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Decelerating autumn CO₂ release with warming induced by attenuated temperature dependence of respiration in northern ecosystems

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Key Points:

- Net autumn CO₂ release is decelerating with temperature in northern ecosystems
- The deceleration of net CO₂ release with warming is ascribed to the attenuation in respiration response to temperature
- This attenuated effect on autumn carbon release counteracts the recent weakening of the warming-stimulated effect on spring carbon uptake

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Abstract

Feedbacks from the carbon cycle in boreal and arctic ecosystems can significantly affect climate change, but the effects of climate change on the high-latitude carbon cycle during the dormant period remain uncertain. By analyzing the long-term atmospheric CO₂ concentration record from Point Barrow in Alaska, we show that warming significantly boosts net CO₂ release in autumn over the period 1974–2014. But this warming-stimulated effect has been attenuated since 1997. This deceleration of net CO₂ release with warming is ascribed to the attenuation in respiration response to temperature, rather than changing relationship between temperature and productivity, or changes in atmospheric transport, fossil fuel emissions or air-sea CO₂ exchanges. The attenuated respiration response is likely due to decoupling between temperature and plant-derived carbon inputs to soil for decomposition. Contrary to previous suggestions, warming no longer results in a higher autumn net CO₂ release.

1 Introduction

The northern land region that includes the tundra and boreal forests is an important component of the global carbon cycle, being a considerable sink for atmospheric CO₂ (Pan et al., 2011; McGuire et al., 2009). There is wide recognition that climate change is having, and will continue to have, fundamental impacts on the northern ecosystem carbon cycle, and in turn, on variations in atmospheric CO₂ (McGuire et al., 2009; Beer et al., 2010; Keenan et al., 2014; Heimann & Reichstein, 2008; Cox et al., 2000; Friedlingstein et al., 2001; Ahlström et al., 2012). In these northern ecosystems, a large proportion of ecosystem carbon is stored in soil and a small fractional change in soil respiration with warming could significantly affect net ecosystem production and atmospheric CO₂ concentration (Jenkinson et al., 1991; Wang et al., 2011; Commans et al., 2017). Therefore, interactions between the climate and the carbon cycle during the dormant season could be just as important in modulating future climate change as interactions during the spring and summer seasons which have been the main focus of previous studies of ecosystem responses to warming (Piao et al., 2017; Keenan et al., 2014; Guerlet et al., 2013).

Evidence has recently emerged to indicate that the response of the carbon cycle to climate change since the late 1990s has been different from that in the previous few decades (Piao et al., 2014, 2017; Peñuelas et al., 2017; Ballantyne et al., 2017). It has long been assumed that warming advances spring phenology and increases ecosystem carbon uptake (Keeling et al., 1996; Richardson et al., 2009). Although this assumption was valid up until the 1990s, it no longer holds because of the weakening temperature control of spring net primary productivity (Piao et al., 2017). Furthermore, warming-induced increases in annual CO₂ amplitude has also disappeared in recent decades (Peñuelas et al., 2017). These observational signals consistently reveal a shift in the effect of warming on carbon uptake from positive to neutral or even negative during spring and summer. However, it remains unclear how warming-stimulated carbon release during the dormant season varies with time. There is a growing consensus that ecosystem productivity shows strong acclimation to warming (Oechel et al., 2000; Smith & Dukes, 2013), and that the warming-stimulated impact on productivity, if it exists, might become more attenuated because of the limited radiation available during the dormant season. The ecosystem respiratory flux is mostly anticipated to increase with warming, although there is some evidence of the presence of respiratory acclimation (Luo et al., 2001; Atkin & Tjoelker, 2003). Therefore, we formulate the hypothesis that warming can accelerate net carbon release during the dormant season and

exacerbate the negative impact of warming on annual carbon sequestration. We test this hypothesis by synthesizing the long-term atmospheric CO₂ concentration record from Barrow station, the terrestrial ecosystem CO₂ exchange estimated from an atmospheric CO₂ inversion system, satellite-based vegetation production datasets and terrestrial ecosystem model simulations.

2 Materials and methods

2.1 Atmospheric CO₂ concentration

The CO₂ concentration records from Point Barrow (71°N, Alaska) cover the period from 1974 to 2014. The observed CO₂ concentration time series consists of three signals: a long-term trend that is mainly driven by fossil fuel emission, a non-sinusoidal seasonal cycle that could reflect seasonal CO₂ exchanges by terrestrial ecosystem and short-term variations that might be due to local influences. In this study, we focus on the northern ecosystem CO₂ exchange at hemisphere scale, therefore we remove the low-frequency signal at years to decades and short-term variations from the original CO₂ observations to obtain the non-sinusoidal seasonal cycle of CO₂ time series following Thoning et al. (1989). A detailed data process protocol can be found in SI Text S1, Figure S1 (Thoning et al., 1989, 2014; Harris et al., 2000; Barlow et al. 2015; Halter, 1981). Given that the detrending method applied on the CO₂ concentration time series might potentially affect the calculation of temperature sensitivity, we generated the synthetic CO₂ time series without changes in temperature sensitivity, and then applied the same analysis to this CO₂ time series to demonstrate that our detrending method do not introduce artifacts of change in temperature sensitivity (SI Text S2, Figure S2).

We calculated the net carbon release in the dormant season (CR) by defining the dormant season as the period from September to the following April, and calculating the change in the CO₂ concentration over that period. As a test of the robustness of the analysis, we also calculated CR from the weekly atmospheric CO₂ concentration from NOAA Earth System Research Laboratory at Barrow.

We also divided the dormant season into two periods: autumn (September to November) and winter (December to the following April). We calculated the autumn carbon release (ACR) as the CO₂ concentration in the last week of November minus that in the first week of September, and winter carbon release (WCR) as the CO₂ concentration in the first week of December subtracted from that in the last week of April in the following year. To test the robustness of the analysis, we also calculated ACR and WCR using alternative definitions of autumn and winter. These alternative definitions use the mean zero-crossing date, defined as the mean day of the year (DOY) when the non-sinusoidal seasonal CO₂ concentration crosses the zero line in the negative to positive direction. The mean zero-crossing date is around DOY 317 during the period from 1974 to 2014. The autumn is therefore the period from the first day of September to DOY 317 and the winter is the period from DOY 318 to the last day of the following April.

2.2 Climate data set

We used mean temperature, precipitation and cloud cover data from the monthly climate dataset from the Climate Research Unit, University of East Anglia (CRU TS4.0 dataset) (Mitchell & Jones, 2005). This data set covers the period from 1901 to 2015, with a spatial resolution of 0.5° × 0.5°. We also used another climate dataset, which applies the WATER and global Change (WATCH) Forcing Data to the ERA-Interim dataset to test the robustness of the analysis.

2.3 Vegetation production and soil moisture datasets

We used the Normalized Difference Vegetation Index (NDVI) retrieved from the third-generation of the Advanced Very High Resolution Radiometer (AVHRR) developed by the Global Inventory Modeling and Mapping Studies (GIMMS) group (version 3g.v0) as a proxy for vegetation activity (Tucker et al., 2005). The GIMMS NDVI dataset covers the period from 1982 to 2013, with a spatial resolution of $0.083^\circ \times 0.083^\circ$. We also used two vegetation production data sets: the monthly GIMMS net primary production (NPP) dataset (Smith et al., 2016), and gross primary productivity (GPP) up-scaled from eddy flux towers using the multi-tree ensemble approach (Jung & Bondeau, 2009). To analyze changes in soil moisture across northern ecosystems, we use the root-zone soil moisture from version 3.1a of the Global Land Evaporation Amsterdam Model (GLEAM) data set (Martens et al., 2017). This dataset assimilates microwave observations of surface soil moisture from the European Space Agency–Climate Change Initiative (ESA–CCI) dataset through a multi-layer water balance module, and covers the period from 1980 to 2016, with a spatial resolution of $0.25^\circ \times 0.25^\circ$.

2.4 Atmospheric CO₂ inversion data

Two atmosphere CO₂ inversion products were used to investigate the response of terrestrial carbon fluxes to warming. We used monthly net biome production (NBP) with a spatial resolution of $3.75^\circ \times 2.5^\circ$, from the JENA CarboScope (version s81_v3.8) for the period from 1982 to 2011. NBP from the Monitoring Atmospheric Composition and Climate (Chevallier et al., 2005) (MACC, version v14r2) between 1979 and 2011 was also used for the analysis.

2.5 Terrestrial ecosystem models

Simulations produced by eight models used in an historical climate carbon cycle model inter-comparison project (Trendy) were used in this study. These models are the Community Land Model Version 4.5 (CLM4.5), the Integrated Science Assessment Model (ISAM), the Joint UK Land Environment Simulator (JULES), Lund-Potsdam-Jena DGVM (LPJ), Lund-Postam-Jena General Ecosystem Simulator (LPJ-GUESS), the Land surface Processes and eXchanges (LPX), the Organizing Carbon and Hydrology In Dynamic Ecosystems (ORCHIDEE), and the Vegetation Integrative Simulator for Trace gases (VISIT). All these models used forcing data from the CRUNCEP dataset, and the simulation setup followed the standard protocol described in the inter-comparison project. Here, we used the S2 simulations, which consider the effect of climate change and rising CO₂ concentration on ecosystem carbon fluxes.

2.6 Heterotrophic respiration estimation

We calculated the heterotrophic respiration (HR) as the difference between inversion-based NBP and satellite-based NPP. Because fire is a prominent disturbance at northern high latitudes and CO₂ emissions from fire contribute to the NBP signal, we used the fourth-generation Global Fire Emission Database (GFED4) to determine the possible influence of emissions from fires on the NBP data. At 50°N , CO₂ emissions from fires mainly occur in the spring (March to May) while between 60°N to 70°N they are mainly in summer (June to August). The amount of CO₂ emissions from fires in the autumn (September to November) is $0.018 \text{ PgC yr}^{-1}$, which is only 0.87% (0.1%) of the HR value calculated from the JENA (MACC) data (Figure S3). Therefore, we suggest that the influence on HR from fire emissions in autumn is quite limited.

Noting that large uncertainties exist in the HR calculated from inversion-based NBP, we compared HR inferred from inversion-based NBP products, with that derived from the Trendy models and that estimated by Hashimoto et al. (2015) (hereafter as 'H2005'). The magnitude of the multi-year average HR inferred from inversion-based NBP (JENA: 2.05 PgC yr^{-1} , MACC: 1.78 PgC yr^{-1}) is compatible with the H2005 HR (1.79 PgC yr^{-1}), and the Trendy models ($2.10 \pm 0.90 \text{ PgC yr}^{-1}$). In addition, there is a significant inter-annual correlation of JENA-derived HR ($R^2 = 0.57$, $P < 0.01$) and MACC-derived HR ($R^2 = 0.47$, $P < 0.01$), and the Trendy HR ($R^2 = 0.50$, $P < 0.01$) with H2005 HR (Figure S4). We conclude that the uncertainties of HR calculated from inversion-based NBP are large, but still within the acceptable range for ecosystem carbon cycle studies.

2.7 Effects of atmospheric transport, air-sea CO_2 exchange and fossil fuel emissions on the change in autumn net CO_2 release

We assessed the impact of variations in atmospheric transport, air-sea CO_2 exchange and fossil fuel emission on the observed changes in ACR between the earlier period (1979–1996) and the later period (1997–2012) using atmospheric transport simulations. We used LMDz4, a 3D atmospheric tracer transport model from the Laboratoire de Météorologie Dynamique (Hourdin et al., 2006), nudged with ECMWF winds. We used land carbon fluxes for the period 1979–2012 from the land surface model ORCHIDEE (Krinner et al., 2005) as boundary conditions for the transport simulations. ORCHIDEE is driven by observed atmospheric CO_2 concentration and historical climate forcing from the CRU-NCEP v4 climate variables at 6-h resolution (Viovy & Ciais, 2014). For air-sea CO_2 exchanges, we used simulations from a biogeochemical model (PlankTOM5) forced by inputs of ions and compounds from river, sediment and dust, combined with a global ocean general circulation model NEMO forced by daily wind and precipitation data from the NCEP reanalysis (Buitenhuis et al., 2010). For fossil fuel CO_2 emissions, we used the monthly global time series taken from the Carbon Dioxide Information Analysis Center (CDIAC) website (<http://cdiac.esd.ornl.gov>) (Andres et al., 2011).

To assess whether changes in atmospheric transport could produce the observed temporal change in ACR, we performed a transport modeling experiment (WCC) in which land and air-sea CO_2 exchanges were fixed at 1979 values, but the atmospheric transport varied according to the ECMWF wind fields. To investigate the possible influence of air-sea CO_2 exchange on ACR, we conducted modeling experiment (WAC) where the atmospheric transport and land carbon fluxes were fixed at 1979 values but air-sea CO_2 exchanges varied according to simulations from NEMO-PlankTOM5. Finally, to assess the effect of changes in fossil fuel emissions, we conducted a third modeling experiment (WCF) in which the land and air-sea CO_2 exchanges were fixed at 1979 values, but fossil fuel emissions were allowed to vary.

2.8 Statistical analysis

We performed a partial correlation analysis between net carbon release and temperature, whilst statistically controlling for inter-annual variations in precipitation and cloud cover for dormant season (R_{CR-T}). Similar analyses were conducted for the autumn (R_{ACR-T}) and winter (R_{WCR-T}). For these analyses, the climate variables were averaged over the region north of 50° N . To ensure bare ground was excluded, we only considered the pixels where the annual NDVI was greater than 0.1. By applying a 15-year moving window on the partial correlation analysis, we found that R_{ACR-T} was significantly positive in the years up to 1995, but not significant in the years since 1996 (Figure S6). Therefore, we divided the analysis into two periods (1974–1996 as the earlier period and 1997–2014 as the later period). We detrended all the variables before the partial correlation analysis to avoid the

potential influences of other factors such as increasing CO₂ concentration and nitrogen deposition, which are the major drivers behind the increasing land CO₂ sink in the past decades (Schimel et al., 2015; Tian et al., 2011). For a more robust analysis, we also performed a moving-window analysis by randomly selecting 12 years for C_{nyear}^{12} ($nyear$ denotes the length of each period) times from the time series for the corresponding period to generate a frequency distribution of the partial correlation coefficient. The 12 years were randomly selected and then detrended for partial correlation analysis. We also conducted a two-sample t -test to determine the significance of changes in correlation.

To investigate whether changes in atmospheric transport, air-sea CO₂ exchanges and fossil fuel emissions could affect R_{ACR-T} , we also calculated ACR based on simulated CO₂ concentrations from the WCC experiment, the difference of simulated CO₂ concentrations between the WAC experiment and WCC experiment, and the difference of simulated CO₂ concentrations between the WCF experiment and WCC experiment. To explore the potential drivers of the change in R_{ACR-T} , we perform the same partial correlation analysis linking temperature to satellite-derived NDVI (R_{NDVI-T}), satellite-based NPP (R_{NPP-T}), flux-tower based GPP (R_{GPP-T}), inversion-based NBP (R_{NBP-T}) and the HR calculated from NBP and NPP (R_{HR-T}). To explore the potential reason for the change in R_{HR-T} , we used the cumulative NPP between May and November to represent plant-derived carbon inputs to soil, and performed partial correlation analyses linking temperature to the cumulative NPP during both periods, whilst statistically controlling for inter-annual variations in precipitation and cloudiness during the period from May to November. Note that this analysis is applied to multi-model mean NPP from the Trendy models, satellite-based NDVI, satellite-derived NPP and flux-tower based GPP. To understand the coupling between productivity and autumn respiration, we used the Trendy models results to calculate the partial correlation coefficient between autumn HR and cumulative NPP, whilst statistically controlling for inter-annual variations in autumn temperature and precipitation.

3 Results and discussion

The autumn net carbon release (ACR) and temperature at the inter-annual timescale are tight correlated during the period 1974–2014 ($R_{ACR-T} = 0.39$, $P < 0.05$) (Figure S5), confirming that warming-induced increase in autumn respiration dominated over autumn photosynthetic gains (Miller et al., 2008; Piao et al., 2008). Unexpectedly, R_{ACR-T} changes from 0.61 ($P < 0.01$) during 1974–1996 to 0.05 ($P = 0.85$) during the later period 1997–2014 (Figure 1), which runs counter to our proposed hypothesis that the stimulating effect of warming on net carbon release would become much more pronounced in recent years. The observed diminished correlation between ACR and temperature implies that warming would not significantly stimulate carbon release (and increase atmospheric CO₂ concentration growth) between September and November. After applying a 15-year moving window to the partial correlation analysis, we found that R_{ACR-T} was significantly positive ($P < 0.05$) for all moving windows, except one with marginal significance ($P < 0.1$), in the years up to 1995, but not significant in the years since 1996 (Figure S6). This diminished stimulating effect of temperature on ACR was also detected in the impact of temperature on the zero-crossing date (also known as the CO₂ sink-source transition date, being the day on which the terrestrial ecosystem shifts from being a carbon sink to being a carbon source). In the earlier period, warmer years imply earlier zero-crossing dates ($R = -0.66$, $P < 0.01$), while in the later period no correlation was found ($R = -0.02$, $P = 0.95$) (Figure S7). The sensitivity of ACR to temperature (γ_{ACR-T}) also significantly decreased from 1.14 ± 0.39 ppm °C⁻¹ during the earlier period to 0.09 ± 0.51 ppm °C⁻¹ during the latter period (Figure S8). However, we should note that the regression coefficient during the latter period is not statistically significant,

suggesting that this change in sensitivity needs to be interpreted with caution. In contrast to the autumn, the effect of temperature on winter carbon release is non-significant in both earlier ($R = -0.11$, $P = 0.63$) and later periods ($R = 0.04$, $P = 0.87$) (Figure 1c).

The robustness test using the alternative definition of the autumn period (Figure S9), changed climate dataset (Figure S10), or CO₂ concentration records from flask samples or weekly in situ measurements (Figure S11) all confirmed that autumn warming no longer accelerates net carbon release in the later period. We also analyzed the temporal change in temperature dependence of NBP from two different atmospheric inversion models (JENA CarboScope and MACC, see methods). These models provide estimates of net CO₂ fluxes that have been optimized using terrestrial ecosystem model simulations and atmospheric CO₂ concentration measurements from a global network in atmospheric transport models. These results were in agreement with the atmospheric CO₂ analyses. NBP from the JENA CarboScope inversion model indicates a non-significant temperature impact on autumn NBP over boreal and arctic ecosystems north of 50° N during 1997–2011 ($R = -0.36$, $P = 0.23$), in contrast to a significant temperature effect for the period 1982–1996 ($R = -0.75$, $P < 0.01$) (Figure 2a). Similar results were also found if NBP from the MACC inversion model was used (1982–1996: $R = -0.67$, $P < 0.05$; 1997–2011: $R = -0.07$, $P = 0.83$, Figure S12). We assessed possible contributions to the change in R_{ACR-T} from changes in atmospheric transport, air-sea CO₂ exchanges and fossil fuel emissions by performing model simulations in the LMDz atmospheric transport model (Hourdin et al., 2006) (see Methods). We found that decadal changes in these processes would not contribute to the observed diminished temperature control on ACR (Figure S13).

Which terrestrial carbon cycle processes cause the diminished positive temperature impact on autumn carbon release? The diminished effect can be investigated by analyzing the changes in the two major components of the carbon balance, i.e. the ecosystem production and the ecosystem respiration. Analysis of satellite-based vegetation index (GIMMS NDVI) (Tucker et al., 2005) as a surrogate for vegetation production shows that autumn NDVI is marginally significantly correlated with temperature in the earlier period ($R = 0.49$, $P < 0.10$), but becomes decoupled from temperature in the later period ($R = -0.37$, $P = 0.17$) (Figure S14). The weakened temperature dependence of satellite-based vegetation index is also evident when considering satellite-based estimates of net primary productivity (NPP) (Smith et al., 2016) (Figure 2b), or satellite-independent estimates of gross primary productivity (GPP) up-scaled from eddy flux towers (Jung et al., 2009) (Figure S15). R_{NPP-T} decreased from 0.84 ($P < 0.01$) in the earlier period to 0.43 ($P = 0.14$) in the later period, and R_{GPP-T} decreased from 0.89 ($P < 0.01$) in the earlier period to 0.46 ($P = 0.11$) in the later period. These results appear to rule out changes in vegetation production as the cause of the diminished temperature effect on ACR.

A significant obstacle to determining climate-driven change in respiration is a lack of direct observations of respiration at large scales. Here, in the absence of direct observations, we analyzed HR obtained from eight models participating in the historical climate carbon cycle model inter-comparison project (Trendy, see Methods). We found that a strong correlation of HR to temperature during the earlier period becomes weak and non-significant during the later period in most of the models (Figure S16). For example, the R_{HR-T} derived from the multi-model ensemble mean decreases from 0.93 ($P < 0.01$) in the earlier period to 0.46 ($P = 0.12$) in the later period. This attenuated response of respiration to temperature was also found when HR was calculated as the difference between NBP (derived from JENA CarboScope or MACC data) and satellite-derived NPP (Figure 2c and Figure S12 b). We found that HR is significantly partially correlated with autumn temperature in the earlier

period (Jena: $R_{HR-T} = 0.83$, $P < 0.01$; MACC: $R_{HR-T} = 0.74$, $P < 0.01$) but not in the later period (Jena: $R_{HR-T} = 0.35$, $P = 0.24$; MACC: $R_{HR-T} = 0.40$, $P = 0.17$).

The observation of an attenuated response of respiration to temperature suggests that other environmental factors in addition to temperature are determining respiration rates. Here, we examine some possibilities. One interpretation is that a decline in soil water content can reduce the thickness of soil water films, thus decreasing substrate availability and reducing the temperature dependence of respiration (Davidson & Janssens, 2006; Suseela & Dukes, 2013; Reynolds et al., 2014). Analyses of CRU-based precipitation (Mitchell & Jones, 2005) and satellite-derived soil moisture (Martens et al., 2017) in autumn (Figure S17) show that the reduction in moisture availability mainly occurs in Europe and part of Alaska, but most of the northern ecosystems experience a wetting tendency in the later period. The same result was found in an analysis of simulated soil moisture from carbon cycle models (Figure S17 c). The result suggests that the moisture limitation is not the main mechanism behind the observed attenuated response of respiration to temperature.

Respiration is also regulated by substrate availability. The seasonal variation of labile carbon input could influence the variations of respiration, and in turn affect the apparent relationship between respiration and temperature (Gu et al., 2004; Wang et al. 2010; Wan & Luo, 2003). If warming no longer stimulates increased vegetation production in the later period, as is increasingly recognized (Piao et al., 2014; Ballantyne et al., 2017), then plant-derived carbon inputs to soils would not commensurately increase with temperature, thus inhibiting the increase of decomposition with temperature. The decoupling of the relationship between temperature and productivity constitutes an interpretation for the attenuated response of respiration to temperature. To test this potential mechanism, we used NPP accumulated from May to November as a surrogate for plant-derived carbon inputs available for decomposition. Using the Trendy model ensemble mean, we found that the inter-annual correlation between cumulative NPP and temperature decreases from 0.65 ($P < 0.05$) in the earlier period to 0.09 ($P = 0.78$) in the later period, indicating that warming would not significantly stimulate plant derived carbon input to soils in the latter period. This model-derived result is robust to the use of different satellite-based productivity datasets (Figure S18). Since there is always a strong correlation between model-derived HR and carbon inputs during both periods (Figure S18 b), the decoupling of the relationship between temperature and productivity explains the attenuated temperature response of respiration during the later period. To further test the robustness of this mechanism, we calculated the correlation between HR and temperature, using HR estimates from a simplified respiration model constrained by global respiration observations (Hashimoto et al., 2015). We found a persistent positively significant correlation between HR and temperature for both periods (Figure S19). As Hashimoto et al. (2015) used a respiration model that considers the effect of temperature and precipitation while ignoring the effect from substrates, this persistent significant coupling between HR and temperature suggests that the attenuated temperature dependence of respiration that we detected from the Trendy models is not likely to be driven by changes of temperature and soil moisture conditions, but most likely to be linked with the recently reported weakening relationship between temperature and productivity (Piao et al., 2017). We are led to conclude that the diminished negative temperature effect on the autumn carbon cycle is most likely due to the attenuated temperature response of respiratory losses. Noting that changes in seasonal net carbon exchange are regulated by both magnitudes and phases of production and respiration, changes in asymmetric patterns between production and respiration could also contribute to the changing response of autumn carbon release to temperature.

Our work reveals a temperature-dependent shift in the autumn carbon cycle similar to that which has occurred during the main growing season over the last three decades (Piao et al., 2017; Peñuelas et al., 2017). This finding suggests a changing paradigm for the impact of temperature on the northern high-latitude carbon cycle. However, these observed changes could partly compensate for each other (Figure 3) as the autumn respiratory acclimation has an ameliorating impact on net CO₂ losses with rising temperatures, which could offset the negative warming impact on net CO₂ uptake during the active growing season (Piao et al., 2017; Peñuelas et al., 2017). Therefore, it would be premature to conclude that the impact of temperature on the annual carbon cycle has fundamentally shifted towards the negative state.

4 Conclusions

A reduction in the response of decomposition to warming means that autumn warming in boreal and arctic ecosystem no longer accelerates net carbon losses and advances the end of the carbon uptake period as previously suggested. The attenuated response of respiration to warming during the dormant period could offset the negative warming impact on net CO₂ uptake during the growing season. The results highlight the importance of incorporating how net carbon losses change with temperature during the dormant period in fully understanding temperature impacts on annual net carbon uptake.

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Data availability: The Barrow CO₂ records are derived from the National Oceanic and Atmospheric Administration (NOAA) Earth System Research Laboratory (NOAA-ESRL, <https://www.esrl.noaa.gov/gmd/dv/data/>, Masarie et al., 2014). The detrending process used on the CO₂ time series was based on the CCGCRV tool available from <https://www.esrl.noaa.gov/gmd/ccgg/mb1/crvfit/crvfit.html>. The fire emission data were derived from the GFED4 dataset (<http://www.globalfiredata.org/data.html>). The CRU TS4.0 climate datasets were obtained from CRU website (<https://crudata.uea.ac.uk/cru/data/hrg/>). The WFDEI climate datasets are derived from <http://www.eu-watch.org>. The GIMMS NDVI dataset is derived from <https://ecocast.arc.nasa.gov/data/pub/gimms/3g.v0>. The NPP dataset is derived from Smith et al. (2016). The GPP dataset is derived from Department for Biogeochemical Integration (BGI) data portal (<https://www.bgc-jena.mpg.de/geodb/projects/Home.php>). The GLEAM soil moisture data are derived from <https://www.gleam.eu/>. The JENA CarboScope carbon fluxes are derived from <http://www.bgc-jena.mpg.de/CarboScope/>. The MACC carbon flux are derived from <http://copernicus-atmosphere.eu/>. The model results are derived from the Trendy project (<http://dgvn.ceh.ac.uk/>). All the analyses were conducted using MATLAB software.

Code availability: The Matlab scripts for atmospheric CO₂ data processing partial correlation analysis are available in Supporting Information.

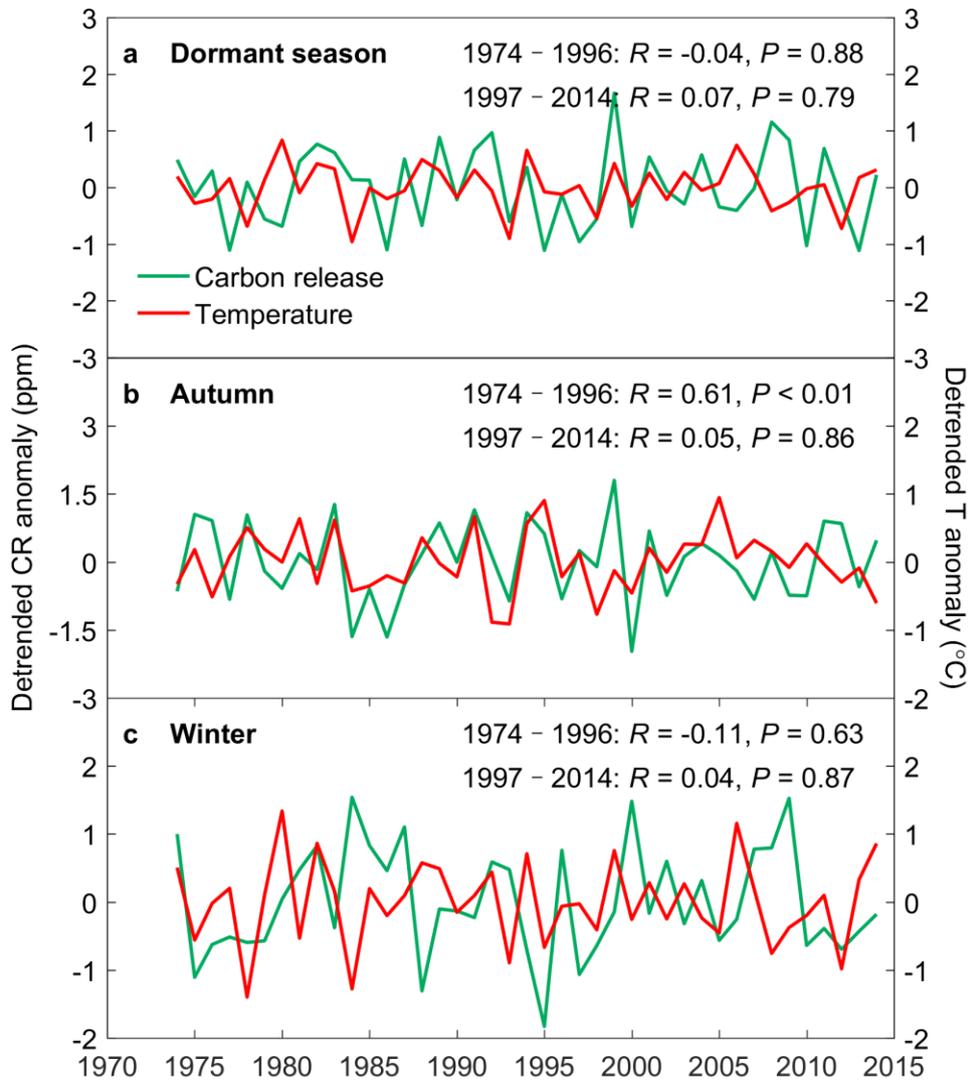
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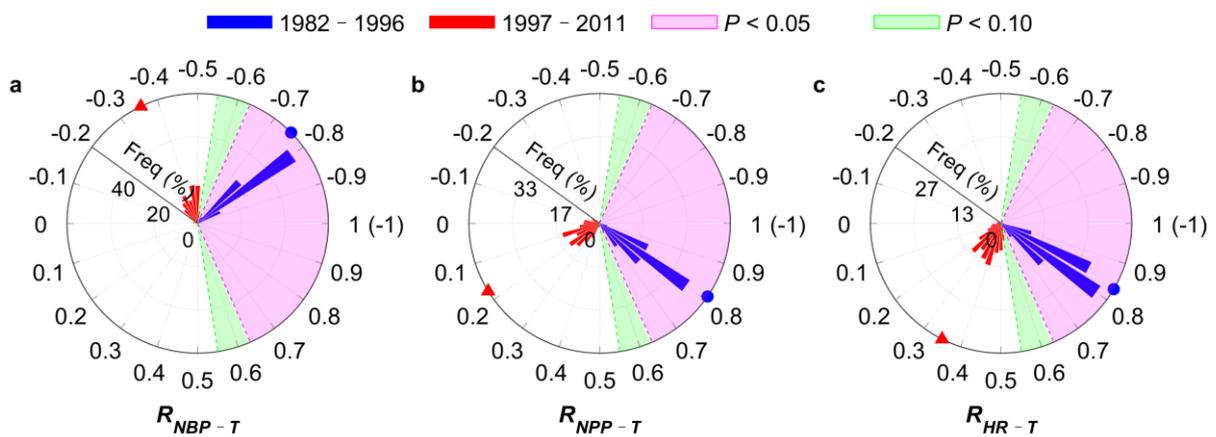
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Figure 1. Temperature control on net carbon release (CR) during the dormant season. Here we define the dormant season as the period from September to the following April (a), which consists of autumn (September to November, b) and winter (December to the following April, c). The lines are time series of the detrended anomaly of net carbon release (green) and mean temperature across land ecosystems north of 50° N (red).



Acc

Figure 2. The relationship between ecosystem carbon fluxes and temperature in autumn. Subplots show the frequency distribution of the partial correlation coefficient of net biome production (NBP, **a**), net primary productivity (NPP, **b**), and heterotrophic respiration (HR, **c**) with average temperature during September to November across land ecosystem north of 50° N, whilst controlling for precipitation and cloudiness during the earlier period (1982–1996, blue bar) and later period (1997–2011, red bar), respectively. For each period, we randomly selected 12 years for C_{nyear}^{12} times (*nyear* denotes the length of each period) to generate the frequency distribution of partial correlation coefficient (the degree of freedom is 8). The shading illustrates the significance level at $P < 0.05$ (magenta) and $P < 0.10$ (green) for the correlation of the 12-year time series, respectively. We also show the value of the partial correlation coefficient for the earlier period (1982–1996, blue) and later period (1997–2011, red) as the markers on the polar axis, and triangular and circular markers denote not significant and significant ($P < 0.05$), respectively.



Accept

Figure 3. Schematic of the effect of warming on seasonal CO₂ uptake and release in northern ecosystems. Filled markers illustrate significant temperature correlation and open markers show non-significant correlation with temperature. In spring, warming advances the source-to-sink transition date and increases CO₂ uptake, decreasing atmospheric CO₂ (Keeling et al., 1996), but this effect disappears in the later period (1996–2012) (Piao et al., 2017). In summer, the effect of warming on net CO₂ uptake becomes significantly negative in the later period, increasing atmospheric CO₂ (Peñuelas et al., 2017). The widely recognized autumn warming-induced advancement in sink-to-source transition date and acceleration in net CO₂ release (Piao et al., 2008) becomes diminished in the later period, which could decrease build-up of atmospheric CO₂. In contrast, the temperature effect on winter net CO₂ release is not significant during both periods.

