Contributions to accelerating atmospheric CO_2 growth from economic activity, carbon intensity, and efficiency of natural sinks

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The growth rate of atmospheric carbon dioxide (CO_2), the largest human contributor to human-induced climate change, is increasing rapidly. Three processes contribute to this rapid increase. Two of these processes concern emissions. Recent growth of the world economy combined with an increase in its carbon intensity have led to rapid growth in fossil fuel CO_2 emissions since 2000: comparing the 1990s with 2000–2006, the emissions growth rate increased from 1.3% to 3.3% y^{-1}. The third process is indicated by increasing evidence ($P = 0.89$) for a long-term (50-year) increase in the airborne fraction (AF) of CO_2 emissions, implying a decline in the efficiency of CO_2 sinks on land and oceans in absorbing anthropogenic emissions. Since 2000, the contributions of these three factors to the increase in the atmospheric CO_2 growth rate have been ≈65 ± 16% from increasing global economic activity, 17 ± 6% from the increasing carbon intensity of the global economy, and 18 ± 15% from the increase in AF. An increasing AF is consistent with results of climate–carbon cycle models, but the magnitude of the observed signal appears larger than that estimated by models. All of these changes characterize a carbon cycle that is generating stronger-than-expected and sooner-than-expected climate forcing.

airborne fraction | anthropogenic carbon emissions | carbon–climate feedback | terrestrial and ocean carbon emissions | vulnerabilities of the carbon cycle

The rate of change of atmospheric CO_2 reflects the balance between anthropogenic carbon emissions and the dynamics of a number of terrestrial and ocean processes that remove or emit CO_2 (1, 2). The long-term evolution of this balance will determine to a large extent the speed and magnitude of human-induced climate change and the mitigation requirements to stabilize atmospheric CO_2 concentrations at any given level.

In recent years, components of the global carbon balance have changed substantially with major increases in anthropogenic emissions (3) and changes in land and ocean sink fluxes due to climate variability and change (4).

In this article, we report a number of changes in the global carbon cycle, particularly since 2000, with major implications for current and future growth of atmospheric CO_2. To quantify the importance of these changes, we update and analyze datasets on CO_2 emissions from fossil fuel combustion and cement production (F_{Foss}), CO_2 emissions from land use change (F_{LUC}), the carbon intensity of global economic activity, and estimated trends in the CO_2 balance of the oceans and of ecosystems on land.

We also quantify the relative importance of key processes responsible for the observed acceleration in atmospheric CO_2 concentrations. This attribution provides insights into key leverage points for management of the carbon cycle and also indicates the present significance of carbon–climate feedbacks associated with the long-term dynamics of natural CO_2 sinks and sources.

Results and Discussion

Growth in Atmospheric CO_2. Global average atmospheric CO_2 rose from 280 ppm at the start of the industrial revolution (≈1,750) to 381 ppm in 2006. The present concentration is the highest during the last 650,000 years (5, 6) and probably during the last 20 million years (7). The growth rate of global average atmospheric CO_2 for 2000–2006 was 1.93 ppm y^{-1} [or 4.1 petagrams of carbon (PgC) y^{-1}, Table 1]. This rate is the highest since the beginning of continuous monitoring in 1959 and is a significant increase over growth rates in earlier decades: the average growth rates for the 1980s and the 1990s were 1.58 and 1.49 ppm y^{-1}, respectively (Fig. 1).

CO_2 Emissions. From 1850 to 2006, fossil fuel and cement emissions released a cumulative total of ≈330 PgC to the atmosphere (1 PgC = 1 petagram or 10^9 metric tons of carbon). An additional 158 PgC came from land-use-change emissions, largely deforestation and wood harvest (see *Methods* for data sources and uncertainties).

Fossil fuel and cement emissions (F_{Foss}) increased from 7.0 PgC y^{-1} in 2000 to 8.4 PgC y^{-1} in 2006, 35% above emissions in 1990. The average F_{Foss} for 2000–2006 was 7.6 ± 0.4 PgC y^{-1} (Table 1). The average proportional growth rate of F_{Foss}[k] increased from 1.3% y^{-1} for 1990–1999 to 3.3% y^{-1} for 2000–2006 (Fig. 1*B*).

Model-based estimates of emissions from land-use change (F_{LUC}) remained approximately constant from 1959 to 2006,

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Abbreviations: AF, airborne fraction; GWP, gross world product; kgC, kilograms of carbon; PgC, petagrams of carbon.

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[k]These growth rates are slightly different from those in ref. 3 because the CDIAC dataset used in ref. 3 was for 2000–2005, and the one used here is for 2000–2006. This update involved revisions to global emissions data for the 1990s, as well as the addition of 2006 data, mainly to resolve earlier discrepancies in emissions data from China (supporting information figure 10 in ref. 3).

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Table 1. Summary of means and proportional trends of the global carbon budget for various time periods

Global carbon budget	Mean 1959–2006	Mean 1970–1999	Mean 1990–1999	Mean 2000–2006	Proportional trend, % y^{-1} 1959–2006
Economy, kgC/U.S. dollars					
Carbon intensity	0.29*	0.30	0.26	0.24	−1.18†
Sources, PgC y^{-1}					
Fossil Fuel (F_{Foss})	5.3	5.6	6.5	7.6	2.12
Land Use Change (F_{LUC})	1.5	1.5	1.6	1.5	0.21
Total ($F_{Foss}+F_{LUC}$)	6.7	7.0	8.0	9.1	1.71
Sinks, PgC y^{-1}					
Atmosphere	2.9	3.1	3.2	4.1	1.89
Ocean	1.9	2.0	2.2	2.2	1.25
Land	1.9	2.0	2.7	2.8	1.87
Distribution of annual emissions					
Atmosphere‡	0.43	0.44	0.39	0.45	0.25 ± 0.21§
Ocean	0.28	0.28	0.27	0.24	−0.42
Land	0.29	0.28	0.34	0.30	0.06

*The proportional trend for a quantity $X(t)$ is $\langle X\rangle^{-1}\langle dX/dt\rangle$, where angle brackets denote an average over the indicated period.
†Data available from 1970 only.
‡This is the airborne fraction.
§This value (mean ± standard deviation) of the proportional trend in AF was determined from the noise-reduced (monthly) series for AF (see *Methods* and *SI Text*). All other proportional trend estimates were derived from the annual series.

averaging 1.5 ± 0.5 PgC y^{-1}. These estimates were based on rates of change in areas of land cultivated, harvested, or reforested (see *Methods*). From 1959 to 1980, ≈30% of emissions from land-use change originated in the extratropics. This extratropical contribution decreased after 1980, reaching zero by 2000. The remaining land-use emissions originated largely from deforestation in tropical America and Asia, with a smaller contribution from tropical Africa. From 2000 to 2006, land-use emissions from tropical Asia rose significantly to 0.6 PgC y^{-1}, whereas emissions from the American tropics decreased from >0.9 PgC y^{-1} in 1990 to 0.6 PgC y^{-1} in 2006. The emissions from these two regions are now similar in magnitude for the first time since the 1950s. Emissions from tropical Africa have remained constant at ≈0.2 PgC y^{-1} for the last 25 years.

From 2000 to 2006, the average total anthropogenic CO_2 emission ($F_{Foss}+F_{LUC}$) was 9.1 PgC y^{-1}, rising from 8.4 PgC y^{-1} in 2000 to 9.9 PgC y^{-1} in 2006, with an annual rate of increase of 2.9% y^{-1} compared with an average rate of increase of 0.7% y^{-1} for the period of the 1990s (Table 1).

Carbon Intensity of the Global Economy. The carbon intensity of gross world product (GWP), defined as the ratio F_{Foss}/GWP, provides a measure of the CO_2 emissions required to produce a unit of economic activity at a global scale. In the 3 decades before 2000, the carbon intensity of GWP[¶] declined from 0.35 kilograms of carbon (kgC)/dollar in 1970 to 0.24 kgC/dollar in 2000. This trend represents a decrease (improvement) of ≈1.3% per year. Since 2000, however, the carbon intensity of GWP stopped decreasing and has increased (deteriorated) at ≈0.3% per year (Fig. 1*A* and Table 1) (3).

Continuous improvements in the carbon intensity of the world economy are postulated in practically all scenarios for future emissions (8). The effect of these projected improvements is to hold the rate of global emissions growth below the rate of global economic growth. The recent combination of rapidly increasing emissions and deteriorating carbon intensity of GWP amplifies the challenge of stabilizing atmospheric CO_2 (9).

¶The GWP data used throughout this paper are based on market exchange rates (MER). In ref. 3, we show that our main conclusions, particularly the reversal of the trend in Fig. 1*A*, are evident using either the MER or purchasing power parity definition for GWP.

Natural Sinks and CO_2 Airborne Fraction (AF). The annual increment in atmospheric CO_2 is substantially smaller than the increment in anthropogenic emissions, because natural sinks on land and in the ocean remove part of the anthropogenic CO_2. The relative efficiency of these sinks can be measured by the annual AF, the ratio of the atmospheric CO_2 increase in a given year to that year's total emissions ($F_{Foss}+F_{LUC}$). AF is a function of the biological and physical processes governing land–atmosphere and ocean–atmosphere CO_2 exchanges, as well as the trajectory of anthropogenic CO_2 emissions. The AF has a large interannual variability and has ranged from 0.0 to 0.8 since 1959 (Fig. 2*A*). This variability is mainly due to the responses of natural sinks, particularly land sinks (Fig. 1*B*), to interannual climate variability (e.g., from El Niño/Southern Oscillation) and volcanic eruptions (10). Of the average 9.1 PgC y^{-1} of total anthropogenic emissions ($F_{Foss}+F_{LUC}$) from 2000 to 2006, the AF was 0.45; almost half of the anthropogenic emissions remained in the atmosphere, and the rest were absorbed by land and ocean sinks. To partition the fluxes between these two sinks, we estimated the annual ocean uptake for 1959–2006 with an ocean general-circulation model coupled to a biogeochemical model, forced by observed climate and CO_2 concentration (11). The model reproduces the observed mean sink of 2.2 ± 0.4 PgC y^{-1} for the 1990s (12). We calculated net land exchange (excluding emissions from land-use change) as the residual. On the basis of this partitioning, the ocean sink accounted for 0.24 of total anthropogenic emissions from 2000 to 2006, and the land sinks accounted for the remaining 0.30.

Changes in the long-term efficiency of the natural sinks in removing atmospheric CO_2, as measured by the ratio of sinks to emissions, are indicated by the proportional trend in the AF $[(1/AF)dAF/dt]$. Over the period 1959–2006, this was +0.25 ± 0.21% y^{-1} (mean ± standard deviation of estimate), with significance $P = 0.89$ for a trend >0 [Table 1 and Fig. 2*A*; see *Methods* and supporting information (SI) *Text* for computational and statistical details]. Although the significance of this trend is lower than the conventional criterion of $P = 0.95$, the observed AF trend is sufficiently significant to justify reflecting it in the attribution of recent changes in the growth rate of atmospheric CO_2.

Climate models that include a representation of carbon cycle

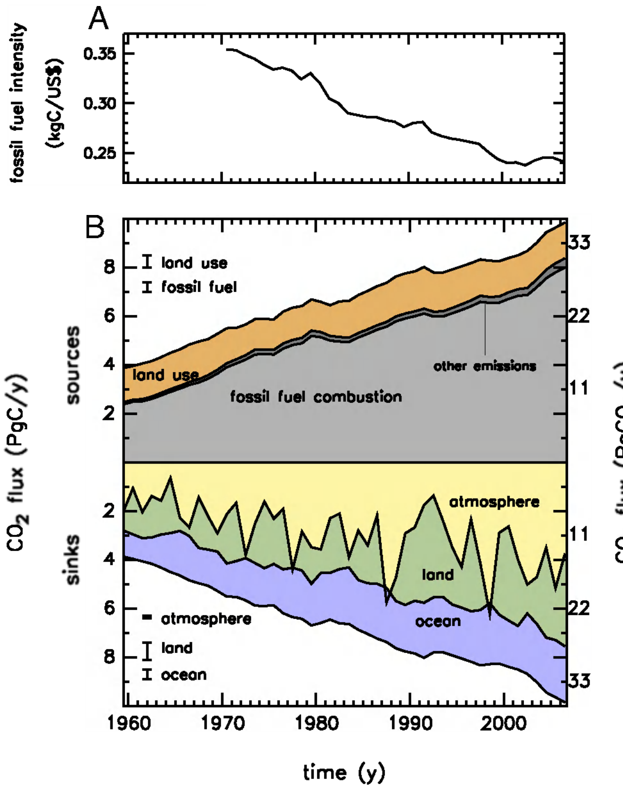

Fig. 1. Fossil-fuel intensity of the GWP from 1970 to 2006 (*A*) and the CO_2 budget from 1959 to 2006 (*B*). Fossil-fuel intensity uses GWP data based on market exchange rates, expressed in U.S. dollars (referenced to 1990, with inflation removed). (*B Upper*) CO_2 emissions to the atmosphere (sources) as the sum of fossil fuel combustion, land-use change, and other emissions, which are primarily from cement production. (*Lower*) The fate of the emitted CO_2, including the increase in atmospheric CO_2 plus the sinks of CO_2 on land and in the ocean. Flux is in Pg y^{-1} carbon (left axis) and Pg y^{-1} CO_2 (right axis).

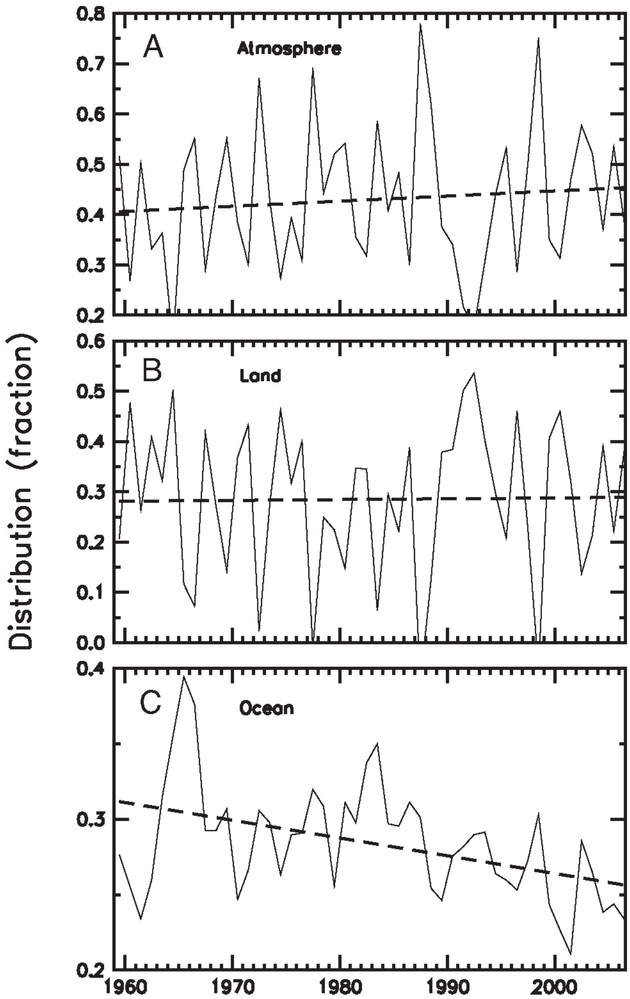

Fig. 2. Fraction of the total emissions (F_{Foss} + F_{LUC}) that remains in the atmosphere (*A*), the land biosphere (*B*), and the ocean (*C*).

sinks estimate a proportional trend in the AF during the 21st century of 0.41 ± 0.23% y^{-1} (mean ± standard deviation across 11 models) under a Special Report on Emission Scenarios (SRES) A2 scenario (13). However, over the 1959–2006 time period, 9 of the 11 models estimate a decrease in AF, and the mean proportional trend is −0.27 ± 0.36% y^{-1} (11 models). These results suggest that the observed carbon-cycle feedbacks occur faster than expected by our current understanding of the processes driving the sinks.

The increase in the AF implies that carbon emissions have grown faster than CO_2 sinks on the land and oceans. Because the land and oceans are both mosaics of regions that are gaining and regions that are losing carbon, this trend could result from any or all of three scenarios: sink regions could have weakened, either absolutely or relative to growing emissions; source regions could have intensified; or sink regions could have transitioned to sources.

Whereas both land and ocean sinks continue to accumulate carbon on average at ≈5.0 ± 0.6 PgC y^{-1} since 2000, large regional sinks have been weakening. In the Southern Ocean, the poleward displacement and intensification of westerly winds caused by human activities has enhanced the ventilation of carbon-rich waters normally isolated from the atmosphere at least since 1980, and contributed nearly half of the decrease in the ocean CO_2 uptake fraction estimated by the model (Fig. 2*C*; ref. 11). On land, a number of major droughts in midlatitude regions in 2002–2005 have contributed to the weakening of the growth rate of terrestrial carbon sinks in these regions (14–17).

Attribution of Factors Driving the Atmospheric CO_2 Growth Rate. The growth rate of atmospheric CO_2 depends on three classes of factors: global economic activity (generated from the use of fossil fuels and land-use change), the carbon intensity of the economy, and the functioning of unmanaged carbon sources and sinks on land and in oceans. Since 2000, a growing global economy, an increase in the carbon emissions required to produce each unit of economic activity, and a decreasing efficiency of carbon sinks on land and in oceans have combined to produce the most rapid 7-year increase in atmospheric CO_2 since the beginning of continuous atmospheric monitoring in 1959. This is also the most rapid increase since the beginning of the industrial revolution (18).

We estimate that 35 ± 16% of the increase in atmospheric CO_2 growth rate between 1970–1999 and 2000–2006 was caused by the decrease in the efficiency of the land and ocean sinks in removing anthropogenic CO_2 (18 ± 15%) and by the increase in carbon intensity of the global economy (17 ± 6%). The remaining 65 ± 16% was due to the increase in the global economy (see *Methods*).

Many of the existing scenarios for the 21st century assume continued economic growth (9), although none assume the long-term maintenance of the growth rates that have characterized China and India over the last decade. The overwhelming majority of the existing scenarios project sustained decreases in the carbon intensity of the global energy system. The recent acceleration of emissions is a consequence of many factors, including an overall surge in energy demand and production of electricity from coal, increased energy per capita, and population growth (3, 19).

The rapid growth in the atmospheric CO_2 growth rate since 2000 is caused by increasing CO_2 emissions (associated in turn with accelerating global economic growth and an increasing carbon intensity of the global economy) and also an increase in the AF of CO_2 emissions. Together, these effects characterize a carbon cycle that is generating stronger-than-expected climate forcing sooner than expected.

Methods

Original data to complete the global carbon budget are generated by multiple agencies and research groups around the world and are collated annually by the Global Carbon Project (www.globalcarbonproject.org). Data are available for the period of 1850–2006 and can be downloaded from www.globalcarbonproject.org/carbontrends.

Atmospheric CO_2 Concentration. We use monthly and annual-mean atmospheric CO_2 concentration analyzed and compiled by the National Oceanic and Atmospheric Administration (NOAA) Earth System Research Laboratory in Colorado (www.esrl.noaa.gov/gmd/ccgg/trends) and published by the Carbon Dioxide Information Analysis Center (CDIAC) along other historical data based on ice core analyses (http://cdiac.ornl.gov/trends/co2/contents.htm). From 1959 to 1980, data came from the Mauna Loa observatory (Hawaii, U.S.) and since 1980 represent a globally averaged CO_2 concentration using weighted observations from many laboratories.

Carbon Emissions from Fossil Fuel. Carbon emissions from fossil fuel combustion were based on country-level energy data, plus estimates on the global consumption of coal, oil, and natural gas, by using standard conversions to CO_2 emission (20, 21). Emissions from the calcining of limestone to produce cement add ≈3.8% to global CO_2 emissions. From 1950 to 2004, we used the energy statistics published by the United Nations (U.N.) Department for Economic and Social Information and Policy Analysis (22). Energy statistics are compiled from annual questionnaires distributed by the U.N. Statistical Office and supplemented by official national statistical publications. For the years 2005 and 2006, data from the British Petroleum *Statistical Review of World Energy* (23) were used. Statistics on cement production are compiled by the U.S. Department of Interior's Geological Survey. Carbon dioxide emissions from fossil fuels and cement since 1751 are archived and distributed by the CDIAC (24).

Carbon Emissions from Land-Use Change. Emissions due to land use change (e.g., harvesting of forest products and clearing for agriculture) include the net flux of carbon between the terrestrial biosphere and the atmosphere resulting from deliberate changes in land cover and land use (25, 26). Global net-carbon fluxes from changes in land use were estimated with a bookkeeping model to track the carbon in living vegetation, dead plant material, wood products, and soils for each hectare of land cultivated, harvested, or reforested. We used the carbon emissions for the period of 1959–2000 (25), calculated the emissions for the period 2000–2005, and revised the estimates for the 1990s (which changed from 2.1 PgC y^{-1} to 1.6 PgC y^{-1}) by using the updated and revised data on land-use change from the U.N. Food and Agriculture Organization Global Forest Resource Assessment (26). Data for 2006 are not available, but it has been assumed to be the same as in the period 1990–2005. Historical data from 1850 are archived and distributed by the CDIAC (27).

Carbon Intensity of the Global Economy. The carbon intensity of the global economy is calculated as F_{Foss}/GWP. This measure is the product of the energy consumed per dollar of economic activity (the energy intensity of the economy) and the carbon emitted per unit of energy (the carbon intensity of the energy). The GWP is the total gross national product of all of the countries in the world, i.e., the total world gross domestic product. The data are collected and analyzed by the United Nations Statistics Division. The data are based on market exchange rates expressed in U.S. dollars and referenced to 1990, with inflation removed.

Trend in AF. We used three time series to determine the trend in the AF, AF $= (dC_a/dt)/(F_{Foss} + F_{LUC})$, where dC_a/dt is the growth rate of atmospheric CO_2 (C_a, PgC y^{-1}). The first "annual" AF series used the annual mean data as described above. The second "monthly" series was constructed from monthly atmospheric CO_2 data, with removal from dC_a/dt of the regularly repeating annual cycle in global CO_2 caused mainly by the spring vegetation flush in the Northern Hemisphere. The third "noise-reduced" series was another monthly series in which a filtering method was used to reduce noise by removing the component of dC_a/dt correlated with El Niño events and volcanic activity. Methodologies for constructing the second and third series are given in *SI Text*.

The trend in AF was estimated by fitting a first-order autoregressive (1) model to the monthly AF data as in ref. 12. The statistical significance of the trend was estimated from a 1,000-member Monte Carlo ensemble simulation, which had similar noise properties as the AF data. Finally, the standard deviation of the trends from the 1,000-member simulation was calculated to provide the uncertainty in the result.

The three time series yielded nearly identical proportional trends in AF, with values of $0.24 \pm 0.33\%\ y^{-1}$ ($P = 0.76$) for the annual series, $0.24 \pm 0.34\%\ y^{-1}$ ($P = 0.79$) for the monthly series, and $0.25 \pm 0.21\%\ y^{-1}$ ($P = 0.89$) for the noise-reduced series. The significance of the results increases between the annual and the monthly series because of the larger number of independent data, as well as between the monthly and noise-reduced series because of the removal of natural variability, which does not show any trends. We used the results with the highest significance, those from the noise-reduced data.

Data Uncertainty. The uncertainty in the sources and sinks of CO_2 were estimated as follows:

- An uncertainty of 5% was assigned to emissions from fossil fuel and cement, which takes into account errors in the reporting of energy statistics and in the conversion from energy consumption to CO_2 emissions.
- An uncertainty of ±0.5 PgC y^{-1} was assigned to land-use change. This uncertainty is revised downwards from previous assessments (28) because our land-use estimates calculated with the revised Food and Agriculture Organization Global Forest Assessment (26) are now consistent with three independent estimates based of satellite data and terrestrial models (29–31). Emissions from land-use change remain as the most uncertain of all quantities required to close the global carbon budget.
- An uncertainty of ±0.04 PgC y^{-1} was estimated for the C accumulation in the atmosphere on the basis of the standard deviation of the observations. This uncertainty is low because of the high quality of atmospheric CO_2 measurements and because of the fast-mixing time scale of the atmosphere, which allows for an estimation of a global mean value with relatively few sites.
- An uncertainty of ±0.4 PgC y^{-1} was assigned to the ocean CO_2 sink on the basis of the convergence of the estimates for the

1990s by both the model used here and estimates based on oceanic and atmospheric observations (32–34), as in ref. 12.

- An uncertainty of ± 0.7 PgC y^{-1} was assigned to the land sink from a quadratic sum of the uncertainty in the other components of the CO_2 budget. Note that the uncertainty of the land plus ocean sinks (± 0.6 PgC y^{-1}) is smaller than their combined uncertainties because it is based on the quadratic sum of the uncertainties in the emissions and atmospheric CO_2 growth rate.
- The uncertainty in AF is 9%, which is based on the quadratic sum of the uncertainties in dC_a/dt and of the total emissions. The trend in annual AF of 0.25% y^{-1} exceeds the uncertainty in the annual AF after 36 years, for a total time series of 48 years.

Attribution of Factors Driving the Atmospheric CO_2 Growth Rate. We estimated the impact of the change in trajectory of carbon intensity between 1970–1999 and 2000–2006 by projecting the trend in carbon intensity during 1970–1999 (−0.0038 kgC/U.S. dollar per year) to the later period. The projected carbon intensity of 0.229 kgC/U.S. dollar is lower than the observed value of 0.242 in 2000–2006. The difference of 0.0129 ± 0.0045 kgC/U.S. dollar includes an uncertainty of ±1 standard deviation estimated from fitting a first-order autoregressive (1) model and computing a 1,000-member simulation, as for the AF, but applied to the departure of the 2000–2006 carbon intensity from the extrapolated trend. The P value of this time series exceeds 0.99. To calculate CO_2 emissions, we multiplied this projected intensity by the GWP for 2000–2006 of $31.4 trillion (including an estimated uncertainty on GWP of ≈5%) to obtain an excess emission in 2000–2006 of 0.405 ± 0.143 PgC y^{-1}. Finally, we used the observed AF of 0.45 (including its 9% uncertainty) to estimate the excess atmospheric CO_2 growth rate in 2000–2006 of 0.182 ± 0.066 PgC y^{-1}. This contribution corresponds to 17 ± 6% of the observed increase in the CO_2 growth rate between 1970–1999 and 2000–2006, which was 1.047 PgC y^{-1}.

We estimated the impact of the increase in AF by multiplying the trend in AF (0.25 ± 0.21% y^{-1}) by the time interval between 1970–1999 and 2000–2006 (18.5 years) and then by the total anthropogenic emissions ($F_{Foss} + F_{LUC}$) during 2000–2006 (9.1 PgC y^{-1}). This product of 0.19 ± 0.16 PgC y^{-1} is the excess CO_2 growth rate due to the increase in AF. It corresponds to 18 ± 15% of the increase in atmospheric CO_2 growth rate between the two time periods [(0.19 PgC y^{-1})/(1.047 PgC y^{-1})].

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SUSTAINABILITY SCIENCE

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