TECHNICAL RESPONSE

CLIMATE CHANGE

Response to Comment on "Satellites reveal contrasting responses of regional climate to the widespread greening of Earth"

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Li *et al*. contest the idea that vegetation greening has contributed to boreal warming and argue that the sensitivity of temperature to leaf area index (LAI) is instead likely driven by the climate impact on vegetation. We provide additional evidence that the LAI-climate interplay is indeed largely driven by the vegetation impact on temperature and not vice versa, thus corroborating our original conclusions.

On the basis of statistical analysis of satellite data, we argued that the observed vegetation greening has contributed to the warming of cold and humid boreal zones through a reduction of surface albedo (*1*). In their Comment, Li *et al*. (*2*) contend that "this positive sensitivity of temperature to the greening can be derived from the positive response of vegetation to boreal warming." They base this claim on two major points: (i) The statistical analysis is unsuitable to isolate the climate response to vegetation greening, and (ii) the importance of radiative processes associated with LAI-driven changes in boreal albedo is limited. In addition, Li *et al*. underpin a climate impact of greening dominated by evapotranspiration cooling in the boreal regions as suggested by model simulations (*3*), implicitly assuming that land models correctly represent the vegetation-climate interplay.

Li *et al*. support the first claim (i) by applying the statistical method used in (*1*) to decoupled simulations from five global terrestrial ecosystem models and conclude that "over the boreal regions, $\delta T^{\mathrm{LAI}}_{\mathrm{decoupled}}$ [i.e., $\partial T_a/\partial \mathrm{LAI}_{\mathrm{decoupled}}$] is positive and at the same magnitude as δT^{LAI} [i.e., $\partial T_S/\partial \mathrm{LAI}$]…, indicating that the positive δT^{LAI} regressed with satellite data … can be derived from the positive response of vegetation to boreal warming." Even though we acknowledge the relevance of feedback loops in plant-climate interactions, we argue that this modeling experiment, being based on decoupled model runs, does not support the conclusions of Li *et al*. because it cannot exclude the direct impact of changes in LAI on surface temperature, and because it does not quantify the relative magnitude of the bidirectional effects and therefore cannot support any conclusion on which of the two dominates.

We stress that our methodology isolates the interactions between LAI and T_S and factors out the signal of covarying drivers such as precipitation and incoming radiation. Nonetheless, we recognize that the statistical approach cannot fully disentangle the short-term temperature control on boreal vegetation and separate it from the feedback. However, our results support the conclusion that at the interannual time scale, the

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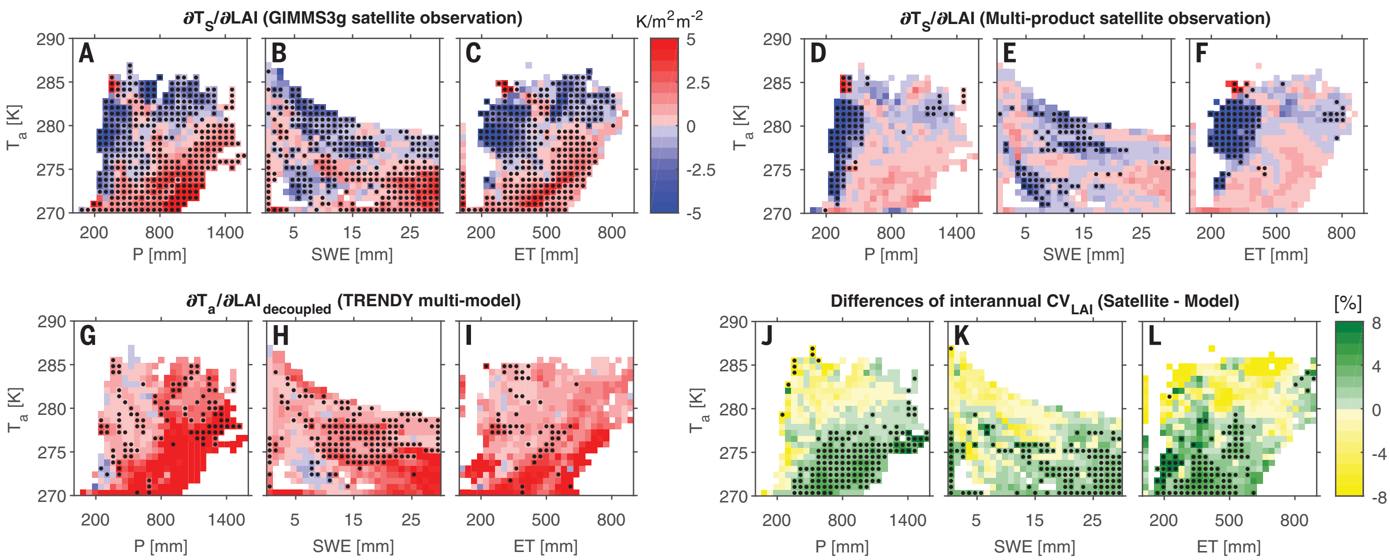

Fig. 1. Sensitivity of temperature to variations in LAI and interannual variations in LAI across climatological gradients. (**A** to **C**) For boreal regions and based on satellite GIMMS3g observations, values of sensitivity of surface temperature to LAI ($\partial T_S/\partial \mathrm{LAI}$) are illustrated against the climatological median temperature (T_a, *y* axis) and precipitation (A), snow water equivalent (B), and evapotranspiration (C) (P, SWE, and ET; *x* axis). (**D** to **F**) Same as (A) to (C) but for multiproduct satellite observations (GIMMS3g, GLASS, GLOBMAP, LTDR, and MODIS). (**G** to **I**) Same as (A) to (C) but for TRENDY (CLM4.5, JULES, OCN, ORCHIDEE, and VISIT) model-derived sensitivity of air temperature to LAI ($\partial T_a/\partial \mathrm{LAI}$). (**J** to **L**) Same as (A) to (C) but for the differences in interannual variations of LAI, expressed as the coefficient of variation ($\mathrm{CV_{LAI}}$), retrieved from each combination of satellite products and TRENDY models (25-member ensemble). Black dots show bins with average value statistically different from zero ($P < 0.05$). Statistical significance in (A) to (C) is calculated for all the observed values falling into the given bin and reflects the robustness of the observed signal. Statistical significance in (D) to (L) is calculated across the members of the ensemble and reflects the robustness of their average signal.

land-climate interplay is largely affected by the LAI impact on temperature. Here, we extend our analyses to provide further evidence. Figure 1 unequivocally shows that the observed temperature variations associated with boreal greening depend in sign and magnitude on the background climate, with a pattern that is fully consistent with the expected biophysical impact of vegetation on temperature. As such, $\partial T_S/\partial$LAI is positive in cold-humid boreal regions with extended snow cover, where the greening can trigger large reductions in albedo but only limited increases in evapotranspiration. On the contrary, in boreal areas with limited snow cover and water availability, the increase in transpiration associated with the greening ultimately yields a negative $\partial T_S/\partial$LAI (Fig. 1, A to C). We note that despite the spread observed over multiple satellite LAI products (*4*), the multiproduct average signal of $\partial T_S/\partial$LAI shows largely consistent patterns (Fig. 1, D to F). If the sensitivity of temperature to boreal greening was mainly driven by the positive response of vegetation to warming, as suggested by Li *et al.*, we should expect a positive value of $\partial T_S/\partial$LAI over the whole boreal climate domain, consistent with the results of the modeling experiment (Fig. 1, G to I). On the contrary, the clear contrast between observations and decoupled simulations suggests that the interplay between climate and LAI at the interannual scale is largely modulated by the vegetation impacts on climate as suggested in (*1*), and not vice versa.

Furthermore, relative to observations, models substantially underestimate the interannual variability of LAI in cold-wet zones, as highlighted by the large difference (up to 8%; $P < 0.05$) in the coefficient of variation (Fig. 1, J to L). Similar discrepancies are also found for growing-season LAI (not shown). Such model limitations are likely to hamper their capacity to represent the interplay between biophysical processes and vegetation changes (*5*, *6*). As acknowledged also by Li *et al.*, we stress that the large model uncertainty may hinder the assessment of the net impact of vegetation greening on boreal climate.

On the second point (ii), Li *et al.* claim that there is a limited impact of LAI on radiative biophysical processes (e.g., albedo) in the boreal zone: “the observed boreal greening occurs during the growing season when the snow-albedo feedback is minimal (*3*)…, the climate impact of growing season greening seems to be dominated by evapotranspiration cooling even in the boreal regions.” This conclusion is based on the rather uncertain predictions of land surface models on the relationship between vegetation and albedo off-season (*7*, *8*). On the other hand, remote sensing observations report on the abundance and spreading of evergreen species in the boreal zone (*9*), whose variation in LAI may substantially affect albedo and temperature also during the dormancy season via the snow-albedo feedback (*10*). The relevance of off-season radiative biophysical processes is suggested by the positive values of winter/spring $\partial T_S/\partial$LAI in the whole boreal climate domain (Fig. 2, A and B). In warm-dry regions, the observed sensitivity becomes negative during the growing season, thanks to the stronger control that LAI exerts on transpiration in less humid ecosystems. These seasonal dynamics cannot be the simple effect of temperature-driven greening, as claimed by Li *et al.*, because in that case we would expect a positive sensitivity throughout the year across the whole boreal region. On the contrary, the emerging seasonal patterns confirm that LAI variation can indeed influence in space and time the short-term net signal of the vegetation-climate interactions.

Ultimately, the net annual LAI impact on climate depends on the relative magnitude and duration of the periods dominated by radiative and nonradiative biophysical processes (*11*, *12*), as clearly proved by the consistency between the climate patterns of $\partial T_S/\partial$LAI in Fig. 1A and the length of the season with negative sensitivity (LNSS) in Fig. 2, C and D. Unfortunately, models show severe limitations in predicting the seasonality of vegetation and the length of the growing season (LGS), here expressed as the number of days when LAI is larger than 30% of its amplitude (*13*) and derived after linear interpolation of monthly LAI values (Fig. 2E). In particular, models systematically overestimate LGS (16 ± 2 days and 44 ± 3 days in cold-wet and warm-dry zones, respectively; multimodel average ΔLGS ± SE). We highlight that the threshold-based approach used to derive LGS is not sensitive to missing LAI data during winter (*14*). The emerging model bias in the estimate of LGS is consistent with previous studies (*15*) and may be one of the causes of the overestimation of LAI-driven evaporative cooling, with potential influences on the derived net climate impact of boreal greening.

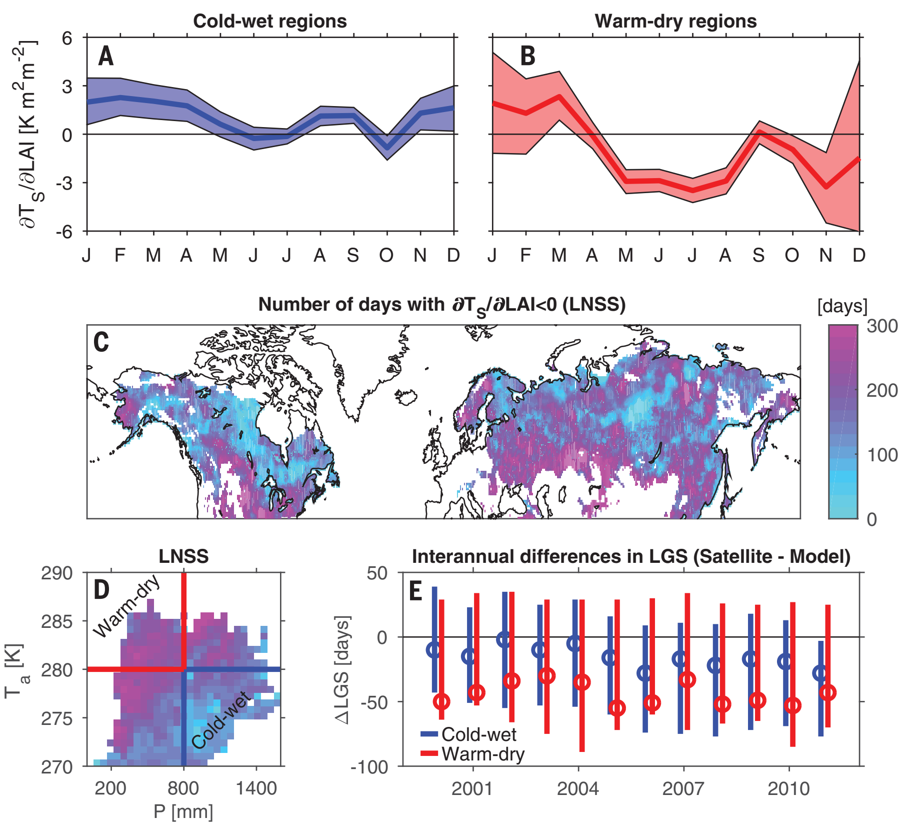

Fig. 2. Seasonal patterns of the sensitivity of surface temperature to LAI and length of the season with negative sensitivity (LNSS). (**A**) Satellite-derived monthly sensitivity of surface temperature to LAI for cold-wet boreal regions ($T < 280$ K and $P > 800$ mm, in blue); lines and shaded areas denote the median values and confidence bounds (±SE). Note that monthly sensitivity of surface temperature to LAI is computed by using annual LAI values and monthly-scale climate drivers in order to minimize the potential biases of satellite retrieval of LAI in snow cover conditions. (**B**) Same as (A) but for warm-dry boreal regions ($T > 280$ K and $P < 800$ mm, in red). (**C** and **D**) Spatial (C) and climate (D) pattern of satellite-derived LNSS (number of days with negative sensitivity of surface temperature to LAI). (**E**) Interannual differences in length of the growing season (ΔLGS) were estimated from observations and models; circles and bars reflect the ensemble median and the five-member ensemble data range, respectively. The GIMMS3g product is used as the reference observational dataset for consistency with (*1*).

Our findings in (*1*), further corroborated by the results reported here, suggest that the impacts of LAI variations on climate are modulating the overall signal of the interannual vegetation-climate interplay. They also highlight the importance of realistically representing the temporal variation of vegetation in land surface models for simulating present and future changes in the energy and water cycle (*5*, *6*). We agree that at longer time scales, like those investigated in (*3*), the strong trend in temperature and covarying changes in atmospheric CO_2 and N deposition may have driven the northern greening. On the other hand, our analysis suggests that at shorter temporal scales, LAI variations affect the interannual spatial and seasonal variability of surface temperature. We agree with Li *et al.* that future studies based on the integration of models and observations are required to reconcile these findings and derive conclusive statements about the climate effects of the widespread greening of Earth.

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