Warming climate extends dryness-controlled areas of terrestrial carbon sequestration

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At biome-scale, terrestrial carbon uptake is controlled mainly by weather variability. Observational data from a global monitoring network indicate that the sensitivity of terrestrial carbon sequestration to mean annual temperature ($T$) breaks down at a threshold value of 16°C, above which terrestrial CO2 fluxes are controlled by dryness rather than temperature. Here we show that since 1948 warming climate has moved the 16°C isotherm poleward. Land surface area with $T > 16°C$ and now subject to dryness control rather than temperature as the regulator of carbon uptake has increased by 6% and is expected to increase by at least another 8% by 2050. Most of the land area subjected to this warming is arid or semi-arid with ecosystems that are highly vulnerable to drought and land degradation. In areas now dryness-controlled, net carbon uptake is ~27% lower than in areas in which both temperature and dryness ($T < 16°C$) regulate plant productivity. This warming-induced extension of dryness-controlled areas may be triggering a positive feedback accelerating global warming. Continued increases in land area with $T > 16°C$ has implications not only for positive feedback on climate change, but also for ecosystem integrity and land cover, particularly for pastoral populations in marginal lands.

Warming climate is altering climate-control mechanisms of terrestrial carbon sequestration1–4. The direct observational evidence5 provided by a global network (FLUXNET) of continuous in situ measurements of land-atmosphere exchanges of CO2, water vapour and energy across biomes and continents, indicates that terrestrial CO2 fluxes are: (1) strongly limited by mean annual temperature ($T$) of less than 16°C at mid- and high-latitudes; (2) strongly limited by dryness at mid- and low-latitudes; and (3) co-limited by both temperature and dryness around the mid-latitude belt (45°N). The sensitivity of terrestrial CO2 fluxes to $T$ breaks down at ~16°C, a threshold value above which no further increase of CO2 uptake with increasing temperature was observed and dryness influence overrules temperature influence. Here, we examine a hypothesis that the threshold-latitude belt at which $T$ is 16°C is shifting poleward as the Earth’s surface warms and hence the areas of dryness-control of terrestrial CO2 fluxes ($T > 16°C$) is expanding. We use global land temperature data6–7 (1948–2012) to test this hypothesis and examine the potential consequences of warming-induced extension of the dryness-controlled area on climate change.

We calculated land area where $T$ is higher than or equal to 16°C for each year during the period from 1948 to 2012 using mean monthly surface temperature data ($0.5° \times 0.5°$ resolution) from the National Centers for Environmental Prediction-National Center for Atmospheric Research (NCEP/NCAR) reanalysis dataset. We refer to land area with $T \geq 16°C$ as dryness-controlled areas where terrestrial CO2 fluxes are limited by dryness and not by temperature5. A pronounced increase in the dryness-controlled area occurred following a slight drop before 1976, mirroring the variation with land warming (Fig. 1a). About 90% of the variance in the extension of the dryness-controlled area was accounted for by land warming ($R^2 = 0.90, p < 0.0001$, see Fig. 1b).

We assume that net ecosystem-atmosphere exchanges of CO2 (NEE) in the areas close to the cold side ($T < 16°C$) of the shifted boundary are controlled by both temperature and dryness5, written as $\text{NEE}^a$ that is predicted by equation (1) (see Methods Summary). For NEE in the area on the warm side ($T > 16°C$) of the shifted boundary, it is written as $\text{NEE}^p$, that is determined by dryness alone through equation (2). How will increasing $T$ affect NEE in area that shifts from control by both $T$ and dryness ($T < 16°C$) to control by dryness alone ($T > 16°C$)? We estimated the difference between $\text{NEE}^a$ and $\text{NEE}^p$ by applying a NEE model (see Methods Summary) that was derived from datasets collected by a worldwide, tower-based, observational network5 to the shifted area. The climate data used in the model were $T$ and dryness averaged over the period...
Dryness was calculated from the monthly datasets of net incoming short-wave radiation and net long-wave outgoing radiation of the NCEP/NCAR reanalysis and the gridded monthly terrestrial precipitation datasets. This data-driven estimate indicates that CO$_2$ transfer from the atmosphere to the biosphere is reduced by 27% in the shifted area where $T$ changed from less than to greater than 16°C. Qualitatively, the model prediction reveals a positive feedback mechanism: climate warming extends the dryness-control area, which reduces CO$_2$ transfer from the atmosphere to biosphere. Thus, because the atmospheric CO$_2$ concentration will increase at a greater rate, the climate will warm at an accelerating rate due to the positive feedback. If the global area under dryness-control (Fig. 1a) continues to increase at only the same rate as

1948–2010 with 0.5° × 0.5° spatial resolution in the shifted area. Dryness was calculated from the monthly datasets of net incoming short-wave radiation and net long-wave outgoing radiation of the NCEP/NCAR reanalysis and the gridded monthly terrestrial precipitation datasets. This data-driven estimate indicates that CO$_2$ transfer from the atmosphere to the biosphere is reduced by 27% in the shifted area where $T$ changed from less than to greater than 16°C. Qualitatively, the model prediction reveals a positive feedback mechanism: climate warming extends the dryness-control area, which reduces CO$_2$ transfer from the atmosphere to biosphere. Thus, because the atmospheric CO$_2$ concentration will increase at a greater rate, the climate will warm at an accelerating rate due to the positive feedback. If the global area under dryness-control (Fig. 1a) continues to increase at only the same rate as
occurred over the preceding half-century, the warming-induced dryness-controlled area will double by 2050.

With climate warming much of Earth’s land has been moderately drying since 1976, averaged over all land areas, based on annual Palmer Drought Severity Index (PDSI) estimates (Fig. 2a) derived from the monthly self-calibrated PDSI data 0.5° × 0.5° resolution over the spatial range from 60°S to 70°N. Our analysis finds that the drying trend in the shifted area was strongest and in land areas where \( T > 16 \) °C encompasses low latitudes in the northern hemisphere, most of Africa, Middle and South America, Australia, South- and Southeast Asia (Fig. 3). In these regions, tower-based FLUXNET...
observations document that at ground-level these large land areas indeed are drying up and this is confirmed by remote sensing data. This drying is attributed to increased evaporation and evapotranspiration due to warming. If the trend of drying up over the large land area where $T > 16\,^\circ C$ continues a strong positive feedback on warming is suggested because of reduced CO$_2$ transfer from the atmosphere to land (expansion of the brown areas in Fig. 3) via NEE that is limited substantially by water availability (see Fig. 2b in Ref. 5), thus inducing additional warming. In contrast, in the land area where mean annual temperature is below $16\,^\circ C$ (green area in Figure 3) a trend toward greater wetness has been observed with climate warming (Fig. 2).

Two large areas between the cold ($<16\,^\circ C$, green color in Fig. 3) and warm zones ($>16\,^\circ C$, brown color in Fig. 3) have different performances during El Niño/Southern Oscillation (ENSO) events (Fig. 2a, Table 1). In this analysis we included El Niño years with an oceanic Niño index (ONI) greater than +1.0 during the period between 1948 and 2012, and La Niña years with ONI less than −1.0 (Table 1). Half of the El Niño years were consistent with the cold phases (dips of temperature curve) of the cold part of the land (CPL, green area in Fig. 3), while 70% of the La Niña years were consistent with the warm phases (peaks of temperature curve) of the CPL (Table 1). The CPL warm/cold phases appeared to be opposite of the warm/cold phases of the ENSO cycle. However, if we assume that WPL temperature responses to the ENSO cycle lag by a year, 90% of El Niño years coincided with the WPL warm phases, while 80% of La Niña years coincided with the WPL cold phases. These fascinating coincidences, that became obvious after lagging the data by a year, can be understood at least theoretically in the following way. In the WPL wet phases, a much larger fraction of net radiation is used for evapotranspiration as latent heat and hence potential warming is reduced, while in the WPL dry phases, comparatively less net radiation is used as latent heat, so the temperature is increased. This energy budget adjustment may need about a year to reach equilibrium for about half of Earth’s land. Temperature responses to the ENSO cycle of the shifted area (purple color in Fig. 3) were similar to the responses of the total global land area because the temperature of the shifted area is close to the land-average temperature. However, the pattern with 60% of El Niño years being wetter while 30% La Niña years were dryer for the shifted area is coincident with the typical precipitation patterns of the ENSO cycle reported by NOAA.

The shifted areas are transitional zones where not only is the climate-control mechanism of NEE switched as discussed above, but also meteorological conditions are more variable and vegetation is highly vulnerable to climate changes and weather extremes. Dominant vegetations in the shifted regions (purple color in Fig. 3) are open shrublands (25%), croplands (22%), grasslands (7%), and desert (13%) (see Supplementary Table 1). Except for the shifted areas in southeastern China (box 4 in Fig. 3) and southeastern United States (box 1 in Fig. 3), most shifted areas are arid and...
The locations of shifted areas in the northern hemisphere are coincident with the descending branch of the Hadley cell (HC) and are consequently associated with low precipitation and high evapotranspiration rates\textsuperscript{15–18}. Several lines of evidence indicate that the HC has intensified and expanded poleward over the past three decades as a consequence of climate warming\textsuperscript{20–22} and that the HC expansion in the northern hemisphere is stronger than in southern hemisphere\textsuperscript{19}. The contemporaneous poleward shift of both the HC and the WPL (significant since late 1970s) and location of the WPL with respect to the HC (northern descending branch of the HC), strongly suggests that the WPL migration poleward is driven by global warming. The drying trend of the shifted area (Fig. 2a–b) should be expected to result in vegetation cover shift, with decreased biodiversity and desertification. A line of evidence from remote sensing imagery indicates that drying is accelerating the degradation of vulnerable shrublands in some semiarid Mediterranean area\textsuperscript{24–25}.

Division of the land into the WPL and CPL by threshold value (16°C) of annual mean temperature based on 64 years (1948–2012) climate data brings new insights into the warming of Earth’s surface. The two parts of the land behave almost opposite to each other in the phases of the ENSO cycle and differ in climate control mechanisms of carbon sequestration\textsuperscript{5,26–27}. The WPL has expanded poleward significantly (Fig. 1) and has become dryer (Fig. 2) in the past four decades. The trend of warming-induced drying of the WPL, by reducing NEE thereby reducing withdraw of CO\(_2\) from the atmosphere, contributes a positive feedback on global warming. Furthermore, as lands are shifted from CPL to WPL becoming more arid and subject to desertification, they also release soil carbon adding additional CO\(_2\) to the atmosphere. It is estimated that 19–29 Pg of carbon were added to the atmosphere from vegetation and soil carbon pools globally by desertification\textsuperscript{28}. The frontal boundary (or the shifted area) of the WPL has been transformed by global warming into more vulnerable regions where weather gradients are stronger (Fig. 2), ecosystems are more sensitive to even slight increases in water deficit (Fig. 3)\textsuperscript{25}, crop yield is reduced by extreme heat waves\textsuperscript{29}, and vegetated land cover and pastoral population are reduced. For instance, in Australia, where wide areas are becoming not suitable for sheep breeding due to reduced precipitation and increased soil salinity. An expansion of the global network\textsuperscript{30} monitoring NEE to target the identified shifted areas would provide data that could improve our ability both to model these regions as they undergo further transitions and to assess the likely impacts on climate as a consequence of altered NEE and increased soil aridity. The present work raises the following two questions: (1) what atmospheric circulation mechanisms support the hypothesis of a year time lag between the WPL temperature response and the ENSO water phases; and (2) is the synergistic poleward expansion of the frontal boundary of the WPL with the HC a long-term or a short-term behavior and what are the consequences of this synergy for global NEE and for the rate of change in atmospheric CO\(_2\)?

### Methods

Details of calculating land temperature, precipitation, net radiation, and PDSI are given in the Supplementary Information. Here we summarize the method used to estimate NEE difference induced by the switch of climate control from the CPL to WPL. For the case of the shifted area in the CPL (purple in Fig. 3), its NEE\textsuperscript{5} is limited by both temperature (T) and dryness (D) and is estimated using a bivariate-nonlinear regression model

\[
\text{NEE}^5 = -3.9855 - 0.0272T + 2.9394D - 0.0114T^2 - 0.6968D^2, \quad (1)
\]

where D is defined as \(R_n / P\), \(R_n\) is mean annual net radiation MJ m\(^{-2}\) yr\(^{-1}\), \(P\) is mean annual precipitation mm yr\(^{-1}\), and \(\lambda = (2.5 \text{ MJ kg}^{-1})\) is the enthalpy of vaporization. For another case of the shifted area in the WPL where NEE\textsuperscript{5} is limited by dryness along (T > 16°C), we use the regression model of D-limited group in Ref.5,

\[
\text{NEE}^D = -1.0110T^2 + 3.1203D^2 + 1.8055D - 8.2528. \quad (2)
\]

All the regression coefficients in equations (1)–(2) are estimated from the published eddy-covariance data (see supplementary Table S1 in Ref. 5).

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Table 1 | Temperature, PDSI, and ENSO events from different areas classified in Figure 3

| Properties | 10 El Nino years* | 10 La Nina years+ |
|------------|-------------------|------------------|
| Global Land Area | T (°C) | 70% warmer | 80% cooler |
| PDSI | 30% dryer | 40% wetter |
| Land Area Above 16°C | T (°C) | Not clear but taking 1 year lag 90% warmer | Not clear but taking 1 year lag 80% cooler |
| PDSI | 90% dryer | 70% wetter |
| Land Area Below 16°C | T (°C) | 50% cooler | 70% warmer |
| PDSI | 50% wetter | 40% dryer |
| The shifted area | T (°C) | 70% warmer | 80% cooler |
| PDSI | 60% wetter | 30% dryer |

*10 El Nino years include: 1957–1958, 1965–1966, 1972–1973, 1982–1983, 1986–1987, 1991–1992, 1994–1995, 1997–1998, 2002–2003, 2009–2010.
+ 10 La Nina years include: 1950–1951, 1955–1956, 1964–1965, 1970–1971, 1973–1974, 1975–1976, 1978–1988, 1998–1999, 2007–2008, 2010–2011.
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Author contributions
C.Y. designed the study, conducted data analysis and wrote the manuscript. S.W. performed all calculations and wrote the method part. G.H. contributed to writing the paper and the idea to link the HC extension.

Additional information
Supplementary information accompanies this paper at http://www.nature.com/scientificreports

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