Local Land Surface Temperature Response to the Widespread Earth Greening

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Abstract. Satellite observations reveal that vegetation greenness has been increasing over most parts of the global land for the past few decades – due to direct factors, i.e., human land-use management, and indirect drivers, i.e., climate change, CO_2 fertilization, and nitrogen deposition. The vegetation greenness is closely related to the land surface biophysical properties (i.e. albedo, aerodynamic resistance, and surface resistance) that regulate the land surface energy budget (LSEB). There are ongoing debates on the attribution of biophysical feedbacks, which is challenging, to land surface temperature (LST) at local to regional scales. Here we use a physics-based framework called the Two Resistance Mechanism (TRM) method to address local vegetation biophysical feedbacks to LST. One goal of this study is to separate the LST changes due to vegetation biophysical feedback from those due to atmospheric changes. Another goal of this study is to quantify the LST change over the past two decades attributable to leaf area index (LAI) change, and evaluate the relative contributions through each biophysical mechanisms.

1. Observed ΔLAI and ΔLST

- Changes (Δ) seen from MODIS LAI and LST
  - e.g. Trends
- What proportions of changes in LST are attributable to changes LAI since 2000?
- One mechanism can cool down the surface while others can warm up the surface, which is dominant?
- LST is an ultimate (competing) results of surface and atmospheric changes

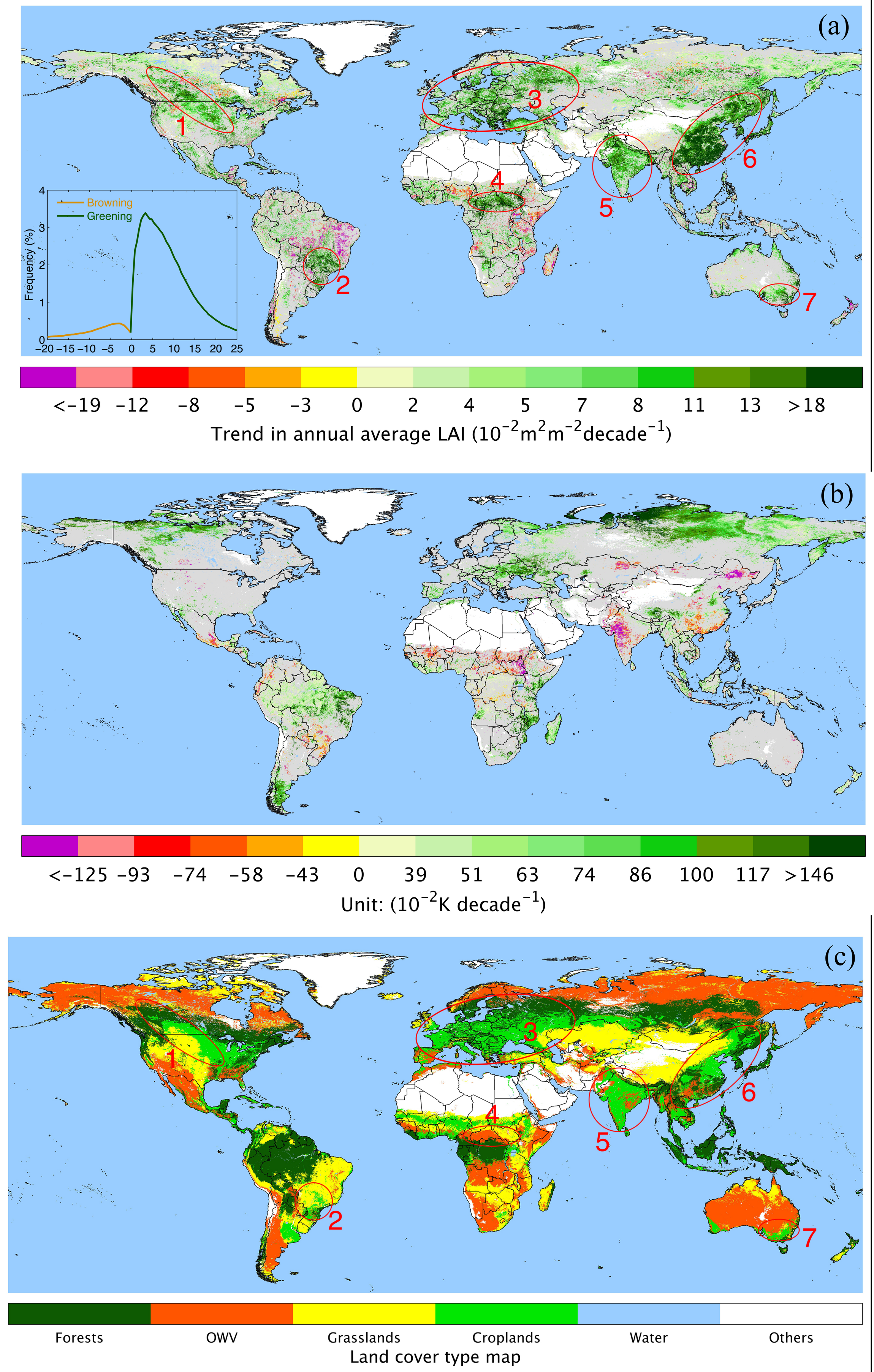

Fig. 1 | (a) Map of trends (p≤0.1) in annual average MODIS LAI over 2000–2017. The inset shows the frequency distribution of statistically significant trends. (b) Map of trends in annual average MODIS LST over 2000-2017. (c) Map of broad vegetation classes

2. The Two Resistance Mechanism

$$R_n = S_{in}(1-\alpha) + \epsilon L_{in} - \epsilon\sigma T_s^4 = H + LE \qquad (1)$$

- R_n is the net radiation
- S_{in} and L_{in} are the incoming shortwave and longwave radiation, respectively
- α and ε are the albedo and emissivity, respectively
- H and LE are the sensible and latent heat fluxes, respectively
- $\varepsilon\sigma T_s^4$ is the outgoing longwave radiation (= L_{out})
- σ is the Stefan-Boltzmann constant and T_s is the LST

$$H = \frac{\rho c_p}{r_a}(T_s - \theta_a) \qquad (2)$$

$$E = \frac{\rho L_v}{r_a + r_s}(q_s^*(T_s) - q_a) \qquad (3)$$

- ρ is the air density
- c_p is the specific heat of air at constant pressure
- L_v is the latent heat of vaporization
- θ_a is the potential temperature of air
- q_a is the specific humidity of air.

- Substituting Eqs. (2) and (3) into Eq. (1) yields a non-linear equation for T_s provided that all the other variables are given as inputs.
- To obtain the analytical expression for T_s, further linearized the non-linear equation for T_s, as shown in Rigden and Li (2017).

3. Decomposition of ΔT_s: atmospheric *vs.* biophysical

- A grand figure: $\Delta T_s^{total} = \Delta T_s^{bio} + \Delta T_s^{atm}$
- Direct and indirect drivers of greening
  - Human land-use management
  - CO_2 concentration increase
  - Climate change
  - Relaxation of climatic constraints to plant physiological functioning
  - Enhanced water and light use efficiencies
- Both can lead to change of surface biophysical parameters
  - Albedo
  - Aerodynamic resistance
  - Surface resistance to water vapor transfer
- Finally lead to changes in local LST (ΔT_s^{bio}) (Rigden and Li, 2017; Liao et al., 2018)

$$\Delta T_s^{bio} = \left(\frac{\partial T_s}{\partial \alpha}\right)\Delta\alpha + \left(\frac{\partial T_s}{\partial r_a}\right)\Delta r_a + \left(\frac{\partial T_s}{\partial r_s}\right)\Delta r_s \qquad (4)$$

- r_a *is* aerodynamic resistance
- r_s *is* surface resistance

- Also the large-scale climate change can cause local LST changes Δt_s^{atm} (Rigden and Li, 2017; Liao et al., 2018)
  - e.g. when air temperature increases, the local LST would respond even if all the biophysical parameters remained the same.

$$\Delta T_s^{atm} = \left(\frac{\partial T_s}{\partial S_{in}}\right)\Delta S_{in} + \left(\frac{\partial T_s}{\partial L_{in}}\right)\Delta L_{in} + \left(\frac{\partial T_s}{\partial \theta_a}\right)\Delta\theta_a + \left(\frac{\partial T_s}{\partial q_a}\right)\Delta q_a \qquad (5)$$

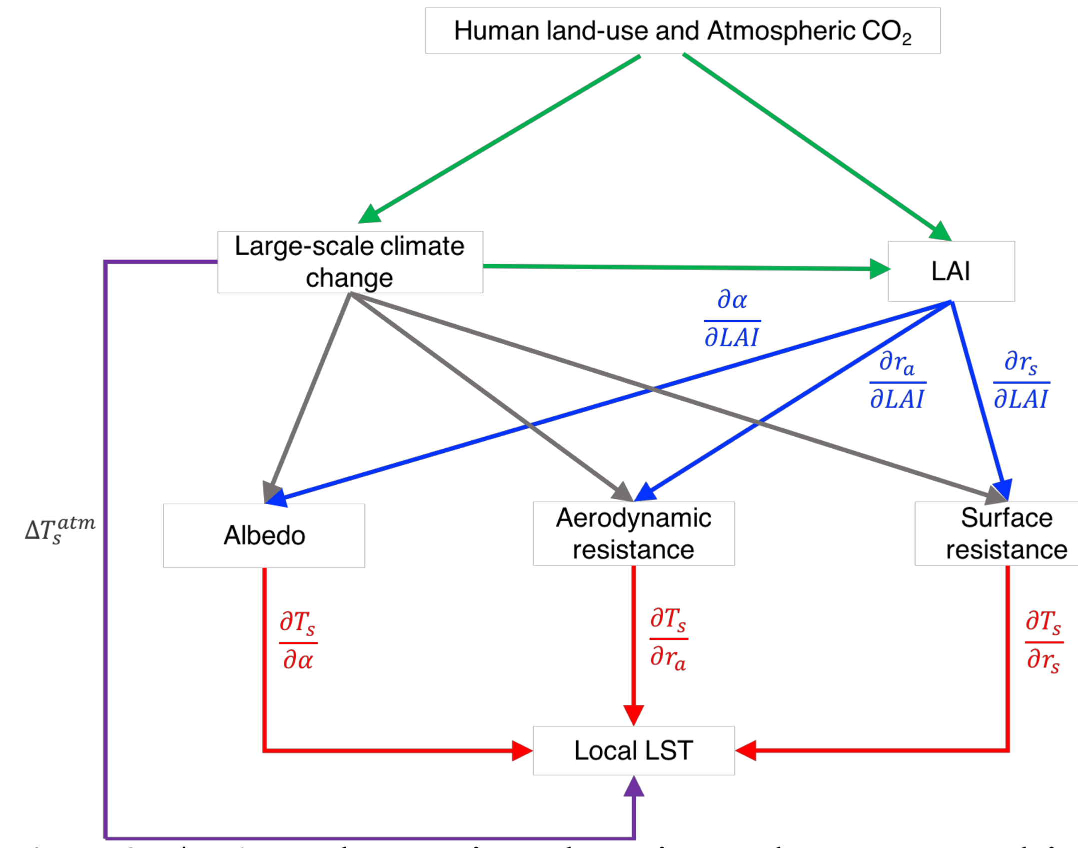

Fig. 2 | A schematic showing the overarching framework of this research and connections between different variables/processes.

4. Decomposition of ΔT_s^{bio}

- Blue pathways and grey pathways can change biophysical properties
  - Large-scale climate change
  - LAI
  - Get the ratio $\gamma = \Delta T_s^{bio/LAI} / \Delta T_s^{total}$

$$\Delta T_s^{bio/LAI} = \left[\left(\frac{\partial T_s}{\partial \alpha}\right)\left(\frac{\partial \alpha}{\partial LAI}\right) + \left(\frac{\partial T_s}{\partial r_a}\right)\left(\frac{\partial r_a}{\partial LAI}\right) + \left(\frac{\partial T_s}{\partial r_s}\right)\left(\frac{\partial r_s}{\partial LAI}\right)\right]\Delta LAI \qquad (6)$$

- Solutions of sensitivity of LST to biophysical parameter (the red ones)
  - Analytically solved if inputs are available
- Solutions of sensitivity of biophysical parameters to LAI
  - Need to run land models with prescribed MODS LAI to numerically solve them
  - E.g. using CLM5 with control and sensitivity runs

$$\frac{\partial \alpha}{\partial LAI} = \frac{\alpha_{sen} - \alpha_{ctl}}{LAI_{sen} - LAI_{ctl}} \qquad (7)$$

  - ‘sen’ and ‘ctl’ indicate sensitivity and control simulations

5. Results of $\frac{\partial T_s}{\partial \alpha}$, $\frac{\partial T_s}{\partial r_a}$ and $\frac{\partial T_s}{\partial r_s}$

- Sensitivity of LST to albedo
  - Mostly negative, indicating that as albedo increases the LST will be reduced.
- Sensitivities of LST to aerodynamic resistance and surface resistance
  - All positive, implying that as the surface becomes smoother (stronger aerodynamic resistance) or drier/less vegetation (stronger surface resistance), the LST will be increased.

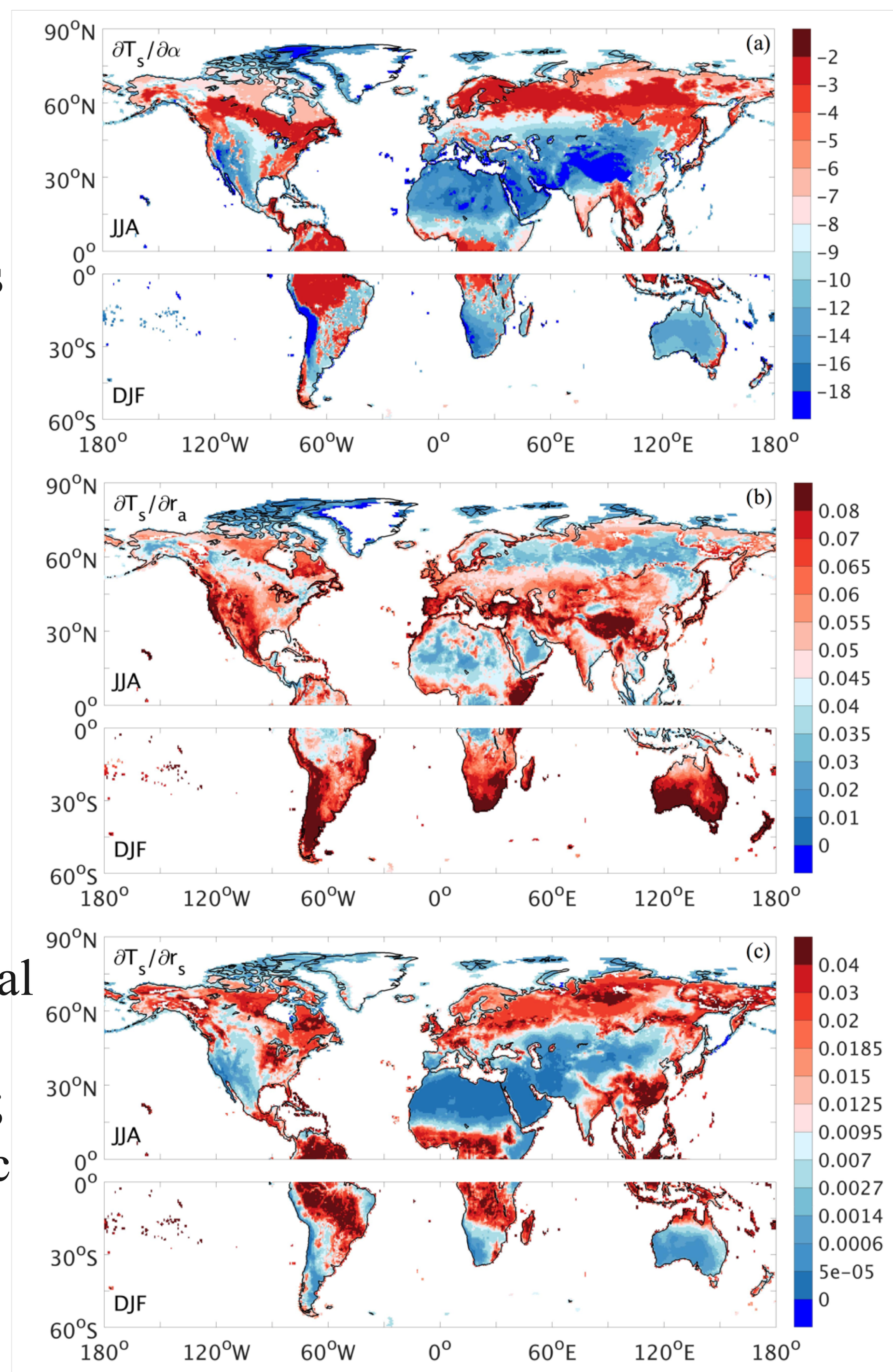

Fig. 3 | Sensitivities of LST to biophysical factors calculated from the MERRA-2 data. (a) the sensitivity of LST to albedo; (b) the sensitivity of LST to aerodynamic resistance; (c) the sensitivity of LST to surface resistance. The results are averaged from 2000 to 2017.

6. Future works

- Running CLM5 to get $\frac{\partial \alpha}{\partial LAI}$, $\frac{\partial r_a}{\partial LAI}$, $\frac{\partial r_s}{\partial LAI}$
- Evaluate the $\Delta T_s^{bio/LAI}$
- Identify the dominant biophysical factor across biomes, latitudinal bands and climatic zones
- Shed further light on the spatial variability of attribution results and case studies

Reference

Rigden, A. J., & Li, D. (2017). Attribution of surface temperature anomalies induced by land use and land cover changes. *Geophysical Research Letters*, *44*(13), 6814–6822.

Liao, W., Rigden, A. J., & Li, D. (2018). Attribution of Local Temperature Response to Deforestation. *Journal of Geophysical Research: Biogeosciences*, *123*(5), 1572–1587.