TECHNICAL COMMENT

CLIMATE CHANGE

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

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Forzieri *et al*. (Reports, 16 June 2017, p. 1180) used satellite data to show that boreal greening caused regional warming. We show that this positive sensitivity of temperature to the greening can be derived from the positive response of vegetation to boreal warming, which indicates that results from a statistical regression with satellite data should be carefully interpreted.

Forzieri *et al.* (*1*) presented a statistical analysis of satellite data to quantify the climate impact of vegetation greening. They used a huge number of observations combined with a method that divided global grids into bioclimatic spaces, making this study of particular importance for understanding the temporal covariations between leaf area index (LAI) and the surface biophysics across different climate zones and during extreme warm-dry/cold-wet years. However, one of their main conclusions, that "the increasing trend in LAI contributed to the warming of boreal zones," raises concerns about whether the climate impact of boreal greening can be isolated from this kind of statistical regression with satellite data.

The conclusion that boreal greening has contributed to boreal warming was established on the basis of the statistically positive sensitivity of land surface temperature (T_S) to LAI (i.e., δT^{LAI}) over the high latitudes including northern Canada, central Europe, and western Siberia (Fig. 1A). We argue that it is not appropriate to directly apply the methodology in Wang *et al.* (*2*) to compute δT^{LAI} "as the partial derivative of surface temperature with respect to LAI in a multiple regression of surface temperature against LAI, precipitation and incoming shortwave radiation after detrending all variables" [supplementary text in (*1*)]. Note that the basic hypothesis in Forzieri *et al.* contrasts with that in Wang *et al.* (*2*), with the latter assuming that the atmospheric carbon dioxide growth rate (reflecting carbon flux fluctuations in tropical terrestrial ecosystems) is determined by the climate (i.e., temperature, precipitation, and incoming solar radiation). Therefore, the causality between vegetation and climate is reversed in Forzieri *et al.* Over the boreal cold regions, warming is the dominant driver of vegetation greening in the high latitudes (*3*, *4*), where the positive δT^{LAI} may be a result of the vegetation response to climate change rather than a metric measuring the climate response to vegetation greening.

To demonstrate the unsuitability of δT^{LAI} for representing the climate impact of vegetation greening, we recomputed the sensitivity, applying the same method as in Forzieri *et al.* but

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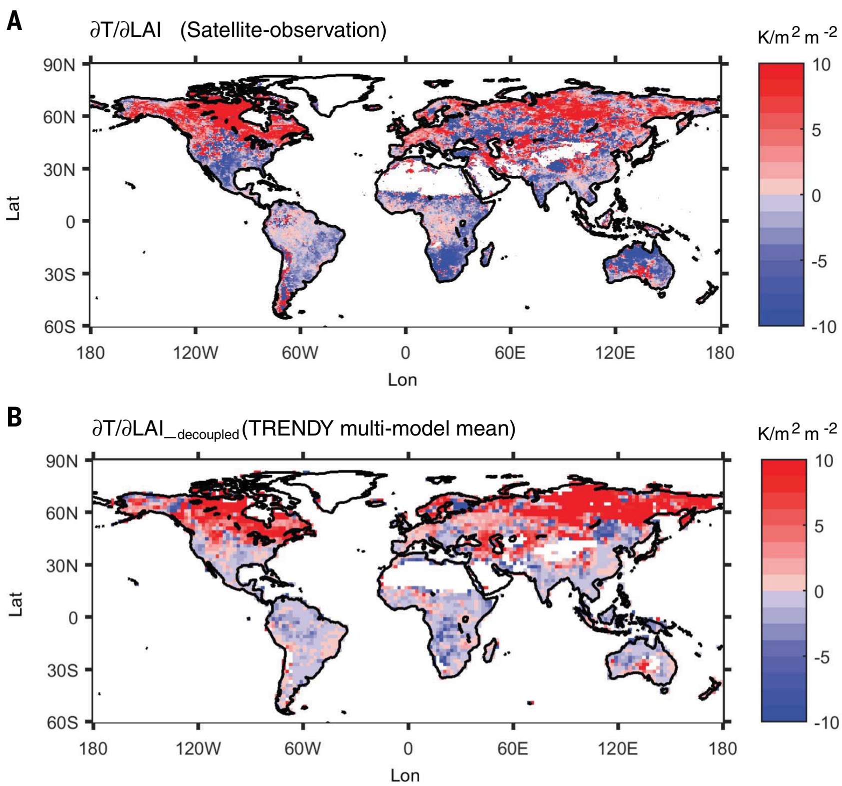

Fig. 1. Temperature sensitivity to leaf area index (LAI). (**A**) Spatial patterns of the sensitivity of land surface temperature (T_S) to LAI from satellite observations ($\partial T/\partial$LAI). (**B**) Sensitivity of observed surface air temperature (T_a) to the simulated LAI from the multimodel mean of five global ecosystem models participating in the TRENDY project ($\partial T/\partial \mathrm{LAI}_{decoupled}$). T_S is the average of the daytime and nighttime temperature. The computation of $\partial T/\partial$LAI and $\partial T/\partial \mathrm{LAI}_{decoupled}$ followed the methodology in Forzieri *et al*. (*1*), using the satellite-observed T_S and LAI for $\partial T/\partial$LAI, and the observed T_a and the simulated LAI for $\partial T/\partial \mathrm{LAI}_{decoupled}$, respectively.

replacing the data with the offline simulations from five global terrestrial ecosystem models (*4*). Because these offline models were driven by the observed climate and atmospheric CO_2 concentration, the causality between vegetation and climate in the simulations was unidirectional; that is, the calculated δT^{LAI} in the offline model simulations (i.e., $\delta T^{\mathrm{LAI}}_{\mathrm{decoupled}}$) mainly reflects the vegetation response to climate change. We found that over the boreal regions, $\delta T^{\mathrm{LAI}}_{\mathrm{decoupled}}$ is positive and at the same magnitude as δT^{LAI} (Fig. 1B versus Fig. 1A), indicating that the positive δT^{LAI} regressed with satellite data, which has been used to reflect the climate feedbacks of vegetation greening in Forzieri *et al.*, can be derived from the positive response of vegetation to boreal warming. Therefore, it may not be possible to isolate the signal of regional climate response to vegetation greening from such a statistical regression with satellite data, the results of which should therefore be carefully interpreted.

Finally, it is worth mentioning that the uncertainty in regional climate change induced by vegetation change remains large in the boreal regions. For observation-based analyses, one limitation could be a lack of evidence to show the causality between vegetation and climate due to the statistical analysis often relying on correlations. For example, it is almost impossible to tell whether boreal forest warms the regional climate or whether boreal forest occurs in relatively warm regions when interpreting the results of the positive spatial relationship between vegetation types and climate in boreal regions (*5*), unless extra information—such as a plantation map (*6*) and/or the background climate variability (*7*)—is available to help exclude the climate impact on vegetation growth and isolate the signal of the vegetation impact on the regional climate. Recently, Zeng *et al.* (*8*) used coupled land-atmosphere global climate models integrated with satellite data to show that a 30-year vegetation greening could have slowed the global land-surface warming, including in the boreal zones, as a result of the dominant effect of evapotranspiration cooling. Relative to boreal afforestation, the observed boreal greening occurs during the growing season when the snow-albedo feedback is minimal [figure S4 in (*8*)]. Although the continuous summer-to-winter greening of coniferous forests and the advance of beginning of leaf growing of deciduous forests still trigger the snow-albedo warming feedback, the climate impact of growing season greening seems to be dominated by evapotranspiration cooling even in the boreal regions (*8*, *9*). Unlike the statistical method used by Forzieri *et al.*, the experimental design in Zeng *et al.* (*8*) could isolate the climate effect of the greening of Earth from the background global warming and other confounding forcings, although substantial uncertainty was also present in their study (e.g., results were dependent on model parameter schemes). We suggest that it is necessary to combine the coupled land-atmosphere model (*8*, *9*), as an important tool, with extra information in observation-based analyses to reduce the uncertainty in quantifying the climate effects of the greening of Earth in future studies.

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