Vegetation change detection using thermal band emissivities over Jornada, New Mexico, USA

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Abstract Detecting land cover change over semi-arid rangeland is important for monitoring vegetation responses to drought, population expansion, and changing agricultural practices. Such change can be detected using vegetation indices, but these do not represent non-green vegetation and are dominated by seasonal changes. An alternative is to observe spatial changes in thermal emissivities, a measure that responds to soil surface composition and vegetation cover. Because soil emissivities are usually stable, temporal emissivity changes could be due to vegetation cover changes. Using ASTER thermal infrared observations, the technique is applied to observations over the Jornada Experimental Range in New Mexico between 2001 and 2003. The study showed spatially coherent regions where broadband emissivities decreased as much as 3%. These coherent regions may correspond to decreased vegetation densities, suggesting that the technique could be helpful for monitoring rangeland cover.

Key words ASTER; emissivity; Jornada; land cover change; thermal infrared

INTRODUCTION

Detecting temporal changes in the spatial distribution of vegetation is important for monitoring rangeland health and assessing outcomes from land management practices. Observing these changes is especially important in arid and semi-arid regions where water is scarce and agricultural demands are high. Using satellite-based remote sensing in visible and near infrared wavelengths, such changes can be very effectively monitored at seasonal time scales using vegetation indices. However, such indices may be inaccurate for rangelands because they cannot readily distinguish background soil from dormant plants. In arid lands this inaccuracy could be significant because vegetation is often non-green, a plant stage not readily distinguished by indices such as the Normalized Difference Vegetation Index (NDVI).

A remote sensing approach that could help reduce this problem is to estimate the land surface emissivity. Emissivity, a measure of efficiency of emitted radiant thermal energy, is estimated from observations within the thermal infrared band and is affected by surface properties such as vegetation cover but not by plant greenness. Commonly, vegetation increases surface emissivities over values otherwise observed for bare soils, meaning that discrimination between the two surfaces is possible. By using repeated remote sensing observations over yearly time scales, changes in emissivity patterns could represent corresponding changes in vegetation densities.

Hence multitemporal analyses of remote sensing observations in the thermal infrared could potentially be very useful for monitoring land cover change. However, accurately estimating surface emissivities, accounting for their spectral variability, correcting for atmospheric effects, and distinguishing between causes of apparent emissivity changes has been challenging. In an effort to reduce some of these uncertainties, and to investigate whether emissivity changes can be resolved operationally, multispectral remote sensing data collected over a semi-arid rangeland were analysed and interpreted. These consist of three years of episodic observations from NASA's Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) over the Jornada Experimental Range in southern New Mexico, USA.

EMISSIVITY ESTIMATION WITH ASTER

Emissivity is defined as the ratio between emitted radiation (L_λ) from a body to that emitted from a blackbody ($L_{\lambda,\mathrm{BB}}$) at the same temperature:

$$\varepsilon_\lambda = \frac{L_\lambda}{L_{\lambda,BB}} \tag{1}$$

Converting the emitted radiation terms to temperatures using the Planck equation, emissivity is equivalent to a proportionality factor distinguishing brightness temperature from true radiometric temperature (Norman & Becker, 1995). Therefore surface emissivity can be estimated with thermal infrared remote sensing, provided the observed surface temperatures can be compared to kinetic surface temperatures. To accomplish this, comparison techniques are also required to remove confounding atmospheric effects and to resolve spectral differences in thermal band emissivities. Correction for atmospheric effects can be done by modelling atmospheric profiles, while resolution of spectral differences can be done using multispectral thermal infrared detectors.

There are few remote sensing platforms with higher spatial resolution thermal infrared capabilities (e.g. Landsat), and also few that are also multispectral. Of these, the ASTER sensor (Abrams, 2000) is unique because it has both multispectral detectors and spatial resolution (90 m) sufficient to resolve land cover units significantly smaller than 1 km. ASTER has 14 bands, including three in the visible to near IR, six in the short wave infrared, and five in thermal infrared wavelengths. ASTER thermal bands are noteworthy because they sample more wavelengths than conventionally used for split-window temperature retrievals (Table 1).

Table 1 ASTER thermal band characteristics.

Band	10	11	12	13	14
Wavelength Center (μm)	8.3	8.65	9.1	10.6	11.3
Resolution (m)	90	90	90	90	90

Several emissivity retrieval algorithms have been developed that utilize multispectral TIR data from sensors such as ASTER (e.g. Li *et al.*, 1999). Each of these is designed to convert N bands of spectral brightness temperatures to a single kinetic surface temperature and N bands of spectral emissivities. One of the better-known algorithms is the temperature-emissivity separation approach (TES, Gillespie *et al.*, 1998), which combines observed radiometric temperatures with an empirical relationship between emissivity spectral contrast and the minimum emissivity. TES is an operational data product (AST05) and is generally accurate to ±1.5°C and ±0.015 for emissivity. Although performance of the TES algorithm is generally excellent, a drawback of the approach is its tendency to underestimate emissivities close to 1.0. For this study emissivity values are often close to 1.0, which means that implementation of TES would lead to underestimated emissivities. A more suitable technique is the normalized emissivity method (NEM; Gillespie, 1985), an initialization routine for TES that replaces the empirical relation with the assumption that a pre-specified maximum emissivity occurs somewhere within the sampled thermal infrared bands. This assumption is not arbitrary and is likely to be accurate for agricultural applications where the maximum land surface emissivities are typically within 1.5% of 0.98. For example, laboratory measurements of 41 soil samples (Salisbury & D'Aria, 1992) show that 39 of these (95%) had $\varepsilon_{max} \geq 0.965$ somewhere within the thermal infrared window.

An emissivity estimated from the NEM approach is useful by itself, but a further step was made to convert it to a more generally useful quantity: broadband emissivity (ε), a property used for surface energy balance studies. Following Ogawa *et al.* (2003) and Ogawa & Schmugge (2004), broadband emissivities from ASTER data can be estimated from the following linear model, where only ASTER bands 11–14 are used.

$$\varepsilon = 0.242 + 0.121\varepsilon_{11} + 0.194\varepsilon_{12} + 0.323\varepsilon_{13} + 0.113\varepsilon_{14} \qquad (2)$$

THE JORNADA EXPERIMENTAL RANGE

The Jornada Experimental Range (Jornada, Fig. 1) is a US Department of Agriculture, Agricultural Research Service (USDA/ARS) semi-arid research site in southern New Mexico and a Long Term Ecological Research (LTER) site (http://jornada-www.nmsu.edu). Jornada is a rangeland containing grasses and shrubs such as black grama and honey mesquite. Immediately south of Jornada is the New Mexico State University Ranch (http://www.nmsu.edu). Both sites have suffered significant degradation, with gains in mesquite populations at the expense of grasses.

Land cover changes have been monitored at Jornada since 1912, with intensive remote sensing observations since 1995 (Havstad *et al.*, 2000). With the launch of NASA's EOS Terra satellite late 1999, these observations have included ASTER image data. Between 2001 and 2003, 21 cloud-free images were acquired, allowing emissivity estimation at 90 m scales, as well as NDVI estimation at 15 m scales. Semi-annual leaf area index (LAI) transects were also acquired at three localities within Jornada. These transects were 150 m long containing LICOR LAI-2000 measurements collected at 1-m intervals for three 30-m sections through grass and shrubs communities.

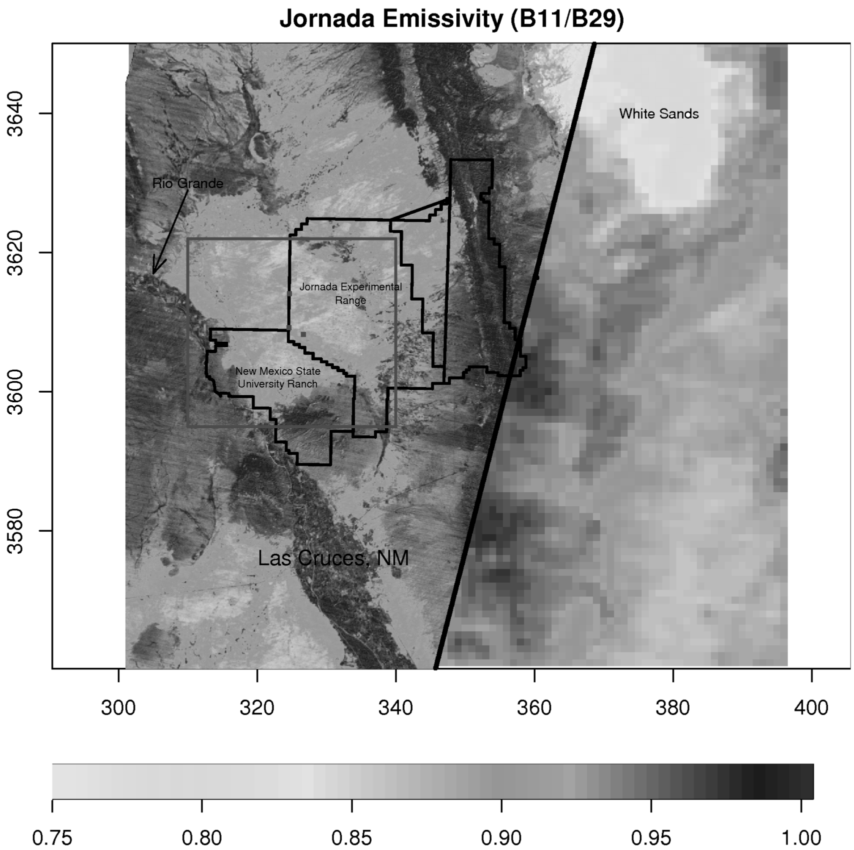

Fig. 1 Jornada overview using ASTER estimated emissivities from band 11. Spectral emissivities are scaled from 0.75 (white) to 1.0 (black). Spliced image to the right is derived from a MODIS equivalent, band 29. Southwest of Jornada is the New Mexico State University Ranch. Image data acquired 16 October 2003.

Surface thermal radiances were retrieved by correcting for atmospheric effects using MODTRAN (Berk *et al.*, 1998) and NOAA atmospheric profile data from Santa Teresa, NM (31.90°N, 106.70°W, ~75 km south of Jornada). These radiances were then converted to surface emissivities and temperatures following the NEM approach, an assumed ε_{max} of 0.98, and conversion with equation (2).

TEMPORAL EMISSIVITY CHANGES

To assess whether significant emissivity changes occurred within the Jornada environs for the 2001–2003 period, ASTER-based broadband emissivities were analysed for linear trends on a pixel-by-pixel basis. Because any changes in emissivity due to change in vegetation cover would likely be small (~0.01–0.05) and similar to emissivity changes due to episodic wetting from rainfall, higher order trends were not used.

Considering a georegistered stack of 21 ASTER images, linear trends for the three year period showed negligible apparent change in land cover over most of Jornada, but revealed spatially coherent regions ~5 × 10 km in extent near the southern and western boundaries of Jornada (Fig. 2), where emissivities decreased by ~3% over a three year period. Variances (R^2) in these same regions were moderate to high, ranging between ~0.55 to 0.85. Viewing estimated emissivities over the central part of the most prominent decreasing emissivity region shows a decreasing linear trend of $-1.9e^{-5}$ emissivity units day^{-1}, which is equivalent to a change in emissivity from ~0.96 in 2001 to ~0.94, at the end of 2003 (Fig. 3). The change, a 2% emissivity decrease, is small but meaningful. The modelled slope is significantly different from zero ($p = 1.4e^{-5}$).

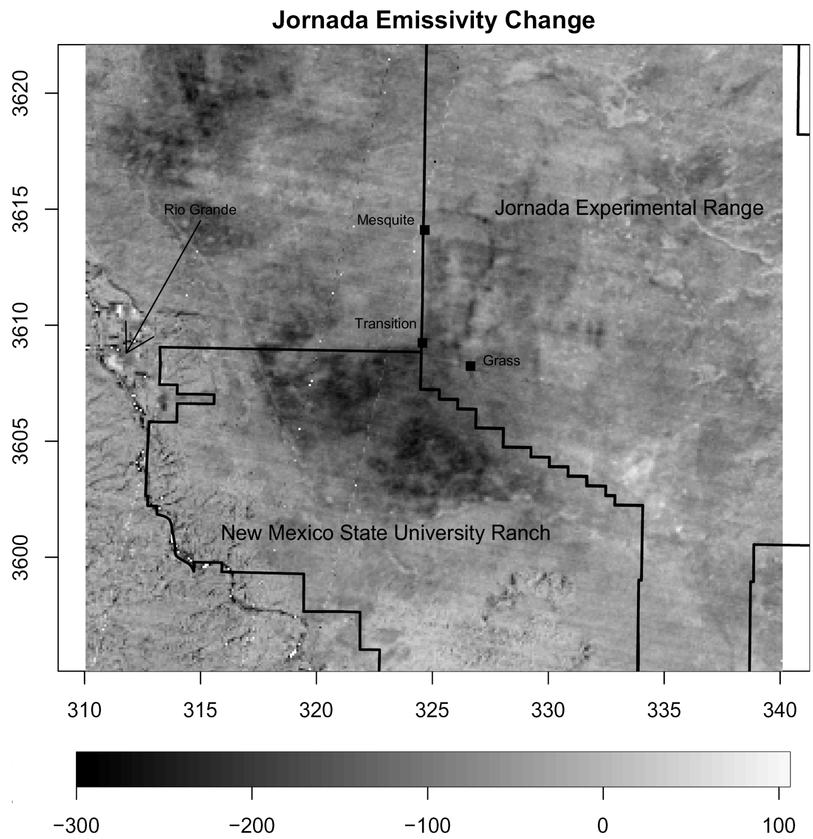

Fig. 2 Linear trend estimation of broadband emissivities over Jornada 2001–2003. Slope units range from $-300e^{-7}$ d^{-1} to $100e^{-7}$ d^{-1} (~ –3% to +1% for three years). LAI transect sites are indicated by box symbols.

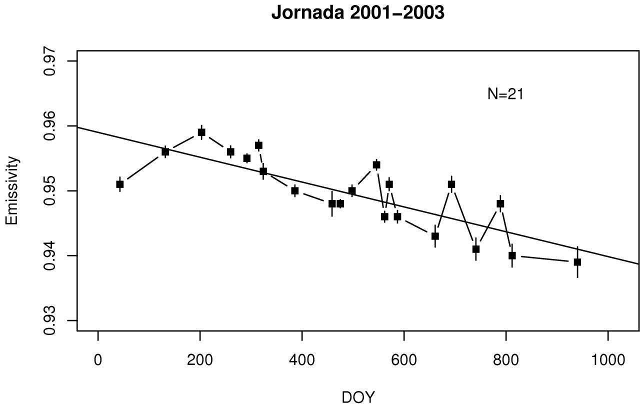

Fig. 3 Broadband emissivity trend over New Mexico State University Ranch.

To determine whether the observed emissivity decreases corresponded to hypothesized vegetation density changes, LAI transect data for the same time periods were plotted (Fig. 4). Unfortunately the transect sites were located away from the centres of the coherent regions described and observed trends are equivocal. Qualitatively the LAI values at the three sites suggest corresponding vegetation density decreases from ~1.5 to ~0.8, but given only six observations the trend is not statistically significant.

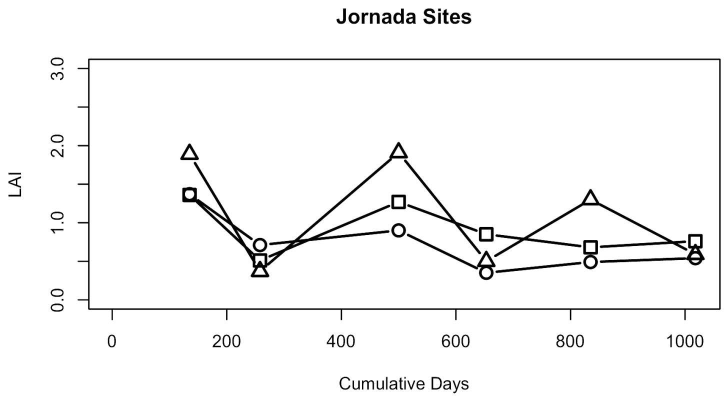

Fig. 4 Temporal LAI change at Jornada ground sites, 2001–2003. Symbols indicate Mesquite site (triangle), Transition site (circle), and Grass (square).

Because of the inconclusive LAI data, correspondence between the remotely sensed patches of decreasing emissivity and decreased vegetation cover cannot be proven. Nevertheless, changing vegetation is the interpreted cause because other possible explanations seem less likely. These include instrument calibration errors, atmospheric correction problems, and localized soil moisture changes. Although errors from each of these could be important, they are unlikely to be systematic. Instrument calibrations are checked and updated regularly. Atmospheric profiles, though not co-located with Jornada, could introduce bias, but could not introduce bias at the kilometer scale. Soil moisture effects can be strong, particularly after rainfall, but the effects are short lived and increase emissivities rather than decrease them. A remaining, but conjectural explanation is that the background soil emissivities in the patch areas were affected by differential grazing patterns.

CONCLUSION

A remote sensing study examining emissivity and land cover changes over the Jornada site for the 2001–2003 period showed spatially coherent patches of land with emissivity decreases of ~3% over three years. The cause for the patches could be due to decreased vegetation densities and is tentatively supported by ground observations. Unfortunately, definitive confirmation is not possible given available data. Nevertheless, the emissivity trends observed are intriguing because the approach could be applied to land cover assessments at any time of year regardless of plant colour.

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