

Biophysical Effects of Different Underlying Surface Types on Land Surface Temperature in the Qinghai Lake Basin: Postprint

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Abstract

This study selected two sites with different land cover types in the Qinghai Lake basin—subalpine shrubland and temperate grassland—and utilized turbulent flux data and automatic weather station data to compare the micrometeorological elements and surface energy balance budget between the two sites during the growing and non-growing seasons, thereby evaluating the biophysical effects of Land Use/Land Cover Changes (LULCC) on land surface temperature. Compared with temperate grassland, subalpine shrubland exhibited lower land surface temperature, air temperature, and soil temperature; the differences in land surface temperature, air temperature, and soil temperature between the two sites were more pronounced during the growing season, whereas the difference in relative humidity was more evident during the non-growing season. Based on the Direct Decomposed Temperature Metric (DTM) theory, the biophysical effects of different underlying surfaces on land surface temperature were analyzed. The results indicated that the primary contributing factors to the cooling effect of shrubland compared with grassland during daytime were shortwave radiation, ground soil heat flux, and sensible heat flux terms, wherein shortwave radiation exerted a positive feedback effect on the cooling of shrubland, while the latter two exerted negative feedback effects. The primary contributing factor to the cooling effect of shrubland during nighttime was the ground soil heat flux term. Under identical climatic and weather backgrounds, different underlying surfaces indeed exerted significant biophysical feedback effects on land surface temperature.

Full Text

Abstract

This study selected two sites with different land cover types—subalpine shrub and temperate steppe—in the Qinghai Lake Basin to investigate the biophysical effects of Land Use/Land Cover Changes (LULCC) on surface temperature. Using turbulent flux data and automatic weather station observations, we compared micrometeorological elements and surface energy balance budgets between the two sites during both growing and non-growing seasons. The subalpine shrub exhibited lower surface temperature, air temperature, and soil temperature compared to the temperate steppe, with these differences being more pronounced during the growing season. In contrast, differences in relative humidity were more evident during the non-growing season. Based on Direct Decomposed Temperature Metric (DTM) theory, we analyzed the biophysical influences of different underlying surfaces on surface temperature. The results indicate that during daytime, the cooling effect of shrubland relative to grassland was primarily due to shortwave radiation, surface soil heat flux, and sensible heat flux terms. Among these, shortwave radiation provided positive feedback to shrub cooling, while the latter two terms provided negative feedback. At night, the surface soil heat flux term was the main contributing factor to shrub cooling. Under identical climatic and weather conditions, different underlying surfaces exert significant biophysical feedback effects on surface temperature.

Keywords: land use and land cover change; surface temperature; radiation budget; surface soil heat flux; turbulent flux; Qinghai Lake Basin

Introduction

Land Use/Land Cover Change (LULCC) represents a primary driver of regional and global climate change, influencing climate through both biogeochemical and biophysical pathways. The biogeochemical effect is primarily reflected in carbon sequestration potential, with its intensity depending on the type of land cover conversion. For example, the carbon sink reduction resulting from grassland-to-cropland conversion is much lower than that from forest-to-cropland conversion. LULCC also affects climate through biophysical effects, which involve alterations to surface parameters such as albedo, leaf area index, and surface roughness, thereby modifying energy partitioning and water cycling between the land surface and atmosphere. If LULCC involves sufficiently large areas, its climate impacts can extend from regional to global scales.

Previous studies have demonstrated that regional climate may be highly sensitive to even minor changes in land surface properties, making accurate and detailed surface data crucial for assessing LULCC impacts on climate. Over the past several decades, more than half of Earth's land surface has been altered by human activities. The effects of anthropogenic land use changes on local climate are complex. While changes in surface albedo are widely recognized

as the strongest climate forcing factor, non-radiative processes such as surface roughness and evapotranspiration also significantly affect surface temperature. These changes are uncertain and difficult to quantify, but they substantially impact surface radiation and energy redistribution processes, leading to distinct surface temperature differences among various surface types under different climate backgrounds.

Satellite observations have been widely applied to study the biophysical effects of LULCC on surface temperature. However, due to the lack of direct measurements for soil heat flux and sensible heat flux, these studies often calculate sensible heat flux based on energy balance equations, introducing considerable errors. The development of flux observation networks measuring energy, water, and carbon exchange between land and atmosphere provides an excellent platform for quantifying and reducing uncertainties in land surface models. Some flux towers are deployed specifically to quantify the biophysical effects of LULCC by utilizing adjacent sites with different underlying surfaces.

The Qinghai Lake Basin, located in northwestern China, is the primary water source for Qinghai Lake, the country's largest inland salt lake. Influenced by the East Asian monsoon, Indian monsoon, and westerly jet stream, the basin features a cold, semi-arid climate with an average annual temperature of -1.1 to 4.0°C, annual precipitation of 291-579 mm, and annual evaporation reaching 1300-2000 mm. The underlying vegetation consists mainly of alpine meadows and alpine shrubs. The basin's ecosystem is fragile, with severe grassland degradation and soil erosion, and human activities exert considerable influence. Given these conditions, we selected two adjacent sites with different underlying surfaces in the Qinghai Lake Basin. With relatively consistent background climates, differences in surface temperature can be attributed to LULCC, allowing investigation of micrometeorological elements, surface energy balance, radiation budget differences, and biophysical effects on surface temperature.

Data and Methods

1.1 Data Sources

The data used in this study were obtained from the "Qilian Mountains Region Sky-Ground-Integrated Monitoring Network" dataset of the National Tibetan Plateau Data Center. This monitoring network combines long-term ground-based collaborative observations, typical sample plot UAV surveys, and high spatiotemporal resolution remote sensing monitoring across the entire region, establishing a comprehensive ecological monitoring system for the Qilian Mountains area. The ground observation dataset covers six major watersheds in the region, including the Qinghai Lake Basin.

We selected two sites from the Qinghai Lake Basin Surface Process Integrated Observation Network in 2021: a temperate steppe site (JJC) and a subalpine shrub site (JLM). The temperate steppe site (100°14 8.99 E, 37°14 49.00 N) is located at the Sancha City Breeding Sheep Farm in Gangcha County, Qinghai

Province, at an altitude of 3210 m. The subalpine shrub site (100°6 3.62 E, 37°31 15.67 N) is located near Dasi in Shaliuhe Town, Gangcha County, at an altitude of 3495 m. Both sites are equipped with eddy covariance systems measuring turbulent fluxes and automatic weather stations (AWS) measuring radiation and micrometeorological elements.

The eddy covariance instruments were installed at a height of 2.5 m with a sampling frequency of 10 Hz, oriented northward. Data were processed using EddyPro software with the following main steps: outlier removal, time lag correction, coordinate rotation (double rotation), frequency response correction, sonic virtual temperature correction, and density (WPL) correction. Air temperature and humidity sensors were mounted at 2 m height, four-component radiometers at 2.5 m, self-calibrating soil heat flux plates at 5 cm depth, and soil temperature probes at 20 cm, 40 cm, 80 cm, 120 cm, 200 cm, and 300 cm depths.

1.2 Methods

The Direct Decomposed Temperature Metric (DTM) theory, initially proposed by Luyssaert et al. and later refined by Juang et al., is based on surface energy balance principles and Taylor series expansion approximations. The surface energy balance equation is:

$$R_n = (1 - \alpha)S_{\downarrow} + \varepsilon L_{\downarrow} - \varepsilon \sigma T_s^4 - H - LE - G$$

where S_{\downarrow} is incoming shortwave radiation ($\text{W} \cdot \text{m}^{-2}$), α is surface albedo, L_{\downarrow} is incoming longwave radiation ($\text{W} \cdot \text{m}^{-2}$), ε is surface emissivity, σ is the Stefan-Boltzmann constant, T_s is surface temperature (K), R_n is net radiation ($\text{W} \cdot \text{m}^{-2}$), LE is latent heat flux ($\text{W} \cdot \text{m}^{-2}$), H is sensible heat flux ($\text{W} \cdot \text{m}^{-2}$), and G is surface soil heat flux ($\text{W} \cdot \text{m}^{-2}$).

Using Taylor series expansion and omitting higher-order terms, the surface temperature difference between different underlying surfaces can be expressed as:

$$T'_s - T_s \approx \frac{1}{4\varepsilon\sigma T_s^3} [(1 - \alpha')S'_{\downarrow} - (1 - \alpha)S_{\downarrow} + \varepsilon'(L'_{\downarrow} - \sigma T_s^4) - \varepsilon(L_{\downarrow} - \sigma T_s^4) - (H' - H) - (LE' - LE) - (G' - G)]$$

The right side of this equation decomposes the biophysical effects into: (1) shortwave radiation forcing related to albedo changes, (2) longwave radiation forcing, (3) changes in sensible and latent heat fluxes, and (4) changes in surface soil heat flux.

DTM theory partitions the biophysical influence of different underlying surfaces on surface temperature into shortwave radiation, longwave radiation, sensible heat flux, latent heat flux, and surface soil heat flux components. For radiation terms, the sign is the same as the surface temperature difference: more net

shortwave and longwave radiation income results in higher surface temperature. For sensible heat flux, latent heat flux, and surface soil heat flux terms, the sign is opposite: stronger upward sensible/latent heat fluxes and stronger downward soil heat flux correspond to lower surface temperature, while stronger downward sensible/latent heat fluxes and stronger upward soil heat flux correspond to higher surface temperature.

Results

2.1 Differences in Micrometeorological Elements

We defined June 1 to September 30 as the growing season and January 1 to April 30 as the non-growing season, analyzing micrometeorological characteristics at both sites during these periods. Figure [Figure 2: see original paper] shows the average diurnal variation of soil temperature at both sites during the growing and non-growing seasons. Due to minimal diurnal variation in deep soil layers, only four soil temperature layers are shown. The diurnal trends were generally consistent between sites and seasons, with soil temperature decreasing in the early morning, reaching minimum values at sunrise, then increasing to maximum values before decreasing again. During the growing season, the minimum temperature occurred earlier and the maximum temperature later due to longer daylight hours. Deeper soil layers exhibited smaller temperature variations because heat transfer occurs layer by layer, with weaker heat absorption and release in deep layers. Under solar radiation, surface soil temperature rises rapidly, transferring some energy to underlying layers.

In both seasons, the subalpine shrub had lower soil temperature than the temperate steppe. Soil temperatures were higher during the growing season than the non-growing season, with greater diurnal ranges. At 20 cm depth, the diurnal range was 9.4 K for shrubland in the growing season versus 3.1 K in the non-growing season, while for steppe it was 8.5 K and 5.4 K, respectively. The steppe showed higher diurnal ranges in both seasons.

Figure [Figure 3: see original paper] presents the average diurnal variations of surface temperature, air temperature, and relative humidity. During the growing season, the temperate steppe exhibited significantly higher surface temperature, with a peak difference of 6.3 K between sites and greater daytime than nighttime differences. In the non-growing season, daytime surface temperature differences were not significant, particularly between 12:00-15:00, though nighttime surface temperature was notably higher at the steppe site.

During the growing season, air temperature at the steppe site was higher than at the shrubland site throughout the day, while in the non-growing season, no significant difference was observed. The diurnal patterns of air and surface temperature differ because they are influenced by different energy sources and factors. Surface temperature is directly affected by solar radiation, while air temperature is primarily influenced by surface temperature through convection and radiation.

Relative humidity showed diurnal variations opposite to temperature at both sites in both seasons. In the growing season, the steppe site had higher temperature, saturation vapor pressure, and actual vapor pressure, yet relative humidity showed no clear difference between sites, indicating higher actual vapor pressure at the steppe site. In the non-growing season, daytime temperature differences were minimal, resulting in similar saturation and actual vapor pressures, while the steppe site showed higher relative humidity, again indicating higher actual vapor pressure. Overall, the steppe site maintained higher actual vapor pressure than the shrubland site in both seasons, consistent with results from other watershed studies comparing different underlying surfaces.

2.2 Surface Energy Balance

2.2.1 Surface Radiation Budget Figure [Figure 4: see original paper] shows that due to the proximity of the two sites and similar background climate, downward shortwave radiation (S_{\downarrow}) differed little between them, averaging approximately $870 \text{ W} \cdot \text{m}^{-2}$ in the growing season and $700 \text{ W} \cdot \text{m}^{-2}$ in the non-growing season. Upward shortwave radiation (S_{\uparrow}) depends on surface albedo and S_{\downarrow} . Although shrubland had higher albedo than steppe (Figure [Figure 5: see original paper]), the difference was small, and shrubland's S_{\uparrow} peaks were lower than steppe's. Upward longwave radiation (L_{\uparrow}) is primarily influenced by surface temperature. The steppe's maximum L_{\uparrow} reached $418.1 \text{ W} \cdot \text{m}^{-2}$ in the growing season, significantly higher than shrubland's due to its higher temperature.

2.2.2 Surface Heat Flux Surface soil heat flux differences significantly impact surface temperature variations between land cover types. Generally perpendicular to the surface, downward soil heat flux represents heat transfer from surface to deeper layers, primarily generated by solar heating and most significant during daytime. Upward soil heat flux represents heat transfer from deep soil to surface, prominent at night. Positive values indicate downward heat transfer, while negative values indicate upward transfer.

Both sites showed positive daytime and negative nighttime values in both seasons (Figure [Figure 6: see original paper]). During the growing season, steppe's maximum and minimum values were $70.1 \text{ W} \cdot \text{m}^{-2}$ and $-26.1 \text{ W} \cdot \text{m}^{-2}$, respectively, while shrubland's were $44.6 \text{ W} \cdot \text{m}^{-2}$ and $-15.1 \text{ W} \cdot \text{m}^{-2}$. In the non-growing season, steppe's values were $53.0 \text{ W} \cdot \text{m}^{-2}$ and $-24.4 \text{ W} \cdot \text{m}^{-2}$, and shrubland's were $20.5 \text{ W} \cdot \text{m}^{-2}$ and $-11.2 \text{ W} \cdot \text{m}^{-2}$. Growing season flux intensities and diurnal ranges exceeded those in the non-growing season. The steppe site exhibited stronger soil heat flux than shrubland during both day and night, with greater differences during daytime.

The partitioning of available energy between sensible and latent heat fluxes significantly affects temperature and humidity within the planetary boundary layer. Figure [Figure 7: see original paper] shows the average diurnal variations of these fluxes, both positive during daytime, peaking in the afternoon, and near zero at night. Sensible heat flux is driven by air temperature differences, while

latent heat flux results from phase changes like evaporation and transpiration. During the growing season, latent heat flux differences were minimal, with peaks of $170.4 \text{ W} \cdot \text{m}^{-2}$ for steppe and $142.2 \text{ W} \cdot \text{m}^{-2}$ for shrubland. Sensible heat flux peaks were $156.1 \text{ W} \cdot \text{m}^{-2}$ and $105.8 \text{ W} \cdot \text{m}^{-2}$, respectively. In the non-growing season, daytime differences were most pronounced between 13:00-16:00, with steppe showing higher latent and sensible heat fluxes.

Energy balance closure was analyzed using the half-hourly energy balance ratio $EBR_{hr} = \frac{H+LE}{R_n-G}$. Both sites showed daytime closure rates of 70-80% in the growing season and 80-90% in the non-growing season, with nighttime closure below 50%. This diurnal characteristic is common across flux stations.

2.3 Biophysical Effects on Surface Temperature

According to DTM theory (Equation (1)), biophysical effects on surface temperature differences can be divided into radiative and non-radiative effects. Radiative effects include shortwave and longwave radiation terms. During daytime, increased solar radiation raises surface temperature, while at night, surface radiation emission cools the surface.

In both seasons, net shortwave radiation differences ($\Delta\alpha S_{\downarrow}$) between shrubland and steppe were negative, with the negative term providing positive feedback to shrub cooling. Growing season differences exceeded non-growing season differences. Downward longwave radiation and emissivity terms ($\Delta L_{\downarrow} - \Delta\epsilon\sigma T_s^4$) showed both positive and negative values throughout the day.

Non-radiative effects include sensible heat flux, latent heat flux, and soil heat flux. Figure [Figure 9: see original paper] shows the average daytime (09:00-15:00) and nighttime (00:00-03:00) values for each biophysical factor. DTM theory assigns equal weight to each energy component, making some contributions larger than observed temperature differences, similar to findings in previous studies. During daytime in both seasons, sensible (ΔH) and latent (ΔLE) heat flux differences were negative, while soil heat flux differences (ΔG) were positive. According to Equation (1), negative sensible and latent heat flux differences provide negative feedback to shrub cooling, while positive soil heat flux differences provide positive feedback. Shortwave radiation differences promote cooling, while longwave radiation effects were minimal.

During the growing season, shortwave radiation had the greatest impact on daytime surface temperature differences, followed by soil heat flux and sensible heat flux terms. In the non-growing season, soil heat flux was most important, followed by shortwave radiation. At night, latent heat flux, soil heat flux, and longwave radiation terms promoted shrub cooling in both seasons, while sensible heat flux effects were opposite between seasons. Soil heat flux was the most important factor for nighttime temperature differences in both seasons, with sensible, latent, and longwave terms also contributing during the growing season.

Conclusions

To analyze land-atmosphere interaction characteristics and LULCC biophysical effects on surface temperature in the Qinghai Lake Basin, we selected subalpine shrub and temperate steppe sites from the basin's observation network. Applying DTM theory, we quantified surface temperature changes caused by differences in surface radiation, soil heat flux, sensible heat flux, and latent heat flux between the two underlying surfaces. The main conclusions are:

- 1) During both growing and non-growing seasons, the temperate steppe site had higher surface temperature, air temperature, and soil temperature than the subalpine shrub site. In the growing season, peak surface and air temperatures were 298.8 K and 288.2 K for steppe versus 292.5 K and 286.5 K for shrubland. Soil temperature at 5 cm depth peaked at 295.4 K for steppe and 288.6 K for shrubland. Differences were more pronounced during the growing season, while relative humidity differences were more evident in the non-growing season.
- 2) During daytime in both seasons, sensible heat flux, latent heat flux, and surface soil heat flux terms inhibited shrub cooling relative to grassland (negative feedback), while shortwave radiation promoted cooling (positive feedback). Longwave radiation effects were minimal. Shortwave radiation had the greatest impact on daytime temperature differences during the growing season, with soil heat flux and sensible heat flux also important. In the non-growing season, soil heat flux was most important, followed by shortwave radiation.
- 3) At night, latent heat flux, soil heat flux, and longwave radiation terms promoted shrub cooling, while sensible heat flux effects differed between seasons. Soil heat flux was the most important factor for nighttime temperature differences in both seasons.

These results demonstrate that under identical climatic conditions, different underlying surfaces produce significant biophysical feedback effects on surface temperature.

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