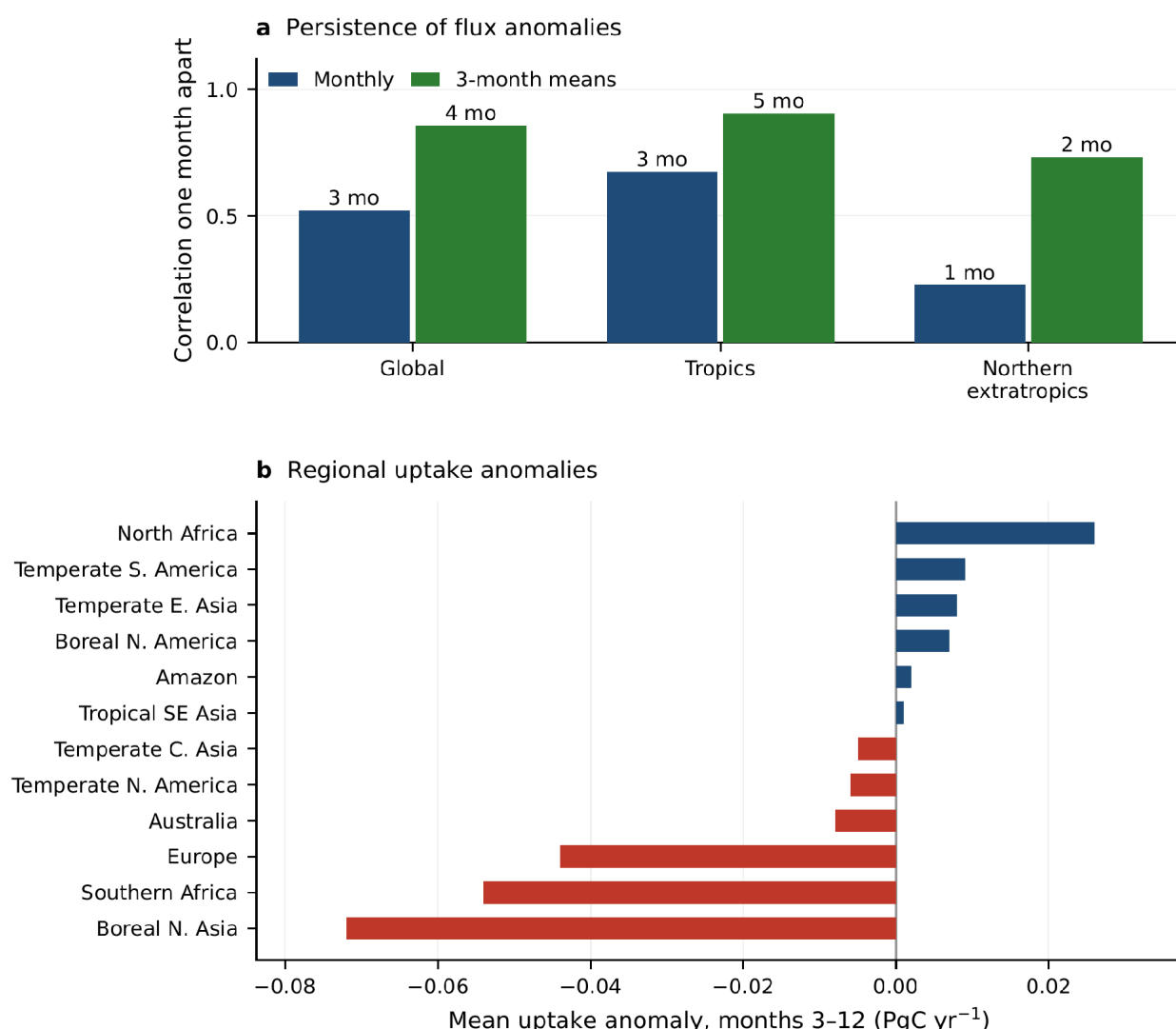
Regional responses and persistence

Global means can conceal uptake in one region offset by losses elsewhere. We therefore examined regional responses and how long flux anomalies persist in the six-member surface-only inversion median, 2000–2024. This check uses the first month of a run above q90, the highest 10% of loss anomalies, rather than the end of a q80 event as in Figure 2. There are fifteen global, twelve tropical and twenty-one northern-extratropical loss onsets. The tropics include 23.5°S – 23.5°N ; the northern extratropics use grid-cell centres strictly north of 23.5°N . The correlation between unsmoothed monthly anomalies falls below $1/e$ (about 0.37) after 1–3 months; three-month averaging extends this to 2–5 months (Fig. S5a). The northern monthly lag-1 correlation is 0.233.

The twelve continental boxes are defined in Table S5. For these boxes, we first took the median flux across available inversions in each grid cell, then summed the area-integrated fluxes within the box. At least three members were required. This differs from the sum-before-median calculation for the global and latitude-band records. The boxes are not an exhaustive division of the globe, and their fluxes need not sum to the global median. We removed the trend and seasonal cycle using the same fitted functions described above. Positive anomalies in this analysis mean greater uptake, the opposite sign to Figure 2.

We averaged each region's anomalies over months 3–12 after the fifteen global onsets (Fig. S5b). Comparisons used 3,000 random sets of fifteen onset months. The first six and last twenty-five months

were excluded as possible onsets to retain complete response windows. Eligible months were equally likely, could be drawn more than once in a set, and were not matched by calendar month. For each set, we calculated the same fixed-period mean. The one-sided p value is the fraction of random means at least as large as the observed uptake mean. None of the twelve regions showed greater uptake at the 5% level. In the later window, months 12–24, global uptake averaged $+0.19 \text{ PgC yr}^{-1}$ ($p = 0.12$), including $+0.14$ in the tropics ($p = 0.16$); northern uptake averages $+0.041 \text{ PgC yr}^{-1}$. Both windows include their stated endpoints. These regional and timing checks did not identify clear additional uptake.



Supplementary Figure S5 | Persistence and regional responses of land-flux anomalies in the six surface-only GCB2025 inversions, 2000–2024. a, Correlation between anomalies one month apart, before and after three-month averaging; labels give the first lag at which correlation falls below $1/e$ (about 0.37). b, Mean regional uptake anomaly during months 3–12 after fifteen global q90 loss onsets, defined as the first month of a run in the highest 10% of loss anomalies. This onset-based q90 definition differs deliberately from the q80 event-end definition used in Figure 2. Blue bars indicate greater uptake and red bars weaker uptake than the fitted trend and seasonal cycle. Region boundaries are in Table S5. The random-month comparisons are described in Supplementary Text S5.

S6. Disturbance size and carbon-pool recovery

A prescribed disturbance need not leave an equally large carbon deficit, because pools begin adjusting while the disturbance is still occurring. The model is Equations 2 to 4 in Methods. Each disturbance is applied at a constant rate for one year (Table S4). All other disturbance terms are zero, and i , E_B and

E_L return to zero after that year. No disturbance-driven transfer between pools is imposed, and turnover rates are unchanged during each disturbance; one experiment uses a faster biomass turnover rate throughout its run (Table S4). Litter combustion isolates fire loss from litter while leaving living biomass intact; biomass combustion isolates direct fire loss from living biomass. The net sink integrated over a year equals the change in total stored carbon. Internal biomass-to-litter transfer alone does not release carbon to the atmosphere.

Table S4 | Settings and outcomes of the two-pool experiments in Figure 3. Each prescribed disturbance totals 2 PgC over one year; i , E_B and E_L are the disturbance terms of Equations 2 to 4 and all return to zero afterwards. Actual losses fall below the prescribed 2 PgC where litter is involved or biomass turns over quickly, because those pools adjust within the event year. Following-year uptake is positive for a sink. The last two columns repeat each experiment with the prescribed disturbance rescaled so that the actual loss is 2 PgC throughout, removing the differing losses from the comparison.

Disturbance	Non-zero event-year terms (PgC yr ⁻¹)	Actual carbon loss (PgC)	Following-year uptake (PgC yr ⁻¹)	Prescribed for a 2 PgC loss (PgC)	Uptake at a 2 PgC loss (PgC yr ⁻¹)
Reduced plant productivity input	$i = -2$	2.00	0.02	2.00	0.02
Litter combustion	$E_L = 2$	1.57	0.62	2.54	0.79
Biomass combustion, all released	$E_B = 2$	2.00	0.02	2.00	0.02
Biomass combustion, 2-year biomass turnover	$E_B = 2$; $k_B = 0.5 \text{ yr}^{-1}$	1.93	0.28	2.07	0.29
Reduced plant productivity input and litter combustion	$i = -1$; $E_L = 1$	1.78	0.32	2.24	0.36

Table S5 | Continental boxes used for the regional inversion analysis in Figure S5b. Grid-cell centres on the stated boundaries are included. These boxes do not form an exhaustive global partition, and they are simple latitude–longitude boxes rather than the RECCAP2 region masks.

Region	Latitude bounds	Longitude bounds
Boreal North America	50–70°N	170–55°W
Temperate North America	25–50°N	130–60°W
Amazon	15°S–5°N	80–45°W
Temperate South America	40–15°S	75–45°W
Europe	35–70°N	10°W–40°E
Boreal North Asia	50–70°N	40–180°E
Temperate Central Asia	30–50°N	40–110°E
Temperate East Asia	20–50°N	110–150°E
North Africa	0–15°N	18°W–45°E
Southern Africa	35°S–0°	5–50°E
Australia	40–12°S	112–155°E
Tropical Southeast Asia	10°S–20°N	90–150°E

S7. Model selection, event timing and pool diagnostics

Model selection and calendar treatment

The original analysis considered 22 models from the TRENDY v14 S3 archive. ISBA-CTRIP and OCN were omitted because their S3 directories were empty; iMAPLE, supplied only in compressed archives,

was outside this original model set and is not added here. Models required at least 30 years of NBP, mean NBP within $\pm 20 \text{ PgC yr}^{-1}$, annual standard deviation below 6 PgC yr^{-1} and negative correlation between detrended NBP and observed CGR. Twenty-one qualified. CARDAMOM covers 2003–2024 and is excluded for its 22-year record, rather than for excessive variability. CLASSIC, DLEM, LPJ-GUESS and LPJmL all contain 2024 and qualify after calendar decoding. The comparison including CARDAMOM is retained in Table S6.

We decoded dates using cftime with each file's units and calendar, using explicit adapters for non-CF month or year counters. Monthly fluxes were integrated with calendar-specific durations. Physical latitude/longitude coordinates were used in preference to bare lat/lon indices, including for ELM. For pool refill, monthly stocks use December values as year-end proxies; annual stock files are used as archived, because most do not specify whether they are year-end states or annual means. To diagnose flux–stock alignment, we compared NBP with changes in total carbon in the same, preceding and following years. Only CLM retains a supported +1 pairing: NBP in year y pairs with stock change in $y+1$, increasing r from 0.47 to 0.69. The previous ELM, IBIS and LPX-Bern shifts are dropped. The reported pool-refill comparison uses the decoded-date December series; the CLM +1 pairing is retained as an alignment sensitivity rather than applied to those estimates. Total carbon includes vegetation, soil and available separate litter; leaves are already included in vegetation.

Annual uptake comparisons

Table S6 compares uptake in the recovery year with the appropriate non-event reference. Additional uptake after observed events was positive in twenty of twenty-one selected models and twenty of all 22 analysed models. The selected models have nine NOAA-defined recovery years and 52 non-high-CGR reference years. CARDAMOM contributes only three recovery and eighteen reference years to the all-22 sensitivity. Quadratic trends use 1959–2024 for every selected model and the available 2003–2024 record for CARDAMOM. Missing years were not filled. Standard errors describe variation across model means, which share forcing and aspects of model development and are not independent observations.

Table S6 | Annual uptake comparisons and sensitivity tests in the TRENDY DGVMs. Values are anomalies in PgC yr^{-1} , positive for uptake. Additional uptake is the recovery mean minus its reference, with the standard error across model means. Observed-event comparisons use non-high-CGR years as the reference; model-defined events use years outside the lowest 20% of NBP anomalies. Dashes mark quantities not reported in this summary. Quoted p values are two-sided tests across models.

Comparison	Recovery mean $\pm$ SE	Reference mean	Additional uptake $\pm$ SE	p
Observed events, 21 selected models	$+0.68 \pm 0.09$	$+0.21$	$+0.47 \pm 0.08$	—
Observed events, all 22 analysed models (including CARDAMOM)	$+0.64$	$+0.20$	$+0.44 \pm 0.08$	—
Model-defined events, quadratic trend	$+0.32 \pm 0.04$	$+0.30$	$+0.022 \pm 0.035$	0.55
Model-defined events, straight-line trend	—	—	-0.045 ± 0.047	0.34
Model-defined events, three following years required	—	—	$+0.029 \pm 0.035$	0.42

Model-defined events group consecutive low-NBP years, and recovery follows the final year of each group. The additional uptake remains close to zero when changing the fitted trend or requiring three following years of coverage (Table S6). Treating observed high-CGR years individually instead gives

thirteen following years, four of which are still high-CGR years, and mean uptake of $+0.29 \text{ PgC yr}^{-1}$. That calculation describes year-to-year transitions rather than recovery after completed events. The mean anomaly in the final high year is $-0.74 \pm 0.07 \text{ PgC yr}^{-1}$ across ten observed events; only nine recoveries are covered because the 2024 event's recovery falls in 2025. Figure 4a uses these nine covered events at every lag, giving a final-high-year mean of $-0.76 \pm 0.07 \text{ PgC yr}^{-1}$ for that plotted subset.

For the same nine recovery years, retaining the primary NOAA trend and reference gives atmospheric-equivalent uptake of $+0.395 \text{ PgC yr}^{-1}$, or $+0.034$ above its reference. The full atmospheric sample also includes 2025. Atmospheric accumulation responds to the full carbon budget, so its difference from modelled land uptake does not by itself measure model error. In Figure 4a, the tropics span 23.5°S – 23.5°N and the northern extratropics lie north of 23.5°N . Following-year uptake anomalies are $+0.68 \text{ PgC yr}^{-1}$ in the tropics, positive in twenty models, and $-0.09 \text{ PgC yr}^{-1}$ in the northern extratropics; the northern mask is strictly $>23.5^{\circ}\text{N}$. The northern value means weaker uptake than the fitted trend, not necessarily an absolute source. GPP anomalies change from -0.68 during the event to $+0.78 \text{ PgC yr}^{-1}$ in the following year; heterotrophic respiration changes from $+0.22$ to $+0.03$ and fire from $+0.05$ to $-0.12 \text{ PgC yr}^{-1}$. The GPP change is about eight times the respiration change and ten times the fire change. Increased GPP can reflect recovery-year climate and contribute to rebuilding pools, so these fluxes alone do not distinguish the two.

Turnover and pool replenishment

For sixteen models with the required data, ecosystem turnover time is the ratio of mean total carbon stock to mean annual GPP over 1995–2024, using annual-mean stocks. Figure 4b plots recovery-year NBP anomalies, which have no clear relationship with turnover time ($r = +0.22$, $p = 0.42$); the fit uses unrounded values. Recovery-year uptake in this comparison, and the GPP, respiration and fire anomalies, use straight-line detrending. The annual NBP comparisons in Table S6 use quadratic trends unless stated otherwise; stock anomalies also subtract quadratic trends.

We then asked whether a given pool loss was followed by more replenishment after observed high-CGR events than in other years. For each pool, $C(y)$ denotes the stock anomaly after removing a quadratic trend over its available 1959–2024 record using the decoded-date stock convention above. Depletion is $C(y-1)-C(y)$, and refill is $C(y+1)-C(y)$. Positive values denote a stock decrease and subsequent increase, respectively; negative values are also retained. An event year is the last high-CGR year of an observed merged event, and all comparisons require the preceding and following stock years. Non-event years are the other eligible years in each model.

For each pool, we fitted two straight lines relating refill to preceding depletion, one for event years and one for other years, combining the available models and years in each fit. Their slope difference gives additional refill per unit of preceding loss, not a carbon flux. We repeated the full comparison 2,000 times after randomly assigning distinct eligible event years within each model, preserving its event count. Figure 4c shows the central 95% of these random differences. The one-sided p value is the fraction at least as large as the observed difference. These random-reference ranges differ from uncertainty on the observed estimate.

Pool data are available for sixteen litter, twenty-one vegetation and soil, and seventeen leaf models. The litter slope difference is $+0.32$ (one-sided $p = 0.002$), outside the central 95% random-year range of -0.23 to $+0.23$. Soil gives $+0.10$ ($p = 0.20$) within its random range; vegetation and leaves give negative estimates within their ranges. To express the litter result on an approximate flux scale, we multiplied its slope difference by the mean absolute year-to-year change in litter-stock anomalies, averaged across models. The resulting value is about 0.10 PgC yr^{-1} , about one-fifth of the additional net uptake of 0.47 PgC yr^{-1} ; this conversion does not isolate a litter contribution to net uptake.

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