

Biophysical Impacts of Deforestation in Different Forest Types on Seasonal Warming in Northern Midlatitudes

Yazhu CUI, Wenjian HUA, Liming ZHOU, Shuyu LIU, Hongwei CHEN, Haishan CHEN

Citation: Cui, Y. Z., W. J. Hua, L. M. Zhou, et al., 2026: Biophysical impacts of deforestation in different forest types on seasonal warming in northern midlatitudes. *J. Meteor. Res.*, **40**(5), 1687–1703, doi: <https://doi.org/10.1007/s13351-026-5355-7>

View online: <http://jmr.cmsjournal.net/article/doi/10.1007/s13351-026-5355-7>

Related articles that may interest you

[Analysis of Pressure Forcings for the Vertical Turbulent Fluxes in the Convective Boundary Layer at Gray Zone Resolutions](#)

Journal of Meteorological Research. 2023, 37(6), 841 <https://doi.org/10.1007/s13351-023-3033-6>

[Overview of the Centennial Progress in Research on the Arctic–Midlatitude Connection](#)

Journal of Meteorological Research. 2025, 39(3), 625 <https://doi.org/10.1007/s13351-025-4906-7>

[Relationship between the Stratospheric Arctic Vortex and Surface Air Temperature in the Midlatitudes of the Northern Hemisphere](#)

Journal of Meteorological Research. 2024, 38(1), 39 <https://doi.org/10.1007/s13351-024-3072-7>

[Meteorological Tower Observed CO₂ Flux and Footprint in the Forest of Xiaoxing’ an Mountains, Northeast China](#)

Journal of Meteorological Research. 2023, 37(1), 126 <https://doi.org/10.1007/s13351-023-2080-3>

[Impacts of Extreme Droughts on Ecosystem Water Use Efficiency Diverge between Forest and Grassland](#)

Journal of Meteorological Research. 2023, 37(5), 710 <https://doi.org/10.1007/s13351-023-3022-9>

[Impact of Spatial Inhomogeneity in Atmospheric CO₂ Concentration on Surface Air Temperature Variations](#)

Journal of Meteorological Research. 2024, 38(5), 969 <https://doi.org/10.1007/s13351-024-4025-x>

Biophysical Impacts of Deforestation in Different Forest Types on Seasonal Warming in Northern Midlatitudes

Yazhu CUI (崔亚朱)^{1,2}, Wenjian HUA (华文剑)*, Liming ZHOU (周黎明)³, Shuyu LIU (刘殊瑜)¹,
Hongwei CHEN (陈虹玮)¹, and Haishan CHEN (陈海山)¹

¹ State Key Laboratory of Climate System Prediction and Risk Management / Key Laboratory of Meteorological Disaster,
Ministry of Education / Collaborative Innovation Center on Forecast and Evaluation of Meteorological Disasters,
Nanjing University of Information Science & Technology, Nanjing 210044, China

² Xuzhou Meteorological Bureau of Jiangsu Province, Xuzhou 221000, China

³ Department of Atmospheric and Environmental Sciences, State University of New York at Albany, Albany, NY 12222, USA

(Received 21 December 2025; revised 30 January 2026; accepted 10 February 2026)

ABSTRACT

The biophysical effects of forests on climate and climate change have been extensively studied by using climate models and satellite data at the global scale. However, the climatic effects of forests vary with specific forest types and locations, and the sign and magnitude of temperature responses resulting from biophysical impacts of temperate forests remain uncertain. In this study, we utilized site-based flux tower observations from the FLUXNET2015 and AmeriFlux datasets in North America and Europe, as well as a decomposed temperature metric, to investigate how distinct forest types influence seasonal changes in surface temperature (T_s). The results indicate that deciduous broadleaf forest (DBF) generally exhibits higher albedo than evergreen needleleaf forest (ENF) except in winter, while ENF is characterized by greater surface roughness and Bowen ratio. Although the larger albedo difference contributes more to T_s reduction at ENF sites than that at DBF sites, the dominant drivers of T_s changes are associated with surface turbulent fluxes, and these mechanisms vary with forest types and seasons. Specifically, deforestation at ENF sites leads to a consistent warming effect throughout the year due to reduced sensible heat flux. In contrast, at DBF sites, the warming effect from decreased sensible heat is partially offset by increased latent heat flux in winter and spring, whereas the warming effect of reduced latent heat flux becomes more pronounced in other seasons. These findings suggest that surface turbulent fluxes are the primary biophysical drivers of local T_s changes, and different forest types play a critical role in modulating seasonal energy exchange processes and temperature responses in the northern midlatitudes. Overall, our study provides insights on the mechanisms of how different temperate forest types influence seasonal T_s changes.

Key words: temperate forests, deforestation, seasonal warming, biophysical impact, turbulent fluxes

Citation: Cui, Y. Z., W. J. Hua, L. M. Zhou, et al., 2026: Biophysical impacts of deforestation in different forest types on seasonal warming in northern midlatitudes. *J. Meteor. Res.*, **40**(5), 1687–1703, <https://doi.org/10.1007/s13351-026-5355-7>.

1. Introduction

Afforestation, reforestation, tree restoration, or the prevention of deforestation is recognized as a key strategy for mitigating climate change through enhancing carbon capture and storage (Canadell and Raupach, 2008; Girardin et al., 2021; Anderegg et al., 2025). However, the cooling effects due to forests' biogeochemical influences can be either enhanced or offset by bio-

physical effects of forests (Bala et al., 2007; Bonan, 2008; Windisch et al., 2021; Alkama et al., 2022; Zhu et al., 2023). For example, changes in forest cover modify land surface properties (e.g., surface albedo, roughness, and evaporative efficiency) and alter exchanges of momentum, energy, and water with the atmosphere, thereby influencing regional and global climate (Pielke et al., 2011; Runyan et al., 2012; Hua et al., 2014; Mahmood et al., 2014; Perugini et al., 2017). The biophysical effects

Supported by the National Key Research and Development Program of China (2022YFF0801601) and Postgraduate Research and Practice Innovation Program of Jiangsu Province (KYCX25_1578).

*Corresponding author: Wenjian HUA, wenjian@nuist.edu.cn

© The Chinese Meteorological Society 2026

of forests are complex and exhibit strong latitudinal dependence and seasonality (Ellison et al., 2017; Forzieri et al., 2017; Pongratz et al., 2021). A comprehensive understanding of the biophysical impacts of forests on regional and global climate is therefore of significant environmental importance and is crucial for future land management policy.

Many studies have used observational data (Lee et al., 2011; Zhang et al., 2014; Li et al., 2015; Alkama and Cescatti, 2016; Ge et al., 2019; Li et al., 2023) and regional or global climate models (Davin and de Noblet-Ducoudré, 2010; de Noblet-Ducoudré et al., 2012; Kumar et al., 2013; Hua et al., 2015; Boysen et al., 2020; Liu et al., 2023; Chen et al., 2026) to examine the biophysical impacts of forests on climate. In general, boreal deforestation is associated with a decrease in temperature due to the enhanced albedo effect, while tropical deforestation tends to increase temperature because of reduced evapotranspiration (e.g., Li et al., 2015). Although there exist seasonal differences, particularly in northern regions with extensive snow cover in winter (Anderson et al., 2011; Hua and Chen, 2013; Bright et al., 2017), the mechanisms of deforestation affecting the tropical and boreal climate through biophysical processes have been well recognized (Pongratz et al., 2021). However, the biophysical effects of temperate/midlatitude deforestation remain ambiguous due to competing biophysical forcings from albedo, roughness, and evapotranspiration (Bonan, 2008; Lawrence et al., 2022). In addition, temperate lands have a variety of forest types, leading to complex forest–climate interactions (Schwaab et al., 2020; Su et al., 2021).

It should be noted that different types of forest loss or gain may have distinct impacts on regional climate (e.g., Duveiller et al., 2018a; Li et al., 2025). For example, deforestation from deciduous broadleaf forests to grasslands caused a 0.17°C increase in global-mean surface temperature, while deforestation from evergreen needleleaf forests to grasslands led to a 0.37°C increase (Duveiller et al., 2018a). The physiological characteristics of different forest types may also affect water or energy exchange between the land and the atmosphere. The sensible heat flux of evergreen needleleaf forests is higher all year round when compared to open lands, while the heat flux of deciduous broadleaf forests is only higher in winter (Zhao and Jackson, 2014; Chen et al., 2018). It is worth mentioning that climate responses in temperate forests are moderate compared with those in tropical and boreal forests (Li et al., 2015; Alkama and Cescatti, 2016), and the role of evaporative forcing is unclear (Bonan, 2008; Pongratz et al., 2021). A thorough assess-

ment of the biophysical impacts of different forest types on the temperate climate is thus necessary.

Furthermore, previous studies often compared forests with grasslands to infer the climatic effects of deforestation. However, in the real world, human-induced forest cover changes may include different forest types converted to distinct open lands (e.g., grassland, pasture, and cropland) for various purposes, including residential, agricultural, commercial, industrial activities, as well as infrastructure and transportation. Population growth may cause agricultural expansion and intensification (i.e., converting forests to croplands) to fulfil growing demands for food and other commodities (Potapov et al., 2022). Further investigation of differences between various forests (i.e., needleleaf and broadleaf forests) and distinct open lands (i.e., grassland and cropland) is thus needed. This will help quantify the influence of different biophysical processes and provide complementary information on the climatic effects of temperate forests.

Given the moderate and highly uncertain climatic effects of different forest cover changes in densely populated temperate regions, this study aims to investigate the biophysical impacts of different forest types on land surface properties and surface temperature in the northern midlatitudes and to further explore the possible biophysical mechanisms. Since the large discrepancies and uncertainties in modeling the climatic impacts of temperate forests (de Noblet-Ducoudré et al., 2012; Boysen et al., 2020; Liu et al., 2023), we use flux towers to examine the seasonal effects of different forest types on surface temperature in the midlatitudes, which can accurately record the exchange of water and energy between the atmosphere and land surface at the ecosystem scale. To further support our analysis, we also use the satellite remote sensing data (Duveiller et al., 2018b). Section 2 describes the observational data and methods. The main results are presented in Section 3, followed by the discussion in Section 4. Section 5 concludes with a summary of the findings.

2. Data and methods

2.1 Observational data

In this study, we use site-based observational datasets from FLUXNET2015 (Pastorello et al., 2020) and AmeriFlux (Baldocchi et al., 2001). The FLUXNET2015 data are available at <https://fluxnet.org/data/fluxnet2015-dataset>. The AmeriFlux data are available at <https://ameriflux.lbl.gov>.

The flux tower data are reported at half-hourly to hourly intervals to provide continuous measurements of

energy fluxes (detailed in Table S1 in the electronic supplemental materials), and the vegetation types in these datasets are all based on the International Geosphere–Biosphere Programme (IGBP) classification (Baldocchi et al., 2001). To examine the seasonal influences of forest cover changes, flux tower sites are selected based on having at least 1 year of available data. Moreover, the analysis variables include wind speed, friction velocity, radiative fluxes (i.e., incoming and outgoing shortwave and longwave radiation), and turbulent fluxes (i.e., sensible heat, latent heat, and ground heat fluxes).

A dataset mapping the biophysical effects of vegetation cover change (Duveiller et al., 2018b) is also used. It is obtained from <https://jeodpp.jrc.ec.europa.eu/ftp/jrc-opendata/ECOCLIM/Biophysical-effects-vgt-change/v2.0>. This dataset is based on the space-for-time method (discussed below) and multiple satellite observations (Duveiller et al., 2018b, 2021a), which provide potential biophysical effects of vegetation cover change (e.g., what is transitioning from and what is transitioning to). The data are provided at monthly time steps at a horizontal resolution of $1^\circ \times 1^\circ$. The vegetation cover definition in this dataset is also based on the IGBP scheme, enabling comparison with site-based flux tower data.

2.2 Analysis methods

2.2.1 The space-for-time method

We apply a space-for-time method to obtain all available samples to compare the open lands with forests across the midlatitudes. This approach has been widely used in the observation-based studies (Lee et al., 2011;

Peng et al., 2014; Zhang et al., 2014; Li et al., 2015; Schultz et al., 2017). This method assumes that all selected open lands and forests are close in distance and share similar background atmospheric conditions. Based on this searching strategy, 19 sites are used, and 13 pairs are available for our analysis (Fig. 1 and Table S1). For each pair, one flux tower is located over open land (e.g., grasslands, open shrublands, or croplands) and the other is located over forest (e.g., deciduous broadleaf forests or evergreen needleleaf forests). For simplicity, we used OSH, GRA, and CRO to represent open shrublands, grasslands, and croplands, while DBF and ENF to represent deciduous broadleaf forests and evergreen needleleaf forests, respectively. The mean horizontal distance between the paired sites is 14.1 km, and the mean elevation difference is 65.4 m. The paired sites share similar atmospheric conditions due to their short horizontal distance, so the differences between open lands and forests can be attributed to contrasting land cover types. We calculate the mean differences in surface temperature and other climate variables between open land and nearby forest (i.e., open land minus forest) to represent the influence of temperate deforestation.

The biophysical impact of temperate deforestation is quantified as the surface temperature (T_s) difference between open land and forest as follows:

$$\Delta T_{s,obs} = T_{s,openland} - T_{s,forest}. \quad (1)$$

As T_s cannot be measured directly at flux towers, the observed surface temperature ($T_{s,obs}$) can be calculated based on the outgoing longwave radiation (R_{lo}) follow-

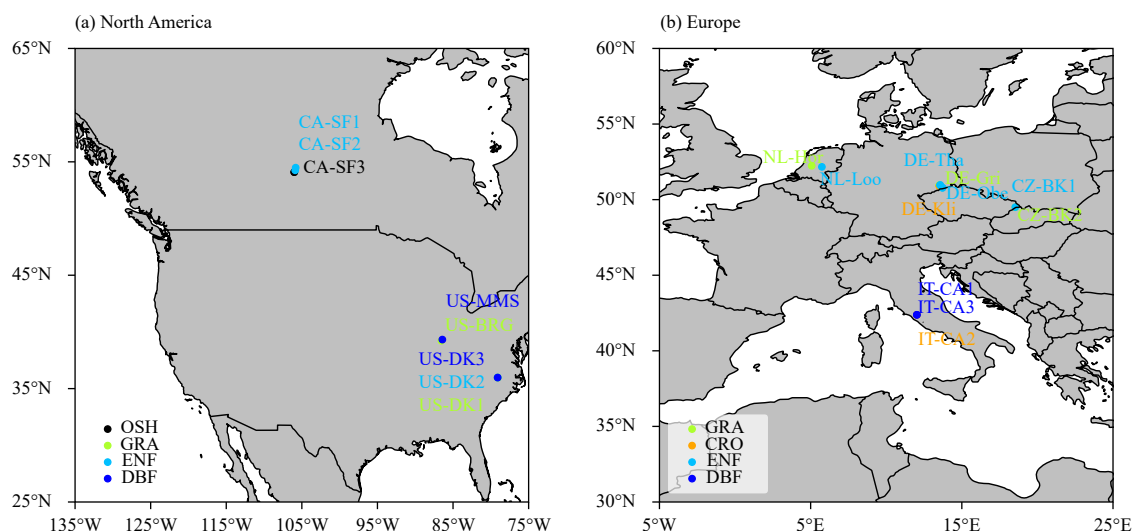


Fig. 1. Locations and land cover types of selected sites in (a) North America and (b) Europe. The land cover type of each site is based on the reported land cover from FLUXNET2015 data. OSH, GRA, and CRO represent open shrublands, grasslands, and croplands, while DBF and ENF represent deciduous broadleaf forest and evergreen needleleaf forest, respectively. The colored dot represents the location and name of each site respectively.

ing the Stefan–Boltzmann law (Luyssaert et al., 2014; Zhang et al., 2020). Energy conservation requires that at the site-level, the incoming energy flux equals the sum of the outgoing energy flux and the energy stored in the biomass. The outgoing longwave radiation is emitted by the surface and is given by the Stefan–Boltzmann law, which depends on the radiometric T_s , the Stefan–Boltzmann constant, and emissivity.

$$R_{lo} = A\sigma\epsilon T_{s,obs}^4, \quad (2)$$

where A is the view factor assumed to be equal to 1, σ is the Stefan–Boltzmann constant, and ϵ is the surface emissivity. Since there is no direct measurement of the emissivity coefficient of the vegetation, ϵ is approximated by an empirical relationship with surface albedo (α), expressed as $\epsilon = -0.16\alpha + 0.99$ (Juang et al., 2007).

2.2.2 Separation of the biophysical effects

Commonly used methods for studying the biophysical feedbacks of land use and land cover change (LULCC) in observations and climate models include the intrinsic biophysical mechanism (IBPM) method and the decomposed temperature metric (DTM) (Chen and Dirmeyer, 2016). In general, the IBPM method separates the biophysical processes that affect T_s changes into albedo, surface roughness, and the Bowen ratio (Lee et al., 2011). Although the formula is relatively simple, it has complex adjustment coefficients (Lee et al., 2011; Luyssaert et al., 2014; Liu et al., 2023) that need to be calculated and are also not completely linear itself. On the other hand, although the DTM method involves many variables, it illustrates the relative contributions of the individual components of the surface energy balance to the T_s perturbation determined with the surface outgoing longwave radiation. To understand the biophysical mechanisms behind the different behaviors of seasonal T_s changes due to temperate deforestation, we thus used a more thorough DTM based on the surface energy balance (Luyssaert et al., 2014; Chen and Dirmeyer, 2016).

First, the net radiation (R_n) can be written as the sum of incoming and outgoing shortwave and longwave radiations:

$$R_n = R_{si} - R_{so} + R_{li} - R_{lo}, \quad (3)$$

where R_{si} is the incoming shortwave radiation and R_{li} is the incoming longwave radiation, R_{so} is the outgoing shortwave radiation and R_{lo} is the outgoing longwave radiation. R_{so} can be expressed as a function of R_{si} and α (i.e., $R_{so} = \alpha R_{si}$). Here, R_n can also be expressed in terms of the ecosystem energy fluxes, so that Eq. (3) can be rearranged to:

$$(1 - \alpha)R_{si} + R_{li} - R_{lo} = H + LE + G + I, \quad (4)$$

where H is the sensible heat flux, LE is the latent heat flux, G is the ground heat flux, and I is the residual flux that is necessary for full energy balance closure at most flux sites (Foken, 2008). At those sites where ground heat flux is unavailable, G is set to zero (Zhang et al., 2020).

Combining Eqs. (2) and (4) gives:

$$(1 - \alpha)R_{si} + R_{li} - \sigma\epsilon T_s^4 = H + LE + G + I. \quad (5)$$

Then, the full derivative of ΔT_s can be estimated by using the first-order Taylor series approximation in Eq. (5) as:

$$\Delta T_{s,cal} = \frac{1}{4\sigma\epsilon T_s^3} [-R_{si}\Delta\alpha + (1 - \alpha)\Delta R_{si} + \Delta R_{li} - \Delta H - \Delta LE - \Delta G - \Delta I - \sigma T_s^4 \Delta\epsilon]. \quad (6)$$

Here, $\Delta T_{s,cal}$ denotes the calculated temperature change across space (e.g., from one tower to the next), reflecting contributions from different components of the energy balance. For simplicity, the contributions of within-site differences in R_{si} and R_{li} are combined into a single term (i.e., the incoming radiation), that is, $\Delta R_i = (1 - \alpha)\Delta R_{si} + \Delta R_{li}$. Thus, Eq. (6) becomes:

$$\Delta T_{s,cal} = \frac{1}{4\sigma\epsilon T_s^3} [-R_{si}\Delta\alpha + \Delta R_i - \Delta H - \Delta LE - \Delta G - \Delta I - \sigma T_s^4 \Delta\epsilon]. \quad (7)$$

According to Eq. (7), the effects of deforestation on T_s can be attributed to changes in the components of the energy balance, including albedo, incoming radiation, sensible heat flux, latent heat flux, ground heat flux, residual imbalance, and surface emissivity. This decomposition method illustrates the relative contributions of the individual components of the surface energy balance to the T_s perturbation, determined from surface outgoing longwave radiation. To quantify the relative contribution of each component to T_s changes, the biophysical processes that affect T_s changes are classified into albedo, turbulent flux, incoming radiation, and surface emissivity, and we then calculate the proportion of each component to the sum of T_s changes.

Note that deforestation alters the land surface properties (e.g., albedo, surface roughness, and Bowen ratio). The Bowen ratio is the ratio of sensible to latent heat fluxes. We calculate the aerodynamic resistance (r_a) according to the bulk aerodynamic conductance (g_a) of the vegetation itself (Monteith and Unsworth, 1990), that is, $r_a = 1/g_a$, where u is the wind speed (m s^{-1}) and u^* is the friction velocity (m s^{-1}) as expressed in Eq. (8):

$$g_a = \left(\frac{u}{u^{*2}} + 6.2u^{*-2/3} \right)^{-1}. \quad (8)$$

To calculate the albedo, aerodynamic resistance, and Bowen ratio, the daytime records during 1000–1500 local time are used (Chen and Dirmeyer, 2016; Novick and Katul, 2020; Zhang et al., 2020). Therefore, we take the half-hourly data and the following criteria into account. For data processing, any day without a complete diurnal cycle (i.e., 48 half-hourly or 24-hourly values) for estimating the required variables is not used for analysis, and the data are filtered to exclude days with rainfall events (precipitation > 0 mm) (Rigden and Salvucci, 2015; Zhang et al., 2020). We finally aggregate the half-hourly data to the hourly and daily scales for analysis. At the daily scale, we only accept $\Delta T_{s,obs}$ and $\Delta T_{s,cal}$ records with the same sign (Luyssaert et al., 2014). In addition, when calculating seasonal averages (e.g., aerodynamic resistance and Bowen ratio), only 25%–75% of all valid data for that season are selected to remove the influence of outliers (Lin et al., 2022).

Since we have selected only 19 sites for our analysis in the northern midlatitudes based on our search strategy (Fig. 1), the site-based observational data may not be a representative sample of temperate deforestation. To ensure the robustness of the results, we also examine the satellite remote sensing data (Duveiller et al., 2018b). Satellite remote sensing data provide T_s changes associated with the conversion of different vegetation types (Duveiller et al., 2021a). To ensure the consistency of vegetation types between the gridded dataset and site-based observations, the fixed gridded data after the change of a certain vegetation cover type is selected according to the paired sites (e.g., when the paired sites include ENF and

GRA, the satellite dataset selects the T_s changes after the transition from ENF to GRA). Then, we use the station location as the center, and the grid cell with the latitude and longitude closest to the station is selected for comparative analysis. Since the gridded dataset only provides monthly mean daytime and nighttime T_s , the monthly mean T_s is calculated as the average of the mean daytime and nighttime values.

3. Results

3.1 Seasonal effects of temperate deforestation

In general, deforestation leads to an increase in surface albedo (Fig. 2a). The solar radiation is relatively weak during boreal winter due to the Earth's revolution, and the land surface in northern mid- to high-latitudes is mainly covered by snow. Thus, deforestation-induced albedo change is enhanced by the snow albedo masking effect during boreal winter (Anderson et al., 2011). The surface albedo significantly increases in winter by about 0.16 due to deforestation, followed by spring, summer, and autumn (Fig. 2a). In addition to albedo changes, deforestation also influences the surface roughness. In general, the aerodynamic resistance for forests is about 25 s m^{-1} in all seasons. However, for open lands, it is smaller in summer than in other seasons but still higher than that for forests. As a result, deforestation decreases surface roughness and increases aerodynamic resistance (Fig. 2b). The decline in surface roughness is accompanied by a weakening of the surface's ability to transport turbulent energy into the atmosphere. The Bowen ratio also has distinct seasonal differences between forests and open lands (Fig. 2c). The largest Bowen ratio of forests is in

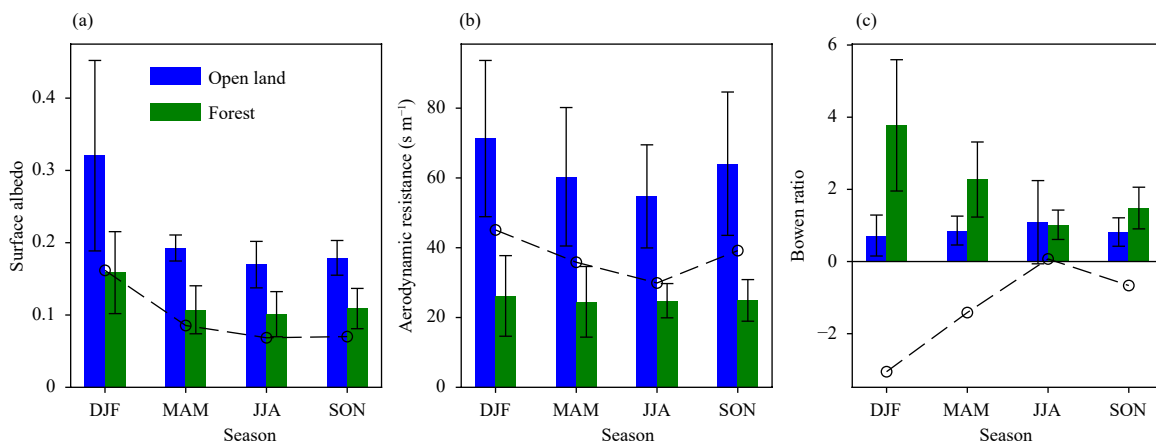


Fig. 2. Seasonal variations between open lands and forests for (a) surface albedo, (b) aerodynamic resistance (s m^{-1}), and (c) Bowen ratio. Error bars are calculated as one standard deviation among selected flux tower sites. The dashed line with circles represents the change of land surface properties due to land cover change (i.e., open land minus forest). DJF, MAM, JJA, and SON denote December–February, March–May, June–August, and September–November, respectively.

winter, which is close to 3.78, followed by spring, autumn, and summer, while the Bowen ratio of open lands is smaller in all seasons. It is worth noting that the magnitudes of Bowen ratio are quantitatively similar in summer for forests and open lands, which may lead to moderate temperature changes resulting from deforestation-induced evapotranspiration effects (Li et al., 2015; Alkama and Cescatti, 2016; Duveiller et al., 2018a).

Deforestation-induced changes in surface properties could further influence seasonal variations in T_s . Figure 3 shows the seasonal variations in ΔT_s between open lands and forests (i.e., open land minus forest). In general, deforestation increases T_s , and the average annual increase is approximately 1.16°C. In addition, T_s increases significantly in summer, with an average increase of 1.65°C. It is worth noting that satellite-based studies show summer warming and moderate winter cooling due to deforestation (Li et al., 2015; Alkama and Cescatti, 2016; Duveiller et al., 2018a). However, our site-based results show that the sign of T_s in response to deforestation in winter differs from that reported in previous studies.

We also examined the T_s changes in response to deforestation based on satellite remote sensing observations (Duveiller et al., 2018b; Fig. 4). The deforestation represents the changes from forests to open lands (Fig. 4 and Fig. S1). Findings show that deforestation could result in a spatially differentiated temperature response, with decreases observed in eastern Europe and increases in western Europe. These results suggest that T_s changes vary in

the sign and magnitudes during winter (Li et al., 2015; Alkama and Cescatti, 2016), which implies that the impacts of deforestation may depend on different vegetation types or species composition (e.g., broad-leaved or needle-leaved tree species; Schwaab et al., 2020).

3.2 Influences of different forest cover types

Land surface properties or climatic effects may vary among different forest types (Fig. 5). For example, the albedo of ENF is lower than that of DBF except in winter (Fig. 5a). The Bowen ratio of ENF is higher than that of DBF (Fig. 5c). Previous studies have indicated that broadleaf forests generally have higher albedo and transpiration than coniferous forests (Zhang et al., 2021; Lin et al., 2022), which is consistent with our results. It is noted that the albedo of ENF is larger than that of DBF in winter. We infer that the differences may result from the locations of site pairs where ENF sites are farther to the north, which have stronger snow masking effects (Fig. 1).

For open lands (i.e., GRA and CRO), the differences in land surface properties depend on vegetation types and seasons. In winter, GRA has a larger surface albedo relative to CRO. However, in other seasons, there is no significant difference between the GRA and CRO, which is close to 0.2 (Fig. 5a). The aerodynamic resistance of GRA and CRO is higher than 55 s m⁻¹ in all seasons, and the GRA is higher than the CRO in winter and autumn (Fig. 5b). In addition, the Bowen ratio of CRO is much higher than that of GRA in summer and the differences reverse in winter (Fig. 5c). The substantial difference in summer may be associated with enhancement of latent heat relative to sensible heat fluxes by increased evaporation with high temperature over grasslands (Teuling et al., 2010). The above results imply that the differences in land surface properties (e.g., different forest types convert to different open lands) may lead to distinct T_s changes (Fig. 5d).

Previous studies mainly focused on the T_s changes between forests and grasslands and used several site pairs to infer that deforestation increases T_s (e.g., Lee et al., 2011; Zhang et al., 2020). However, we show that there also exist seasonal differences in T_s between different forest types and grasslands. For example, the T_s change from ENF to GRA is much larger than that from DBF to GRA in all seasons, and the largest difference is about 1°C in summer (Fig. 5d). Moreover, it is worth noting that the T_s changes associated with conversions from forests (i.e., ENF or DBF) to CRO exhibit similar responses to forests-to-GRA transitions in winter and spring, but show opposite effects in the other seasons.

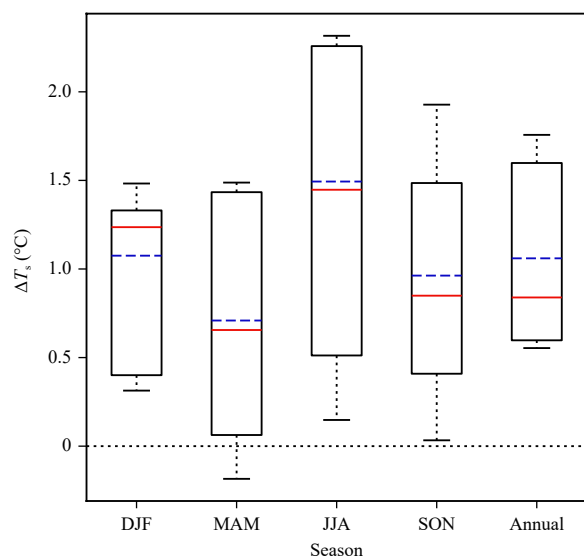


Fig. 3. Seasonal effects of deforestation on ΔT_s (°C). The boxplots show the variations in ΔT_s among selected flux tower sites, with the solid red line for the median, the box for the 25th–75th percentile range, and the whiskers for the 10th–90th percentile range. The mean ΔT_s is shown by a horizontal dashed blue line.

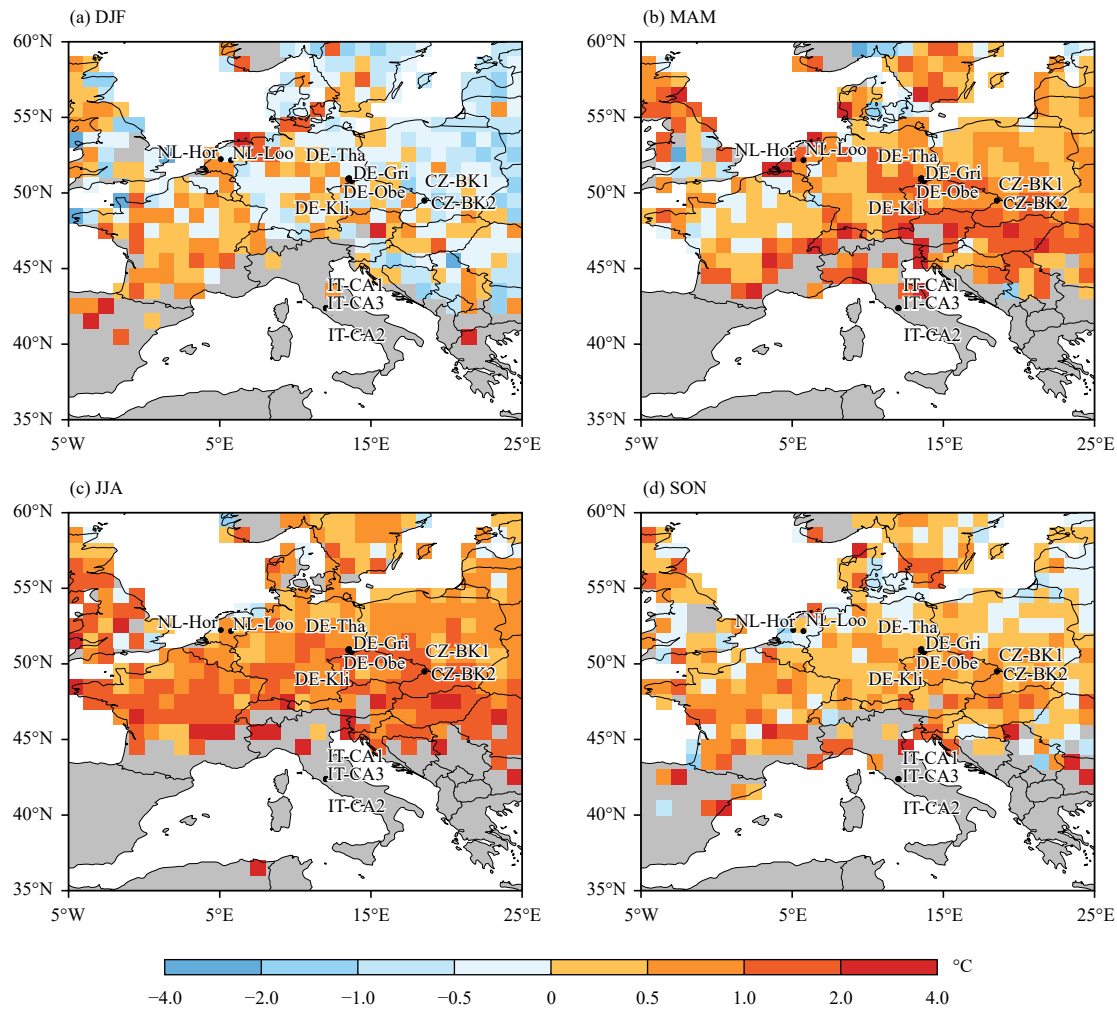


Fig. 4. Seasonal effects of deforestation (from forests to grasslands or croplands) on T_s (shaded, $^{\circ}\text{C}$) for (a) DJF, (b) MAM, (c) JJA, and (d) SON based on satellite-based data. As the daily mean surface temperature is not available (Duveiller et al., 2018b), we use the average of day-time (around 1330 local time) and nighttime (around 0130 local time) temperature to estimate the changes of daily mean T_s due to vegetation cover changes (Hua et al., 2023).

The change from DBF to CRO can be 2°C higher than that from ENF to CRO, especially in summer. Schwaab et al. (2020) pointed out that broadleaved tree species locally reduce T_s in summer compared to needle-leaved species in Europe, which is related to the background temperature, such as in the Mediterranean regions where some DBF sites that we selected in this study (Fig. 1). For instance, when the background temperature is relatively high, forests tend to be dominated by high evapotranspiration, which is also significantly accompanied by high T_s changes due to deforestation. In addition, given land management differences like cropping systems, those may explain the differences in T_s change due to deforestation from ENF or DBF to CRO. CRO is defined as lands covered with temporary crops, followed by harvest and a bare-soil period (e.g., single- and multiple-cropping systems) in the FLUXNET data. Thus, there are dif-

ferences in surface evapotranspiration across regions and at different crop coverage periods, which may affect the changes in T_s after deforestation across regions.

To further validate this finding, we also examined the T_s change from temperate forests (ENF and DBF) to open lands (GRA and CRO) in the satellite data (Figs. 6, 7). In general, temperate deforestation could lead to moderate warming in boreal winter at the site pairs where they are located (Fig. 6). It is worth noting that different temperate deforestations also show moderate cooling in northern regions. Previous studies have shown that the cooling effects are mainly driven by the albedo, which in turn is strongly influenced by snow during winter (Li et al., 2015; Alkama and Cescatti, 2016). In contrast, temperate deforestations show warming in summer (Fig. 7). Although the site-based and satellite data do not perfectly correspond in some midlatitude regions, the two

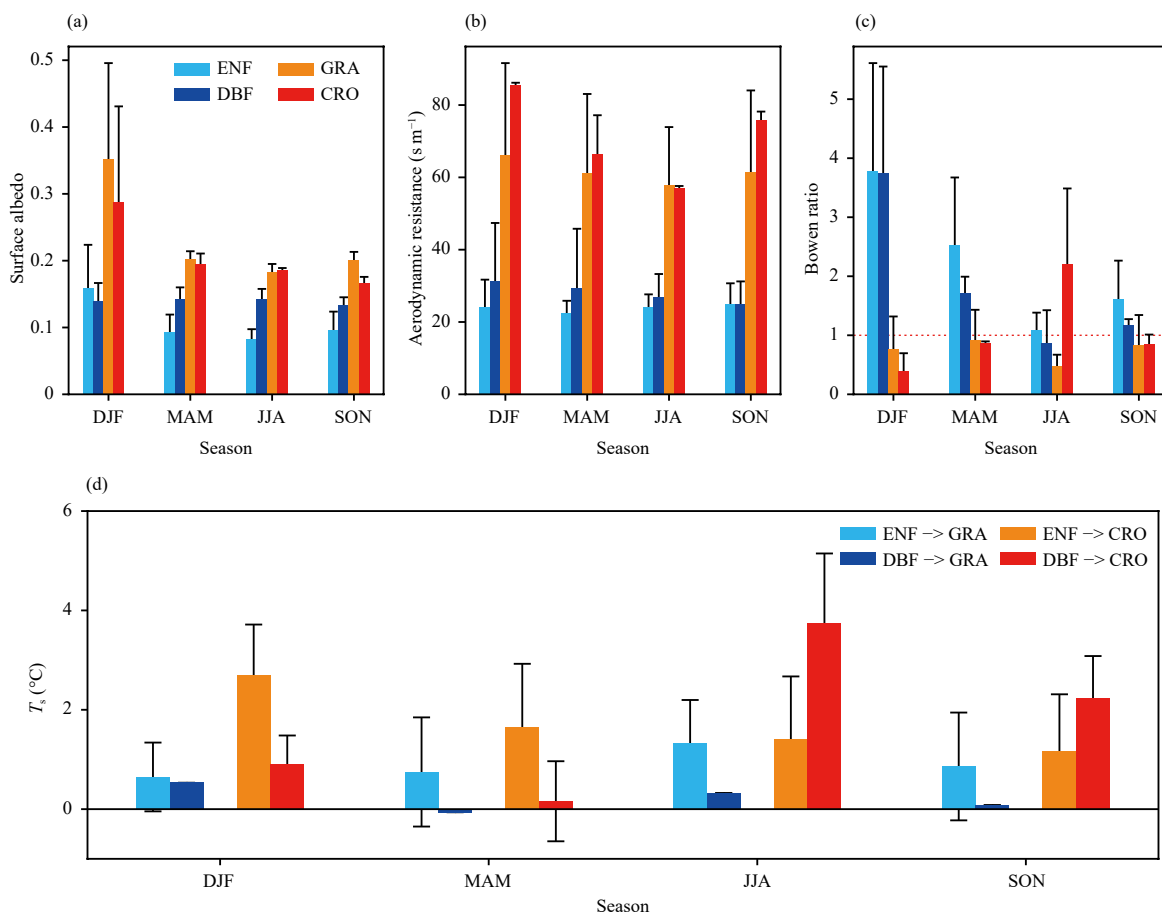


Fig. 5. Seasonal changes among different vegetation types for (a) surface albedo, (b) aerodynamic resistance (r_a , $s\ m^{-1}$), and (c) Bowen ratio. (d) The observed T_s responses to deforestation. Error bars are calculated as one standard deviation among selected flux tower sites. ENF $\rightarrow$ GRA represents the conversion from ENF to GRA, and other labels follow the same convention.

datasets show consistent results that the T_s changes of the site-based data and the satellite data are consistent at the gridded points that correspond to the site pairs (Figs. 6a, c, and Figs. 7a, c), except for the DBF sites near the Mediterranean, where the gridded data are missing, and the pairs indicate a significantly higher T_s increase in summer.

Overall, our results show that different forest types exhibit distinct seasonal changes in T_s . It is thus significant to determine which biophysical mechanisms drive T_s changes and why they vary across seasons and forest types.

3.3 Attribution of T_s responses to deforestation across different forest types

To investigate the possible mechanisms for temperate deforestation-driven T_s changes, the DTM method is used to separate different biophysical effects. Before examining individual biophysical factors, we need to know whether the decomposed temperature metric can realistically capture changes in T_s . At the seasonal scale, the calculated and observed ΔT_s follow the 1 : 1 line in all

seasons, with high correlation coefficients ($r > 0.9$; Fig. 8). Therefore, the DTM method can be used to investigate the biophysical effects of deforestation (Luyssaert et al., 2014; Chen and Dirmeyer, 2016).

We focus on the biophysical processes of temperate deforestation that affect the T_s . In general, the increase of albedo reduces T_s due to decreased absorbed solar radiation in all seasons (Fig. 9). Moreover, due to the albedo differences between ENF and DBF (Fig. 5a), the contributions of albedo on reducing T_s at ENF sites are higher than at DBF sites in spring, summer and autumn (Fig. 9). However, differences in turbulent flux changes arising from the distinct properties of the two forest types (i.e., surface roughness and Bowen ratio) lead to different T_s responses between the two forest types (Fig. 9).

In winter, replacing ENF with GRA (Fig. 9a) leads to a decrease in sensible heat flux, which in turn increases T_s , whereas the effect of latent heat flux on T_s is weak. This could result in a 3.1 $^{\circ}C$ increase in total. In contrast, when converting DBF to GRA, the warming effect caused by the decrease of sensible heat flux is mostly

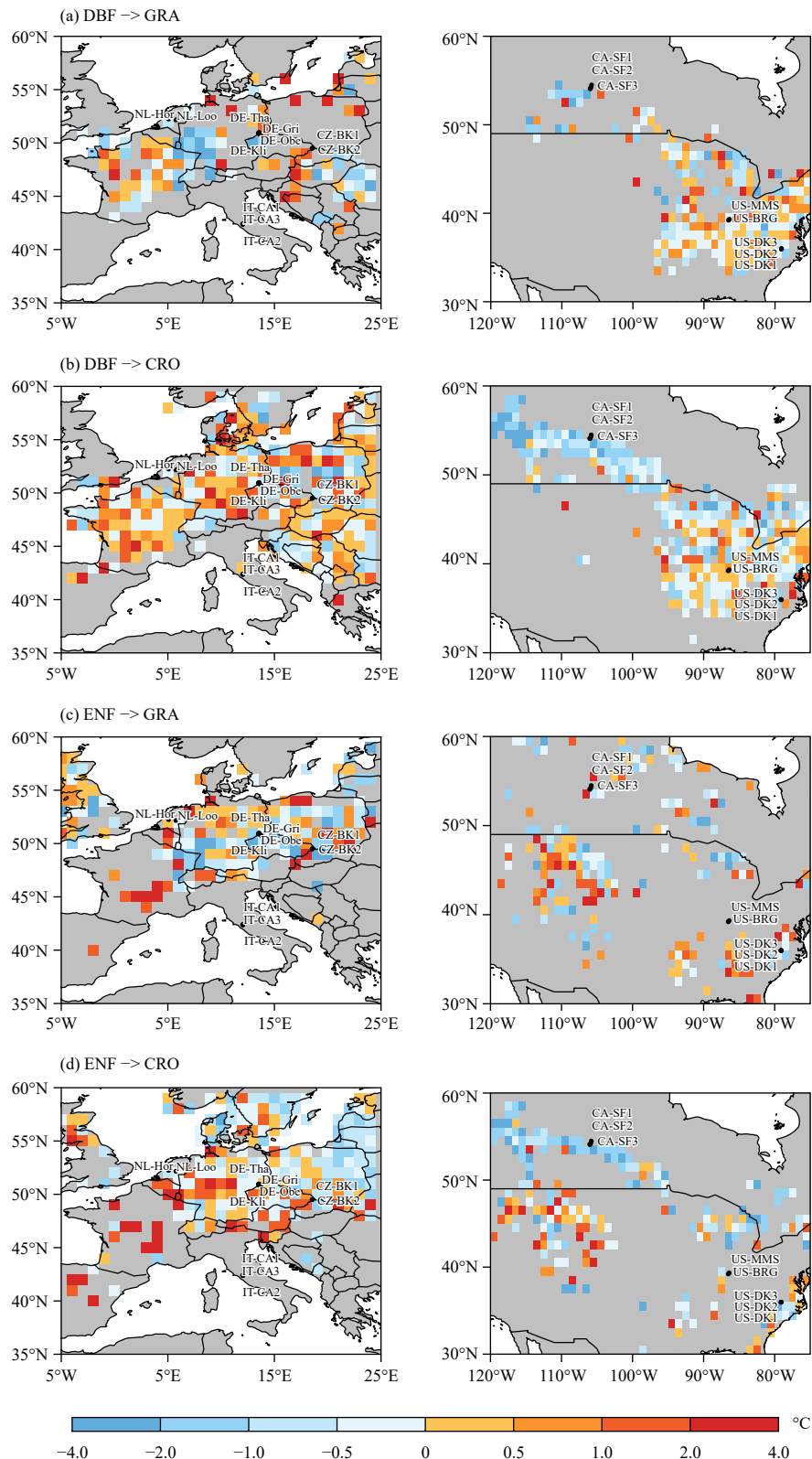


Fig. 6. Changes in T_s (shaded, °C) following vegetation type transitions during boreal winter: (a) from DBF to GRA, (b) from DBF to CRO, (c) from ENF to GRA, (d) from ENF to CRO. The left and right columns show the comparisons between satellite- and site-based T_s changes in Europe and North America, respectively.

offset by the cooling effect caused by the increase of latent heat flux, which only results in a 2.0°C increase.

When ENF is replaced by GRA in summer (Fig. 9c), the decrease of sensible heat flux significantly increases T_s

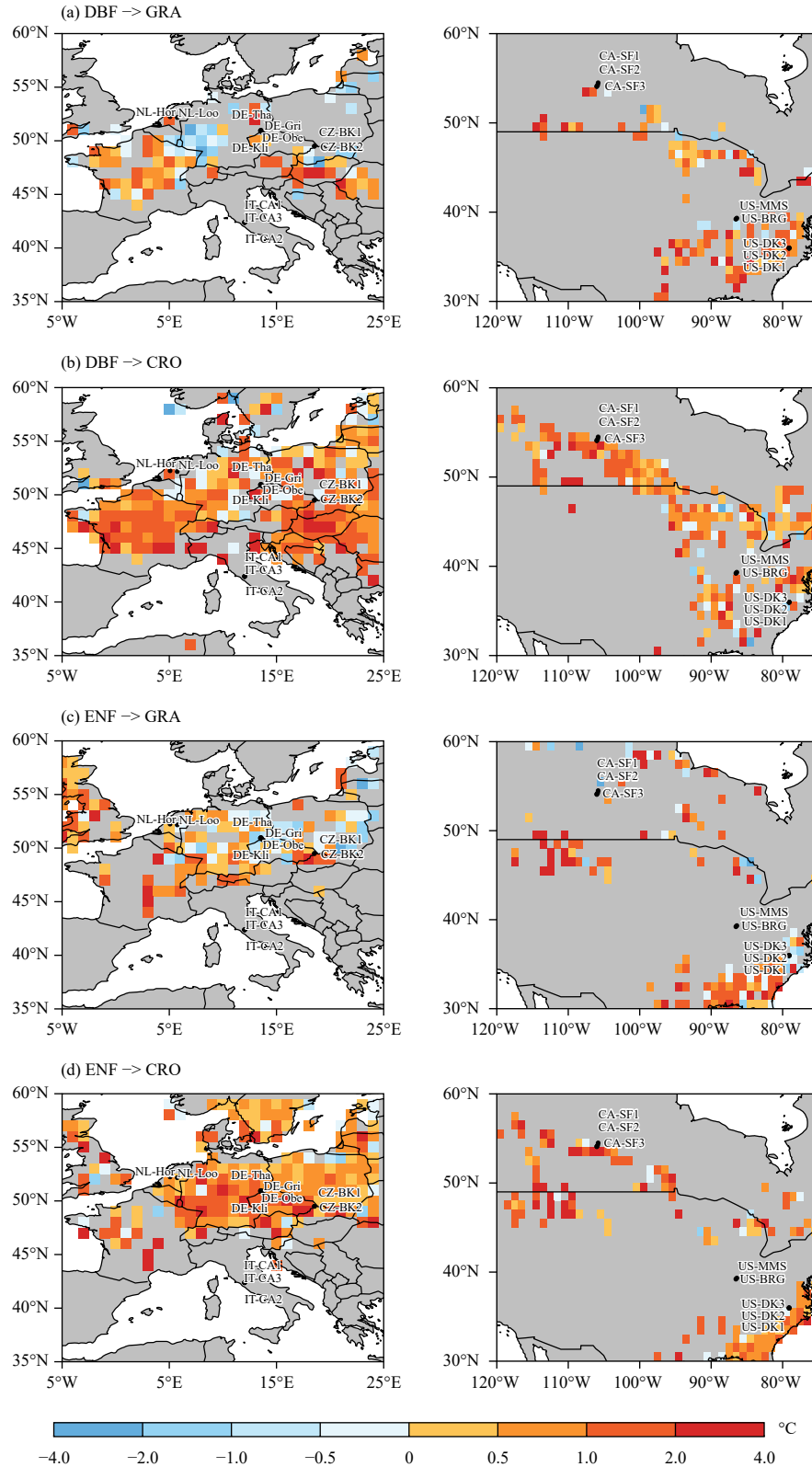


Fig. 7. As in Fig. 6, but for boreal summer.

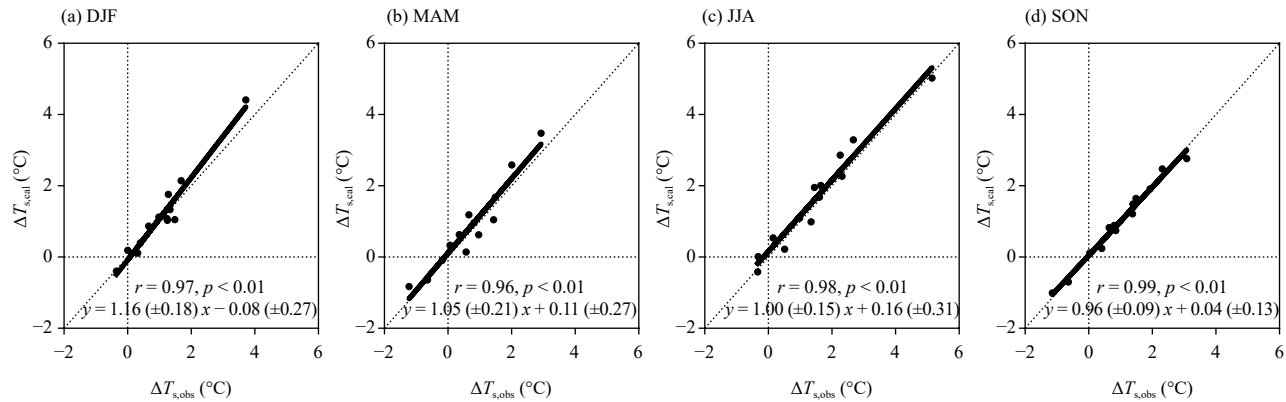


Fig. 8. The relationship between the observed ΔT_s and the calculated ΔT_s based on the DTM method. The dashed lines represent the 1 : 1 line and the solid lines denote the regression results for (a) DJF, (b) MAM, (c) JJA, and (d) SON.

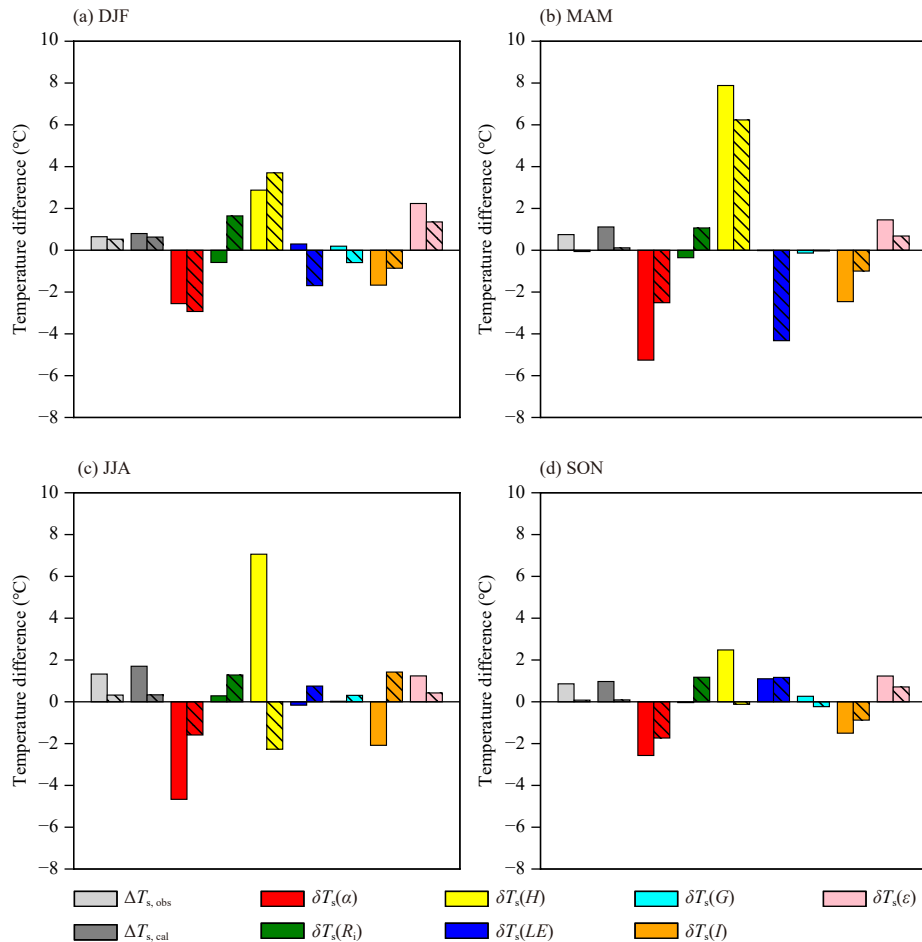


Fig. 9. The observed and calculated grassland-forest surface temperature differences ($\Delta T_{s,obs}$ and $\Delta T_{s,cal}$, $^{\circ}\text{C}$), together with their contributing components, for (a) DJF, (b) MAM, (c) JJA, and (d) SON. The contributing components are denoted by $\delta T_s(X)$, where X represents the corresponding energy-balance component; for example, $\delta T_s(\alpha)$ denotes the contribution of the change in surface albedo to ΔT_s . The other symbols follow the same convention. The bars without and with hatching represent the results from ENF to GRA and those from DBF to GRA, respectively.

by 7°C . While converting DBF to GRA, the increase of sensible heat flux causes a cooling effect, and the decrease of latent heat flux results in a mild warming effect. This evidently results in a net decrease of -1.5°C . However, the effect of cooling is offset by the warming

effect of the increase in incoming radiation.

During MAM (Fig. 9b), the biophysical processes are similar to those in DJF for the two forest types. When converting ENF to GRA during SON (Fig. 9d), the decreases of sensible heat flux and latent heat flux result in

2.5°C and 1.1°C increases, respectively. However, decreasing the latent heat flux increases T_s and the effect of sensible heat flux on T_s is weak when DBF is replaced by GRA. In addition, incoming radiation effects are relatively important at DBF sites, and the influence of ground heat flux on T_s is weak at the seasonal scale compared to other components.

We also analyze the situations when different forest types are converted to CRO. The results show that the biophysical processes influencing T_s are similar to that from forests to GRA (Fig. 10). However, in summer and autumn (Figs. 10c, d), the increase of T_s from DBF to CRO was significantly higher than that from ENF to CRO, and the difference was mainly due to the increase of T_s caused by the rapid decrease of latent heat flux after deforestation. Zhao and Jackson (2014) also reported that sensible heat flux increased when DBF was replaced with CRO, whereas latent heat flux decreased. For conversions from ENF, sensible heat flux showed a greater reduction than latent heat flux.

Our results show that the combined effects of albedo and turbulent heat flux on local T_s change exceed 50% by quantifying the contributions of various biophysical factors (Fig. 11). Among these, turbulent heat flux is the dominant biophysical factor affecting T_s . However, there are significant differences in the contributions of different biophysical factors to T_s across different forest types. When ENF is converted to GRA (Fig. 11a), the contribution of albedo to T_s across seasons ranges from 24% to 30%, while the contribution of turbulent heat flux ranges from 32% to 46%. In contrast, when DBF is replaced by GRA, there exist seasonal variations in the relative contributions of albedo and turbulent heat flux on T_s changes. In spring and summer, the contribution of turbulent heat flux is higher, reaching up to about 66%, whereas in autumn and winter, the contributions of albedo and turbulent heat flux are approximately equal (Fig. 11b). Furthermore, even when forests are converted to CRO, the relative contribution of turbulent heat flux on T_s change in different forest regions is consistent.

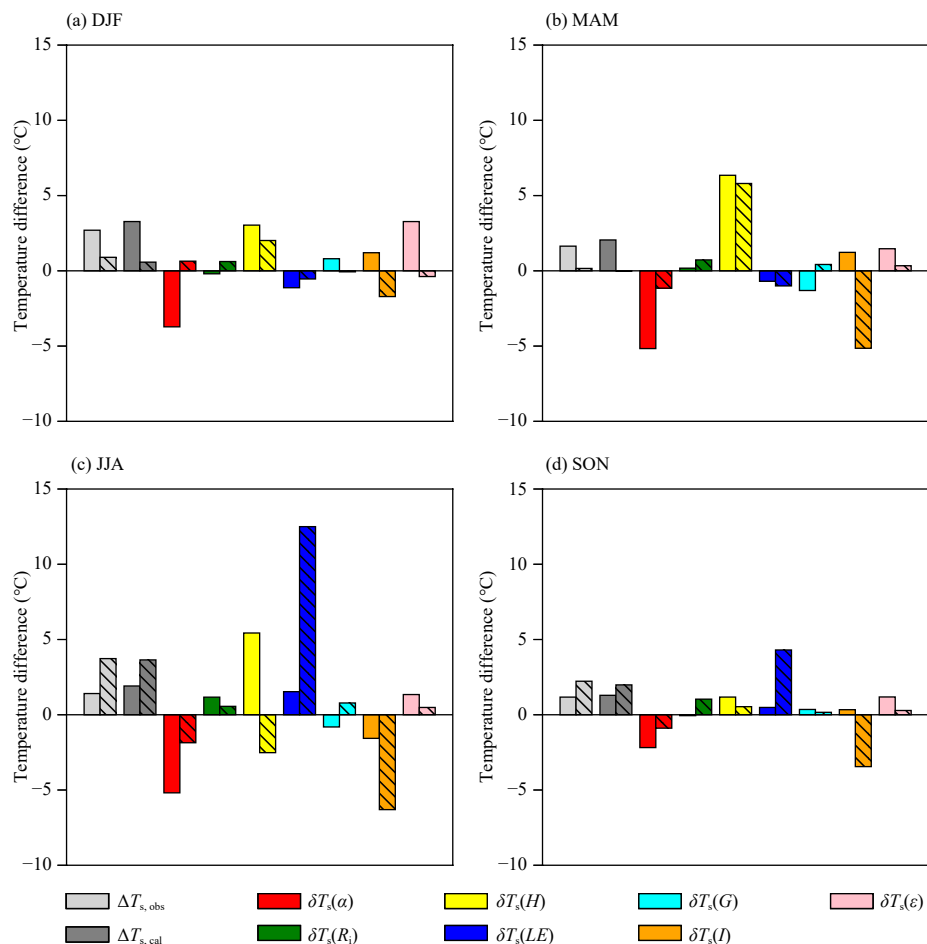


Fig. 10. As in Fig. 9, but for the cropland–forest surface temperature differences. The bars without and with hatching represent the results from ENF to CRO and those from DBF to CRO, respectively.

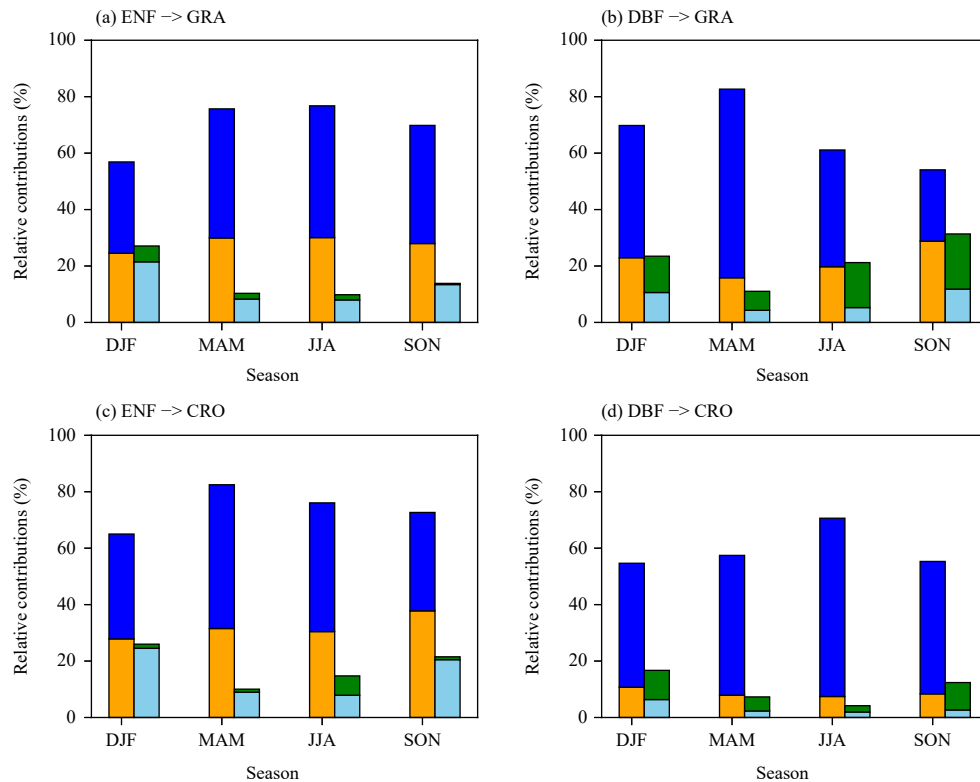


Fig. 11. Relative contributions (%) of changes in albedo (orange), turbulent flux (blue), incoming radiation (green), and surface emissivity (light blue) on changes in land surface temperature in different seasons (a) from ENF to GRA, (b) from DBF to GRA, (c) from ENF to CRO, and (d) from DBF to CRO.

ently stronger than that of albedo (Fig. 11).

4. Discussion

This study examined the mechanisms underlying T_s responses across different forest types in the midlatitudes. However, there are some uncertainties in attributing the forest cover changes in observations. First, the selected site pairs are inevitably influenced by the uneven spatial and temporal distribution of flux towers. Although the number and spatial distribution of the selected sites cannot fully represent conditions across the midlatitudes, they nevertheless provide a useful basis for studying temperate deforestation. To ensure the robustness of the results, we also examined the satellite remote sensing data. The results were qualitatively similar to the selected site-based flux tower observations.

Second, measurement errors and instrumental uncertainties may also affect the results. For example, estimates of outgoing longwave radiation depend on the installation height of the radiative sensor. At forest sites, radiometers are installed above the canopy, such that the measured outgoing longwave radiation primarily originates from the canopy surface rather than from the ground (Pastorello et al., 2020). Because sensor installation

heights vary across sites, the observed T_s ($T_{s,obs}$) retrieved from outgoing longwave radiation may therefore contain substantial uncertainties (Su et al., 2019; Zhang et al., 2020). Accordingly, our T_s results should be interpreted with this caveat in mind. In addition, the residual term required to close the surface energy balance (Foken, 2008) can be non-negligible and may contribute substantially to T_s variability at certain sites. In several sites, ground heat flux was set to zero. Nevertheless, those do not change our conclusions but influence the accuracy in determining what mechanism mainly affects T_s at the seasonal scale (Zhang et al., 2020).

Third, the atmospheric background may not be the same due to the distance between the pairs. Although we exclude the effect of precipitation during data processing, we cannot completely exclude the effect of clouds, which block incoming radiation and reflect longwave radiation, which may also be possible indirect climate feedbacks due to deforestation (Duveiller et al., 2021b). Furthermore, extreme events (e.g., heatwaves) are likely to occur in summer, which may have a significant impact on surface flux and temperature changes (Teuling et al., 2010).

The biophysical mechanisms of deforestation are decomposed into components such as albedo, sensible heat,

and latent heat fluxes using a temperature decomposition method based on the surface energy balance (Luyssaert et al., 2014; Vanden Broucke et al., 2015). This method can be used to quantify the relative importance of surface fluxes in T_s changes, but it does have some limitations. (1) The nonlinear processes among the terms were ignored when the formula was used for calculation (Luyssaert et al., 2014; Liu et al., 2023). For example, as albedo changes, the amount of net radiation absorbed by the surface also changes, leading to a redistribution of surface fluxes (Winckler et al., 2019). Therefore, the DTM method may lead to the underestimation of the contribution from sensible and latent heat fluxes. (2) Previous observation-based and model simulations used a similar approach, classifying the biophysical mechanisms into effects of radiative forcing, aerodynamic resistance, and Bowen ratio (Lee et al., 2011; Wang et al., 2017; Burakowski et al., 2018; Liu et al., 2023). This method assumes that the effects of each component are independent and points out that the decrease in surface roughness is the main biophysical mechanism driving the increase in local T_s due to deforestation. From an energy balance perspective, the relative contributions of surface roughness and evapotranspiration cannot be directly distinguished. However, the decrease in surface roughness means that the coupling of land and atmosphere is weakened, and the transport capacity of surface flux to the atmosphere is also weakened (Liao et al., 2018).

Based on the energy balance equation, the important role of surface roughness on T_s can be indirectly reflected from the reduction of surface flux. Moreover, in the midlatitudes, the sensible heat flux decreased most significantly at ENF sites, while the latent heat flux decreased most significantly at DBF sites due to deforestation, reflecting the capacity of forest type itself to redistribute surface energy (Zhao and Jackson, 2014). Overall, previous studies often simply attributed the reduction of H to a decrease in surface roughness when using the DTM method (Chen and Dirmeyer, 2016). However, the interactions between different terms are complex. Therefore, multiple temperature decomposition methods can be adopted for comparative discussion in future research, and the formula with temperature decomposition can be further split or modified to identify possible correlations among different components (Duveiller et al., 2021b).

In addition to observation-based studies, global or regional climate models have also been widely used to examine the impacts of deforestation (e.g., Hua et al., 2023). Some modeling studies show that T_s decreased in winter due to snow masking forest effects and increased in summer in the midlatitudes (Perugini et al., 2017;

Chen and Dirmeyer, 2020). However, our results used observational site pairs and found that deforestation makes the T_s of most site pairs increase in the midlatitudes. In such cases, similar remote effects from advection and atmospheric circulation between neighboring regions are likely removed by observation-based methods. In contrast, the total (local plus non-local) effects were typically considered in coupled models, where non-local effects (e.g., atmospheric feedbacks or heterogeneous land-atmosphere interactions) always have a strong influence on T_s in models (Winckler et al., 2019; Hua et al., 2023; Liu et al., 2023), which generally resulted in a decreased T_s in the midlatitudes (Perugini et al., 2017; Lawrence et al., 2022). Thus, the non-local effects of deforestation across different forest types on T_s in different seasons and regions warrant further research.

5. Conclusions

Using site-based flux tower data and the DTM method, we investigated the biophysical impacts of different forest types on seasonal warming in boreal midlatitudes. We compared two different forest types (i.e., ENF and DBF) with open lands (i.e., GRA and CRO) and found that the albedo of DBF is higher than that of ENF except in winter, and the surface roughness and Bowen ratio of ENF are higher than those of DBF.

We then used the DTM method to quantify the relative importance of surface energy balance in determining the T_s changes. In general, T_s changes at ENF sites are greater than at DBF sites. Although the contributions of increased albedo to reducing T_s from deforestation are higher at ENF sites than at DBF sites, the dominant mechanisms of deforestation on T_s depend on the changes in turbulent flux and vary across forest types. When deforestation occurs at ENF sites, the decrease of sensible heat flux has a warming effect in all seasons, while at DBF sites, the warming effect of the decrease of sensible heat flux is offset by the cooling effect of the increase of latent heat flux in winter and spring, but the opposite is true in summer and autumn.

Furthermore, we found that the contribution of turbulent heat flux to T_s at ENF sites is approximately 42%, slightly higher than that of albedo (about 30%). For DBF sites, the contribution of turbulent heat flux is about 43%, which is much higher than that of albedo (about 15%). In addition, other factors influencing T_s change are attributable to the combination of incoming radiation, residuals, and surface emissivity.

Our results are consistent with previous studies (Duveiller et al., 2018a; Zhang et al., 2020). However, our

results further highlight that different forest types exhibit distinct biophysical responses to deforestation, leading to significant seasonal variations in T_s . These differences highlight the critical role of forest type in modulating land–atmosphere energy exchanges and underscore its importance in shaping forest–climate interactions. It should be noted that the site-based flux tower data are limited in the midlatitudes except in North America and Europe; further efforts to explore biophysical impacts of different forest types using satellite data or modelling approaches are needed. Nevertheless, our results provide insight into the mechanisms associated with seasonal T_s changes driven by forest cover changes.

Electronic supplementary material. Supplementary material is available in the online version of this article at <https://doi.org/10.1007/s13351-026-5355-7> and is accessible for authorized users.

REFERENCES

- Alkama, R., and A. Cescatti, 2016: Biophysical climate impacts of recent changes in global forest cover. *Science*, **351**, 600–604, <https://doi.org/10.1126/science.aac8083>.
- Alkama, R., G. Forzieri, G. Duveiller, et al., 2022: Vegetation-based climate mitigation in a warmer and greener World. *Nat. Commun.*, **13**, 606, <https://doi.org/10.1038/s41467-022-28305-9>.
- Anderegg, W. R. L., L. Blanchard, C. Anderson, et al., 2025: Towards more effective nature-based climate solutions in global forests. *Nature*, **643**, 1214–1222, <https://doi.org/10.1038/s41586-025-09116-6>.
- Anderson, R. G., J. G. Canadell, J. T. Randerson, et al., 2011: Biophysical considerations in forestry for climate protection. *Front. Ecol. Environ.*, **9**, 174–182, <https://doi.org/10.1890/090179>.
- Bala, G., K. Caldeira, M. Wickett, et al., 2007: Combined climate and carbon-cycle effects of large-scale deforestation. *Proc. Natl. Acad. Sci. USA*, **104**, 6550–6555, <https://doi.org/10.1073/pnas.0608998104>.
- Baldocchi, D., E. Falge, L. H. Gu, et al., 2001: FLUXNET: A new tool to study the temporal and spatial variability of ecosystem-scale carbon dioxide, water vapor, and energy flux densities. *Bull. Amer. Meteor. Soc.*, **82**, 2415–2434, [https://doi.org/10.1175/1520-0477\(2001\)082<2415:FANTTS>2.3.CO;2](https://doi.org/10.1175/1520-0477(2001)082<2415:FANTTS>2.3.CO;2).
- Bonan, G. B., 2008: Forests and climate change: Forcings, feedbacks, and the climate benefits of forests. *Science*, **320**, 1444–1449, <https://doi.org/10.1126/science.1155121>.
- Boysen, L. R., V. Brovkin, J. Pongratz, et al., 2020: Global climate response to idealized deforestation in CMIP6 models. *Biogeosciences*, **17**, 5615–5638, <https://doi.org/10.5194/bg-17-5615-2020>.
- Bright, R. M., E. Davin, T. O'Halloran, et al., 2017: Local temperature response to land cover and management change driven by non-radiative processes. *Nat. Climate Change*, **7**, 296–302, <https://doi.org/10.1038/nclimate3250>.
- Burakowski, E., A. Tawfik, A. Ouimette, et al., 2018: The role of surface roughness, albedo, and Bowen ratio on ecosystem energy balance in the Eastern United States. *Agric. For. Meteorol.*, **249**, 367–376, <https://doi.org/10.1016/j.agrformet.2017.11.030>.
- Canadell, J. G., and M. R. Raupach, 2008: Managing forests for climate change mitigation. *Science*, **320**, 1456–1457, <https://doi.org/10.1126/science.1155458>.
- Chen, H. W., W. J. Hua, S. G. Zhu, et al., 2026: Contrasting responses of near-surface air temperature to historical land cover change in CESM. *Adv. Atmos. Sci.*, **43**, 827–844, <https://doi.org/10.1007/s00376-025-5058-5>.
- Chen, L., and P. A. Dirmeyer, 2016: Adapting observationally based metrics of biogeophysical feedbacks from land cover/land use change to climate modeling. *Environ. Res. Lett.*, **11**, 034002, <https://doi.org/10.1088/1748-9326/11/3/034002>.
- Chen, L., and P. A. Dirmeyer, 2020: Reconciling the disagreement between observed and simulated temperature responses to deforestation. *Nat. Commun.*, **11**, 202, <https://doi.org/10.1038/s41467-019-14017-0>.
- Chen, L., P. A. Dirmeyer, Z. C. Guo, et al., 2018: Pairing FLUXNET sites to validate model representations of land-use/land-cover change. *Hydrol. Earth Syst. Sci.*, **22**, 111–125, <https://doi.org/10.5194/hess-22-111-2018>.
- Davin, E. L., and N. de Noblet-Ducoudré, 2010: Climatic impact of global-scale deforestation: Radiative versus nonradiative processes. *J. Climate*, **23**, 97–112, <https://doi.org/10.1175/2009JCLI13102.1>.
- de Noblet-Ducoudré, N., J.-P. Boisier, A. Pitman, et al., 2012: Determining robust impacts of land-use-induced land cover changes on surface climate over North America and Eurasia: Results from the first set of LUCID experiments. *J. Climate*, **25**, 3261–3281, <https://doi.org/10.1175/JCLI-D-11-00338.1>.
- Duveiller, G., J. Hooker, and A. Cescatti, 2018a: The mark of vegetation change on Earth's surface energy balance. *Nat. Commun.*, **9**, 679, <https://doi.org/10.1038/s41467-017-02810-8>.
- Duveiller, G., J. Hooker, and A. Cescatti, 2018b: A dataset mapping the potential biophysical effects of vegetation cover change. *Sci. Data*, **5**, 180014, <https://doi.org/10.1038/sdata.2018.14>.
- Duveiller, G., J. Hooker, and A. Cescatti, 2021a: Addendum: A dataset mapping the potential biophysical effects of vegetation cover change. *Sci. Data*, **8**, 12, <https://doi.org/10.1038/s41597-020-00787-6>.
- Duveiller, G., F. Filippini, A. Ceglar, et al., 2021b: Revealing the widespread potential of forests to increase low level cloud cover. *Nat. Commun.*, **12**, 4337, <https://doi.org/10.1038/s41467-021-24551-5>.
- Ellison, D., C. E. Morris, B. Locatelli, et al., 2017: Trees, forests and water: Cool insights for a hot world. *Global Environ. Change*, **43**, 51–61, <https://doi.org/10.1016/j.gloenvcha.2017.01.002>.
- Foken, T., 2008: The energy balance closure problem: An overview. *Ecol. Appl.*, **18**, 1351–1367, <https://doi.org/10.1890/06-0922.1>.
- Forzieri, G., R. Alkama, D. G. Miralles, et al., 2017: Satellites reveal contrasting responses of regional climate to the widespread greening of Earth. *Science*, **356**, 1180–1184, <https://doi.org/10.1126/science.aal1727>.

- Ge, J., W. D. Guo, A. J. Pitman, et al., 2019: The nonradiative effect dominates local surface temperature change caused by afforestation in China. *J. Climate*, **32**, 4445–4471, <https://doi.org/10.1175/JCLI-D-18-0772.1>.
- Girardin, C. A. J., S. Jenkins, N. Seddon, et al., 2021: Nature-based solutions can help cool the planet—if we act now. *Nature*, **593**, 191–194, <https://doi.org/10.1038/d41586-021-01241-2>.
- Hua, W.-J., and H.-S. Chen, 2013: Impacts of regional-scale land use/land cover change on diurnal temperature range. *Adv. Climate Change Res.*, **4**, 166–172, <https://doi.org/10.3724/SP.J.1248.2013.166>.
- Hua, W. J., H. S. Chen, and X. Li, 2014: Review of land use and land cover change in China and associated climatic effects. *Adv. Earth Sci.*, **29**, 1025–1036, <https://doi.org/10.11867/j.issn.1001-8166.2014.09.1025>. (in Chinese)
- Hua, W. J., H. S. Chen, S. L. Sun, et al., 2015: Assessing climatic impacts of future land use and land cover change projected with the CanESM2 model. *Int. J. Climatol.*, **35**, 3661–3675, <https://doi.org/10.1002/joc.4240>.
- Hua, W. J., L. M. Zhou, A. G. Dai, et al., 2023: Important non-local effects of deforestation on cloud cover changes in CMIP6 models. *Environ. Res. Lett.*, **18**, 094047, <https://doi.org/10.1088/1748-9326/acf232>.
- Juang, J. Y., G. Katul, M. Siqueira, et al., 2007: Separating the effects of albedo from eco-physiological changes on surface temperature along a successional chronosequence in the southeastern United States. *Geophys. Res. Lett.*, **34**, L21408, <https://doi.org/10.1029/2007GL031296>.
- Kumar, S., P. A. Dirmeyer, V. Merwade, et al., 2013: Land use/cover change impacts in CMIP5 climate simulations: A new methodology and 21st century challenges. *J. Geophys. Res. Atmos.*, **118**, 6337–6353, <https://doi.org/10.1002/jgrd.50463>.
- Lawrence, D., M. Coe, W. Walker, et al., 2022: The unseen effects of deforestation: Biophysical effects on climate. *Front. For. Glob. Change*, **5**, 756115, <https://doi.org/10.3389/ffgc.2022.756115>.
- Lee, X., M. L. Goulden, D. Y. Hollinger, et al., 2011: Observed increase in local cooling effect of deforestation at higher latitudes. *Nature*, **479**, 384–387, <https://doi.org/10.1038/nature10588>.
- Li, J., Z.-L. Li, X. Y. Liu, et al., 2025: Contrasting temporal dynamics of land surface temperature responses to different types of forest loss. *Innovation*, **6**, 100875, <https://doi.org/10.1016/j.xinn.2025.100875>.
- Li, Y., M. S. Zhao, S. Motesharrei, et al., 2015: Local cooling and warming effects of forests based on satellite observations. *Nat. Commun.*, **6**, 6603, <https://doi.org/10.1038/ncomms7603>.
- Li, Y. T., Z.-L. Li, H. Wu, et al., 2023: Biophysical impacts of earth greening can substantially mitigate regional land surface temperature warming. *Nat. Commun.*, **14**, 121, <https://doi.org/10.1038/s41467-023-35799-4>.
- Liao, W. L., A. J. Rigden, and D. Li, 2018: Attribution of local temperature response to deforestation. *J. Geophys. Res. Biogeosci.*, **123**, 1572–1587, <https://doi.org/10.1029/2018JG004401>.
- Lin, H. Q., Y. Li, and L. Zhao, 2022: Partitioning of sensible and latent heat fluxes in different vegetation types and their spatiotemporal variations based on 203 FLUXNET sites. *J. Geophys. Res. Atmos.*, **127**, e2022JD037142, <https://doi.org/10.1029/2022JD037142>.
- Liu, S. Y., W. J. Hua, L. M. Zhou, et al., 2023: Local and non-local biophysical impacts of deforestation on global temperature during boreal summer: CMIP6-LUMIP multimodel analysis. *J. Geophys. Res. Atmos.*, **128**, e2022JD038229, <https://doi.org/10.1029/2022JD038229>.
- Luyssaert, S., M. Jammet, P. C. Stoy, et al., 2014: Land management and land-cover change have impacts of similar magnitude on surface temperature. *Nat. Climate Change*, **4**, 389–393, <https://doi.org/10.1038/nclimate2196>.
- Mahmood, R., R. A. Pielke, K. G. Hubbard, et al., 2014: Land cover changes and their biogeophysical effects on climate. *Int. J. Climatol.*, **34**, 929–953, <https://doi.org/10.1002/joc.3736>.
- Monteith, J. L., and M. H. Unsworth, 1990: *Principles of Environmental Physics* (2nd ed.). E. Arnold, London, 291 pp.
- Novick, K. A., and G. G. Katul, 2020: The duality of reforestation impacts on surface and air temperature. *J. Geophys. Res. Biogeosci.*, **125**, e2019JG005543, <https://doi.org/10.1029/2019JG005543>.
- Pastorello, G., C. Trotta, E. Canfora, et al., 2020: The FLUXNET2015 dataset and the ONEFlux processing pipeline for eddy covariance data. *Sci. Data*, **7**, 225, <https://doi.org/10.1038/s41597-020-0534-3>.
- Peng, S.-S., S. L. Piao, Z. Z. Zeng, et al., 2014: Afforestation in China cools local land surface temperature. *Proc. Natl. Acad. Sci. USA*, **111**, 2915–2919, <https://doi.org/10.1073/pnas.1315126111>.
- Perugini, L., L. Caporaso, S. Marconi, et al., 2017: Biophysical effects on temperature and precipitation due to land cover change. *Environ. Res. Lett.*, **12**, 053002, <https://doi.org/10.1088/1748-9326/aa6b3f>.
- Pielke, R. A., A. Pitman, D. Niyogi, et al., 2011: Land use/land cover changes and climate: Modeling analysis and observational evidence. *WIREs Climate Change*, **2**, 828–850, <https://doi.org/10.1002/wcc.144>.
- Pongratz, J., C. Schwingshackl, S. Bultan, et al., 2021: Land use effects on climate: Current state, recent progress, and emerging topics. *Curr. Climate Change Rep.*, **7**, 99–120, <https://doi.org/10.1007/s40641-021-00178-y>.
- Potapov, P., S. Turubanova, M. C. Hansen, et al., 2022: Global maps of cropland extent and change show accelerated cropland expansion in the twenty-first century. *Nat. Food*, **3**, 19–28, <https://doi.org/10.1038/s43016-021-00429-z>.
- Rigden, A. J., and G. D. Salvucci, 2015: Evapotranspiration based on equilibrated relative humidity (ETRHEQ): Evaluation over the continental U.S. *Water Resour. Res.*, **51**, 2951–2973, <https://doi.org/10.1002/2014WR016072>.
- Runyan, C. W., P. D’Odorico, and D. Lawrence, 2012: Physical and biological feedbacks of deforestation. *Rev. Geophys.*, **50**, RG4006, <https://doi.org/10.1029/2012RG000394>.
- Schultz, N. M., P. J. Lawrence, and X. Lee, 2017: Global satellite data highlights the diurnal asymmetry of the surface temperature response to deforestation. *J. Geophys. Res. Biogeosci.*, **122**, 903–917, <https://doi.org/10.1002/2016JG003653>.
- Schwaab, J., E. L. Davin, P. Bebi, et al., 2020: Increasing the broad-leaved tree fraction in European forests mitigates hot temperature extremes. *Sci. Rep.*, **10**, 14153, <https://doi.org/10.1038/s41598-020-14153-1>.

- 1038/s41598-020-71055-1.
- Su, Y. X., L. Y. Liu, J. P. Wu, et al., 2019: Quantifying the biophysical effects of forests on local air temperature using a novel three-layered land surface energy balance model. *Environ. Int.*, **132**, 105080, <https://doi.org/10.1016/j.envint.2019.105080>.
- Su, Y. X., C. Q. Zhang, X. Z. Chen, et al., 2021: Aerodynamic resistance and Bowen ratio explain the biophysical effects of forest cover on understory air and soil temperatures at the global scale. *Agric. For. Meteorol.*, **308**, 108615, <https://doi.org/10.1016/j.agrformet.2021.108615>.
- Teuling, A. J., S. I. Seneviratne, R. Stöckli, et al., 2010: Contrasting response of European forest and grassland energy exchange to heatwaves. *Nat. Geosci.*, **3**, 722–727, <https://doi.org/10.1038/ngeo950>.
- Vanden Broucke, S., S. Luyssaert, E. L. Davin, et al., 2015: New insights in the capability of climate models to simulate the impact of LUC based on temperature decomposition of paired site observations. *J. Geophys. Res. Atmos.*, **120**, 5417–5436, <https://doi.org/10.1002/2015JD023095>.
- Wang, X. Q., W. D. Guo, B. Qiu, et al., 2017: Quantifying the contribution of land use change to surface temperature in the lower reaches of the Yangtze River. *Atmos. Chem. Phys.*, **17**, 4989–4996, <https://doi.org/10.5194/acp-17-4989-2017>.
- Winckler, J., C. H. Reick, R. M. Bright, et al., 2019: Importance of surface roughness for the local biogeophysical effects of deforestation. *J. Geophys. Res. Atmos.*, **124**, 8605–8618, <https://doi.org/10.1029/2018JD030127>.
- Windisch, M. G., E. L. Davin, and S. I. Seneviratne, 2021: Prioritizing forestation based on biogeochemical and local biogeophysical impacts. *Nat. Climate Change*, **11**, 867–871, <https://doi.org/10.1038/s41558-021-01161-z>.
- Zhang, M., X. Lee, G. R. Yu, et al., 2014: Response of surface air temperature to small-scale land clearing across latitudes. *Environ. Res. Lett.*, **9**, 034002, <https://doi.org/10.1088/1748-9326/9/3/034002>.
- Zhang, Q., M. Barnes, M. Benson, et al., 2020: Reforestation and surface cooling in temperate zones: Mechanisms and implications. *Glob. Change Biol.*, **26**, 3384–3401, <https://doi.org/10.1111/gcb.15069>.
- Zhang, Z. J., F. J. Zhang, L. C. Wang, et al., 2021: Biophysical climate impact of forests with different age classes in mid- and high-latitude North America. *For. Ecol. Manag.*, **494**, 119327, <https://doi.org/10.1016/j.foreco.2021.119327>.
- Zhao, K. G., and R. B. Jackson, 2014: Biophysical forcings of land-use changes from potential forestry activities in North America. *Ecol. Monogr.*, **84**, 329–353, <https://doi.org/10.1890/12-1705.1>.
- Zhu, L., W. Li, P. Ciais, et al., 2023: Comparable biophysical and biogeochemical feedbacks on warming from tropical moist forest degradation. *Nat. Geosci.*, **16**, 244–249, <https://doi.org/10.1038/s41561-023-01137-y>.