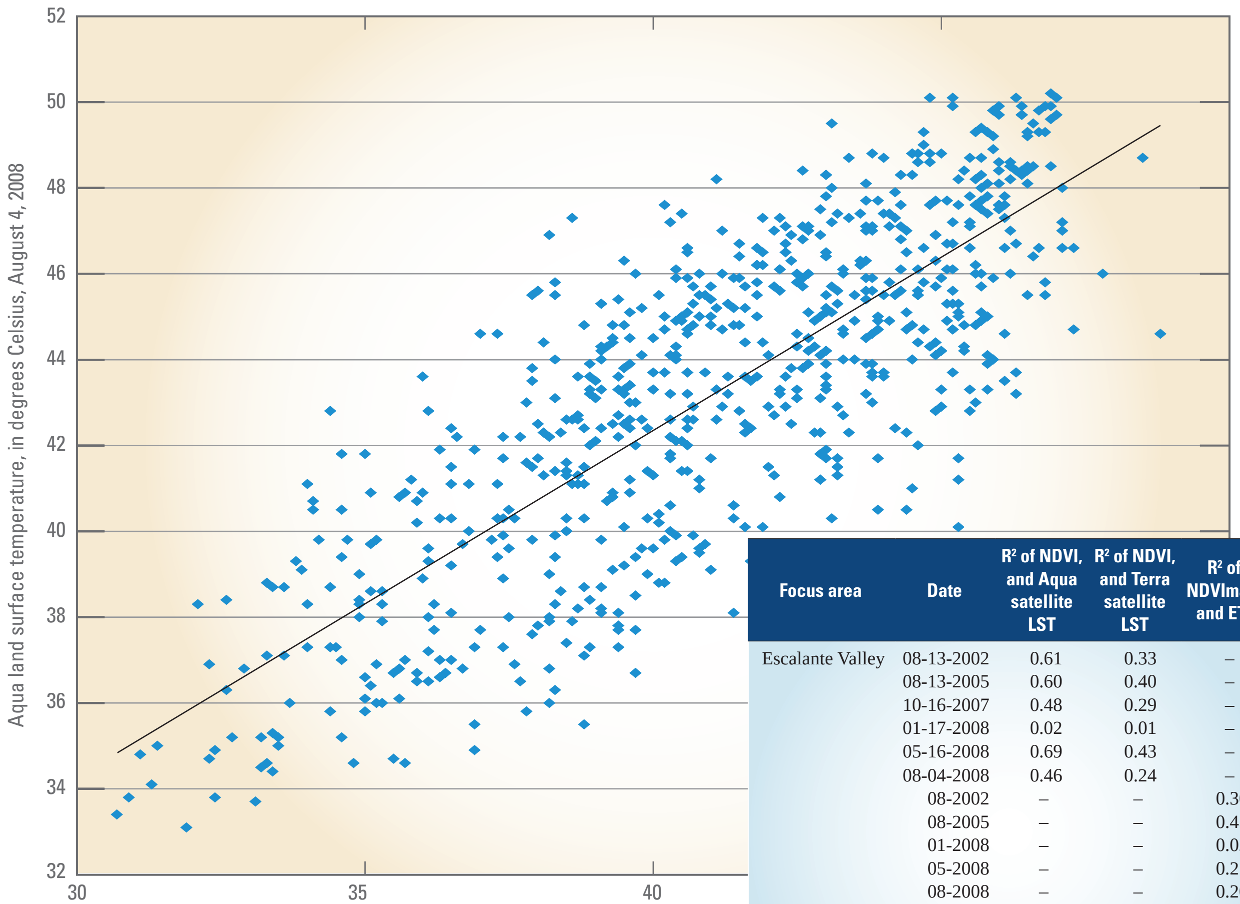
Groundwater Resources Program

Evaluation of the Relation between Evapotranspiration and Normalized Difference Vegetation Index for Downscaling the Simplified Surface Energy Balance Model



Focus area	Date	R^2 of NDVI, and Aqua satellite LST	R^2 of NDVI, and Terra satellite LST	R^2 of NDVImax, and ET_a
Escalante Valley	08-13-2002	0.61	0.33	–
	08-13-2005	0.60	0.40	–
	10-16-2007	0.48	0.29	–
	01-17-2008	0.02	0.01	–
	05-16-2008	0.69	0.43	–
	08-04-2008	0.46	0.24	–
	08-2002	–	–	0.30
	08-2005	–	–	0.45
	01-2008	–	–	0.02
	05-2008	–	–	0.21
	08-2008	–	–	0.20
Palo Verde Valley	08-04-2008	0.72	0.50	–
Columbia Plateau	08-13-2005	0.59	0.50	–
	08-2005	–	–	0.61

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U.S. Department of the Interior
U.S. Geological Survey

Evaluation of the Relation between Evapotranspiration and Normalized Difference Vegetation Index for Downscaling the Simplified Surface Energy Balance Model

By Jonathan V. Haynes and Gabriel B. Senay

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Conversion Factors, Datum, and Abbreviations and Acronyms

Conversion Factors

Multiply	By	To obtain
	Length	
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

°F=(1.8×°C)+32.

Datum

Horizontal coordinate information is referenced to the World Geodetic Survey Datum of 1984 (WGS 84).

Abbreviations and Acronyms

ET_a	actual evapotranspiration
ET_f	evapotranspiration fraction
ET_o	reference evapotranspiration
GDAS	Global Data Assimilation System
GIS	Geographic Information System
LST	land-surface temperature
METRIC	Mapping EvapoTranspiration at High Resolution and with Internalized Calibration
MODIS	Moderate Resolution Imaging Spectroradiometer
NASA	National Aeronautics and Space Administration
NDVI	Normalized Difference Vegetation Index
NDVImax	maximum monthly Normalized Difference Vegetation Index
PRISM	Parameter-elevation Regressions on Independent Slopes Model
SEBAL	Surface Energy Balance Algorithm for Land
SSEB	Simplified Surface Energy Balance
WGS84	World Geodetic System 1984

Evaluation of the Relation between Evapotranspiration and Normalized Difference Vegetation Index for Downscaling the Simplified Surface Energy Balance Model

By Jonathan V. Haynes and Gabriel B. Senay

Abstract

The Simplified Surface Energy Balance (SSEB) model uses satellite imagery to estimate actual evapotranspiration (ET_a) at 1-kilometer resolution. SSEB ET_a is useful for estimating irrigation water use; however, resolution limitations restrict its use to regional scale applications. The U.S. Geological Survey investigated the downscaling potential of SSEB ET_a from 1 kilometer to 250 meters by correlating ET_a with the Normalized Difference Vegetation Index (NDVI) from the Moderate Resolution Imaging Spectroradiometer instrument (MODIS). Correlations were studied in three arid to semiarid irrigated landscapes of the Western United States (Escalante Valley near Enterprise, Utah; Palo Verde Valley near Blythe, California; and part of the Columbia Plateau near Quincy, Washington) during several periods from 2002 to 2008. Irrigation season ET_a-NDVI correlations were lower than expected, ranging from R^2 of 0.20 to 0.61 because of an eastward 2–3 kilometer shift in ET_a data. The shift is due to a similar shift identified in the land-surface temperature (LST) data from the MODIS Terra satellite, which is used in the SSEB model. Further study is needed to delineate the Terra LST shift, its effect on SSEB ET_a, and the relation between ET_a and NDVI.

Introduction

Irrigation water use is an important and often poorly understood water-budget component. If actual evapotranspiration (ET_a) can be estimated sufficiently in irrigated areas, irrigation water use can be well defined. The Simplified Surface Energy Balance model (SSEB) has proven to be an effective tool for estimating ET_a (Senay and others, 2007; Senay and others, 2011a; Senay and others, 2011b). However, resolution limitations (1 km) of the Moderate Resolution Imaging Spectroradiometer (MODIS) land-surface temperature (LST) data constrain the use of the SSEB model to regional scale projects. The ability to downscale SSEB ET_a would allow smaller scale studies, or those requiring a finer resolution, to use these valuable ET_a estimates.

ET_a shares a well-established, strong relation with the Normalized Difference Vegetation Index (NDVI; Senay and others, 2011a). NDVI is derived from information collected by MODIS aboard the National Aeronautics and Space Administration's (NASA's) Aqua and Terra satellites. NDVI is created from the red and near-infrared wavelengths, and is a measure of vegetation vigor. A 16-day NDVI composite, representing the maximum NDVI during the 16-day period, is available from each satellite every 16 days. The start date for each Aqua satellite composite is 8 days after the Terra satellite start date in order for a 16-day NDVI composite to be available from either satellite every 8 days. Data are available at several resolutions including 1 km and 250 m. By defining the relation between 1 km ET_a and 1 km NDVI, and applying it to the 250 m NDVI, ET_a could be downscaled to 250 m, approaching field scale.

Purpose and Scope

This report presents the results of a study to investigate the correlation between ET_a and NDVI to assess downscaling feasibility. The correlation between NDVI and MODIS LST, a primary component of SSEB, also was studied. Correlations presented herein were investigated in three arid to semiarid irrigated landscapes of the Western United States (Escalante Valley near Enterprise, Utah; Palo Verde Valley near Blythe, California; and part of the Columbia Plateau near Quincy, Washington) during several periods from 2002 to 2008.

Simplified Surface Energy Balance

The SSEB model estimates ET_a using LST, air temperature, and reference ET data (Senay and others, 2011b). SSEB uses a simplified process adapted from the Surface Energy Balance Algorithm for Land (SEBAL; Bastiaanssen and others, 1998) and Mapping EvapoTranspiration at high Resolution and with Internalized Calibration (METRIC; Allen and others, 2007) models. When solving the energy balance at the land surface, SEBAL and METRIC both assume that the difference between LST and air temperature varies linearly with LST. SSEB further assumes that the difference between LST and air temperature also varies linearly with ET_a. Cells with the greatest differences have little to no ET_a. Cells with the smallest differences have the maximum ET_a. This principle is executed in the SSEB model by calculating the ET fraction (ET_f). ET_f is calculated for every cell in the model by comparing its temperature difference to that of the minimum and maximum differences.

ET_a is computed as the product of the ET_f and the reference ET (ET_o). Parameter-elevation Regressions on Independent Slopes Model (PRISM) air temperature data (Daly and others, 1993) and MODIS Terra 1-km, 8-day LST data (MOD11A2; National Aeronautics and Space Administration Land Processes Distributed Active Archive Center, 2008) are used to calculate ET_f. ET_o is generated from the Global Data Assimilation System (GDAS; Kanamitsu, 1989) using the standard Penman-Monteith equation for short-grass (Allen and others, 1998). ET_o values are based on the assumptions that cells are completely vegetated and that irrigation water is ample to meet crop demand. ET_f is calculated for every 8-day MODIS LST period, whereas ET_o is computed daily. Therefore, ET_o is responsible for daily variability in ET_a. All ET_a data analyzed in this report were first aggregated to a monthly time period.

Methods

Monthly 1-km ET_a data were created for Escalante Valley, Utah, in ESRI grid format and World Geodetic System 1984 (WGS84) datum using the methods described in Senay and others (2011b). Data were created for 2000–2009. The 1-km, 16-day MODIS NDVI data from Aqua (MYD13A2) and Terra (MOD13A2) satellites were downloaded from the NASA Land Processes Distributed Active Archive Center (National Aeronautics and Space Administration Land Processes Distributed Active Archive Center, 2008) for Escalante Valley, Utah, in hierarchical data format and Sinusoidal projection. These data were projected to WGS84 using the MODIS Reprojection Tool for Projection and Format Conversion (National Aeronautics and Space Administration Land Processes Distributed Active Archive Center, 2007). Data were selected within the Escalante Valley and saved in ESRI grid format. ESRI ArcGIS 9.3.1 was used to process all GIS data for this report.

Maximum monthly NDVI (NDVImax) data were built from the 16-day data to compare NDVI to monthly ET_a. An Escalante Valley focus area was delineated to include most irrigated lands and a buffer of native vegetation (fig. 1*A*). All ET_a and NDVImax data cells in this focus area were sampled in August 2002, 2005, and 2008. Additionally, data cells in this focus area were sampled in January and May 2008 to analyze correlations during winter and spring. Correlations between the sampled ET_a and NDVImax data were analyzed using Microsoft® Excel® (table 1).

MODIS 1-km LST and NDVI data from the Aqua and Terra satellites were acquired for August 13, 2002; August 13, 2005; October 16, 2007; January 17, 2008; May 16, 2008; and August 4, 2008, and were not re-projected to avoid interpolation errors. These data were used to investigate differences between Aqua and Terra satellite data, and Terra LST's influence on SSEB ET_a. LST is one of the primary data components of the SSEB model. LST-NDVI correlations were calculated and compared using the same methodology used to create the ET_a-NDVImax correlations. LST and NDVI, however, are negatively correlated because of the cooling effect of evapotranspiration. LST and NDVI data were compared using individual tiles representing specific dates and times, rather than as monthly composites such as ET_a and NDVImax. LST is available every 8 days from both satellites occurring on the same dates. NDVI is available every 16 days from both satellites, alternating every 8 days. Because NDVI is available only from Aqua or Terra satellites for any given date, it was sometimes necessary to compare LST from one satellite with NDVI from the other satellite.

Findings from Escalante Valley were compared with those from two similar western irrigated landscapes: Palo Verde Valley near Blythe, California, and part of the Columbia Plateau near Quincy, Washington. The same methodologies described for the Escalante Valley were used, including establishing focus areas for cell sampling that include irrigated lands and a buffer of native vegetation. All three agricultural areas receive little precipitation during the growing season and typify irrigation regimes in arid and semiarid climatic regions of the Western United States. The Palo Verde Valley focus area contains all the irrigated land near Blythe, California, and is split between California and Arizona by the Colorado River. The Columbia Plateau focus area near Quincy, Washington, is contained between the Columbia River to the west, Sentinel Mountain to the south, Potholes Reservoir to the east, and Monument Hill to the north. For the Palo Verde Valley focus area, the August 4, 2008, LST-NDVI correlation was computed. For the Columbia Plateau focus area, the August 13, 2005, LST-NDVI and the August 2005 ET_a-NDVImax correlations were computed. Columbia Plateau ET_a data are from a previous U.S. Geological Survey study (Kahle and others, 2011); data were not available for 2008.

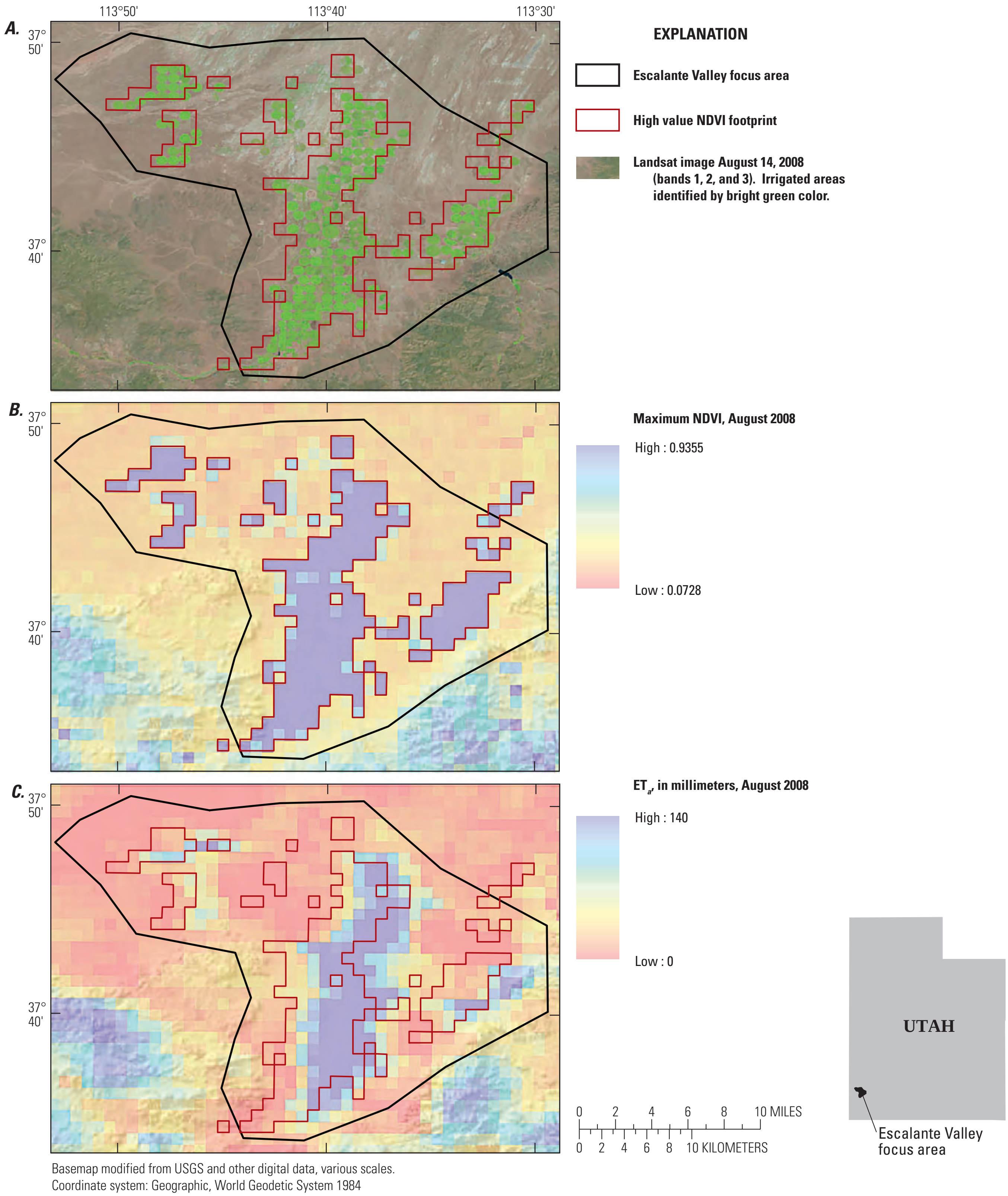


Figure 1. Eastward shift in actual evapotranspration (ET_a) compared to maximum monthly Normalized Difference Vegetation Index (NDVImax) and Landsat, Escalante Valley focus area near Enterprise, Utah. (*A*) Landsat image August 14, 2008 (bands 1, 2, and 3); (*B*) NDVImax, August 2008; (*C*) Simplified Surface Energy Balance (SSEB ET_a), August 2008.

Table 1. Correlations between Simplified Surface Energy Balance derived actual evapotranspiration, Moderate Resolution Imaging Spectroradiometer (MODIS) Normalized Difference Vegetation Index, maximum monthly Normalized Difference Vegetation Index, and MODIS land-surface temperature for the Escalante Valley, Utah, Palo Verde Valley, California, and Columbia Plateau, Washington, focus areas.

[**R^2 of NDVI, and Aqua satellite and Terra satellite LST:** Correlations between various Normalized Difference Vegetation Index (NDVI) and land-surface temperature (LST) data. **R^2 of NDVImax and ET_a:** Correlation of maximum monthly NDVI and actual evapotranspiration. –, not applicable]

Focus area	Date	R^2 of NDVI,and Aqua satellite LST	R^2 of NDVI, and Terra satellite LST	R^2 of NDVImax, and ET_a
Escalante Valley	08-13-2002	[1]0.61	[1]0.33	–
	08-13-2005	[1]0.60	[1]0.40	–
	10-16-2007	[1]0.48	[1]0.29	–
	01-17-2008	[1]0.02	[1]0.01	–
	05-16-2008	[2]0.69	[2]0.43	–
	08-04-2008	[2]0.46	[2]0.24	–
	[3]08-2002	–	–	0.30
	[3]08-2005	–	–	0.45
	[3]01-2008	–	–	0.02
	[3]05-2008	–	–	0.21
	[3]08-2008	–	–	0.20
Palo Verde Valley	08-04-2008	[2]0.72	[2]0.50	–
Columbia Plateau	08-13-2005	[1]0.59	[1]0.50	–
	[3]08-2005	–	–	0.61

[1]MODIS NDVI from the Terra satellite.

[2]MODIS NDVI from the Aqua satellite.

[3]Represents a monthly aggregate.

Results

The August 2002, 2005, and 2008 ET_a and NDVImax data were sampled and correlations were determined for the Escalante Valley focus area. In all cases, the correlations between ET_a and NDVImax were poor, with R^2 values ranging from 0.20 to 0.45 (table 1). Analyses of January and May 2008 data also indicated poor correlations, with R^2 values equal to 0.02 and 0.21, respectively.

Visual inspection of the August 2002, 2005, and 2008 data and the January and May 2008 data showed an eastward 2–3 km shift in ET_a cells when compared to NDVImax (fig. 1*C*). The poor ET_a-NDVImax correlations that were observed are likely caused by this shift. The shift is most easily seen when comparing high-value ET_a cells with high-value NDVImax cells. The high-value NDVImax cell footprint in figure 1*B* is used in figures 1*A* and 1*C* as a frame of reference. The locations of center pivot circular irrigated fields using Landsat imagery (identified in bright green; fig. 1*A*) matched well with NDVImax indicating that the NDVI data are accurate and that the shift is a result of one or more of the data sets used to calculate ET_a.

MODIS LST data, a component of SSEB ET_a, were investigated to determine if those data were responsible for the observed shift. The LST data from both the Aqua and Terra satellites were compared to the NDVI. A similar but smaller shift (1–2 km) was inherent in all LST data from the Terra satellite (fig. 2*C*). MODIS LST data from the Aqua satellite, however, only show possible traces of shifting compared to NDVI (fig. 2*B*). MODIS NDVI from Aqua and Terra satellites show no indications of shifting when compared to each other or to the Landsat imagery. This visual analysis is corroborated by the Aqua-Terra LST correlation and the Aqua-Terra NDVI correlation in August 2008 (fig. 3). Aqua LST and Terra LST from August 4, 2008, show a moderate correlation ($R^2 = 0.64$) because of the Terra LST shift. Aqua NDVI and Terra NDVI from August 4 and August 12, 2008, respectively, show a strong correlation ($R^2 = 0.96$) because of no shift.

LST and NDVI data from Aqua and Terra satellites were sampled and correlations were determined for August 13, 2002; August 13, 2005; October 16, 2007; January 17, 2008; May 16, 2008; and August 4, 2008. Similar to the ET_a-NDVImax relation, correlations between Terra LST and NDVI were poor because of the Terra LST shift. R^2 values ranged from 0.24 to 0.40 for August 13, 2002; August 13, 2005; and August 4, 2008 (table 1). The Aqua LST-NDVI correlation consistently was better than the Terra LST-NVDI correlation because of no shift, with R^2 values ranging from 0.46 to 0.61.

MODIS LST and NDVI both use a Sinusoidal grid tiling system, with each tile equal to 10×10 degrees starting at the equator (National Aeronautics and Space Administration Land Processes Distributed Active Archive Center, 2012). The Escalante Valley is on the margins between two MODIS tiles (h08v05 and h09v05). One possibility is that shifting is occurring on the margins of the tiles because of distortion. To rule out the position on the tile as the cause of shifting, correlations were analyzed for the Palo Verde Valley and Columbia Plateau focus areas.

The Palo Verde Valley is located near the center of the western MODIS tile (h08v05) shared by the Escalante Valley. Visual inspection of the imagery showed a similar shift of Terra LST compared to Aqua and Terra NDVI, and Aqua LST. LST and NDVI data were sampled in the irrigated and adjacent area for August 4, 2008. Aqua and Terra correlations showed improvement compared to correlations in Escalante Valley; however, the difference in correlations between Aqua and Terra satellites was consistent with those of Escalante Valley because of shifting (Aqua $R^2 = 0.72$; Terra $R^2 = 0.50$).

The Columbia Plateau focus area lies in the northeastern quarter of the adjacent MODIS tile (h09v04). ET_a and NDVImax data were sampled for August 2005, with $R^2 = 0.61$. LST and NDVI data were sampled for August 13, 2005, with $R^2 = 0.50$ for Terra satellite and $R^2 = 0.59$ for Aqua satellite. In this case, the ET_a-NDVImax correlation is similar to the Aqua LST-NDVI correlation. The difference between Aqua and Terra LST-NDVI correlations is much smaller than in the previous examples. Visually, the Aqua-Terra LST shift is still persistent; however, the ET_a-NDVI shift is more subtle.

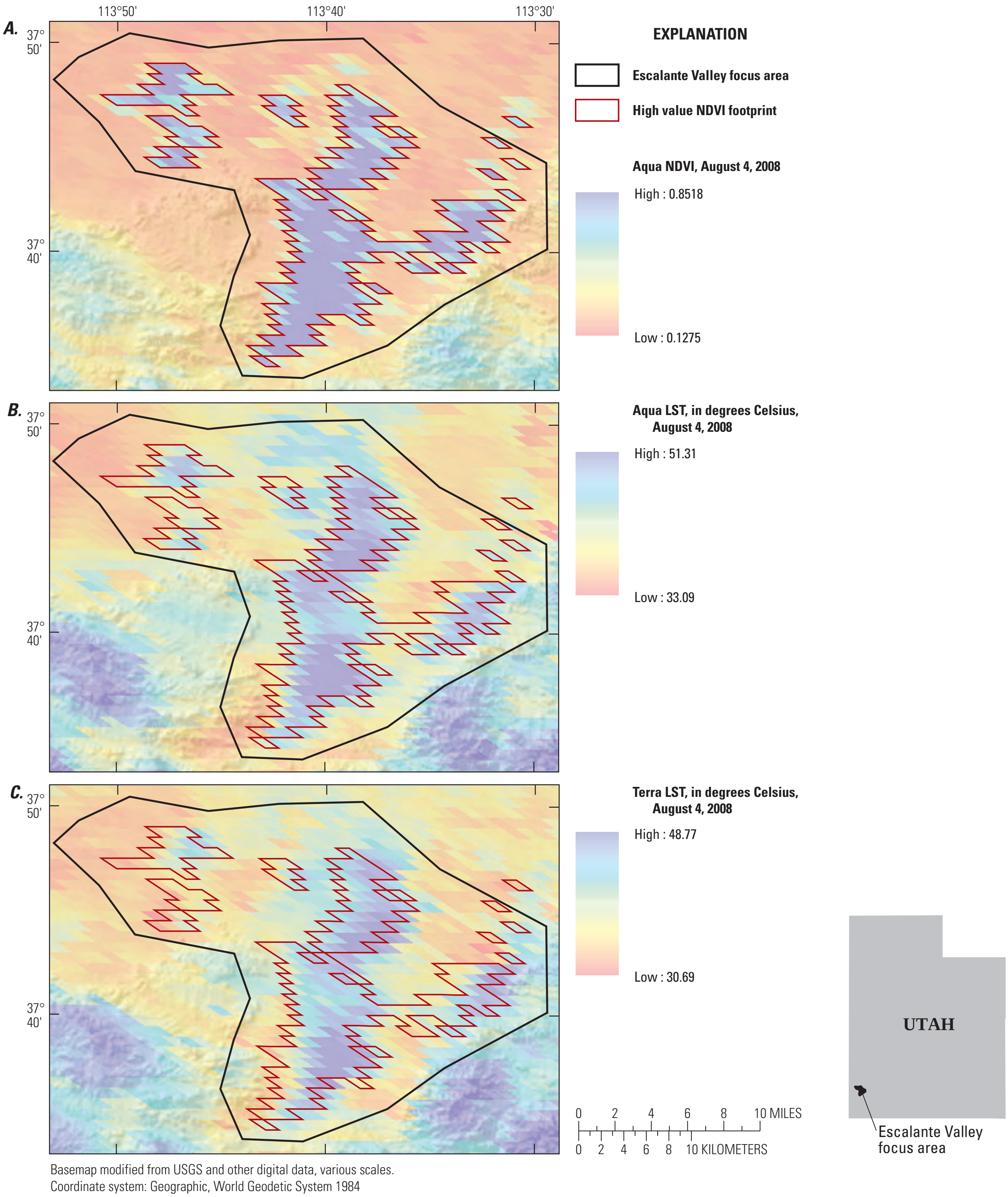
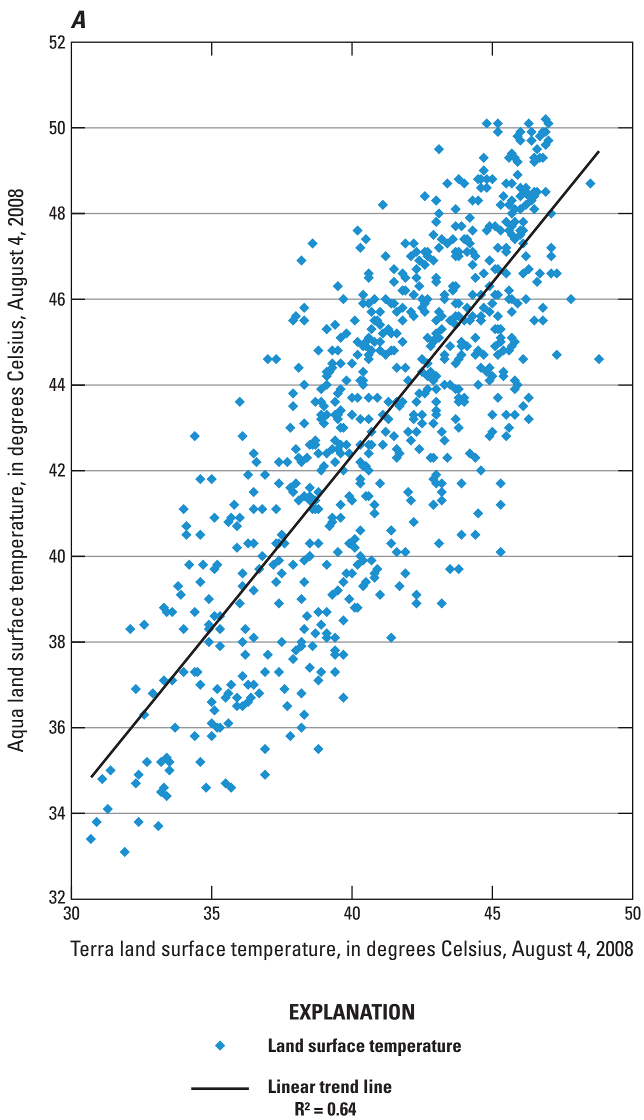


Figure 2. Eastward shift in Moderate Resolution Imaging Spectroradiometer (MODIS) Terra land-surface temperature (LST) compared to MODIS Aqua LST and Normalized Difference Vegetation Index (NDVI), Escalante Valley focus area near Enterprise, Utah. (*A*) MODIS Aqua NDVI, August 4, 2008; (*B*) MODIS Aqua LST, August 4, 2008; (*C*) MODIS Terra LST, August 4, 2008.



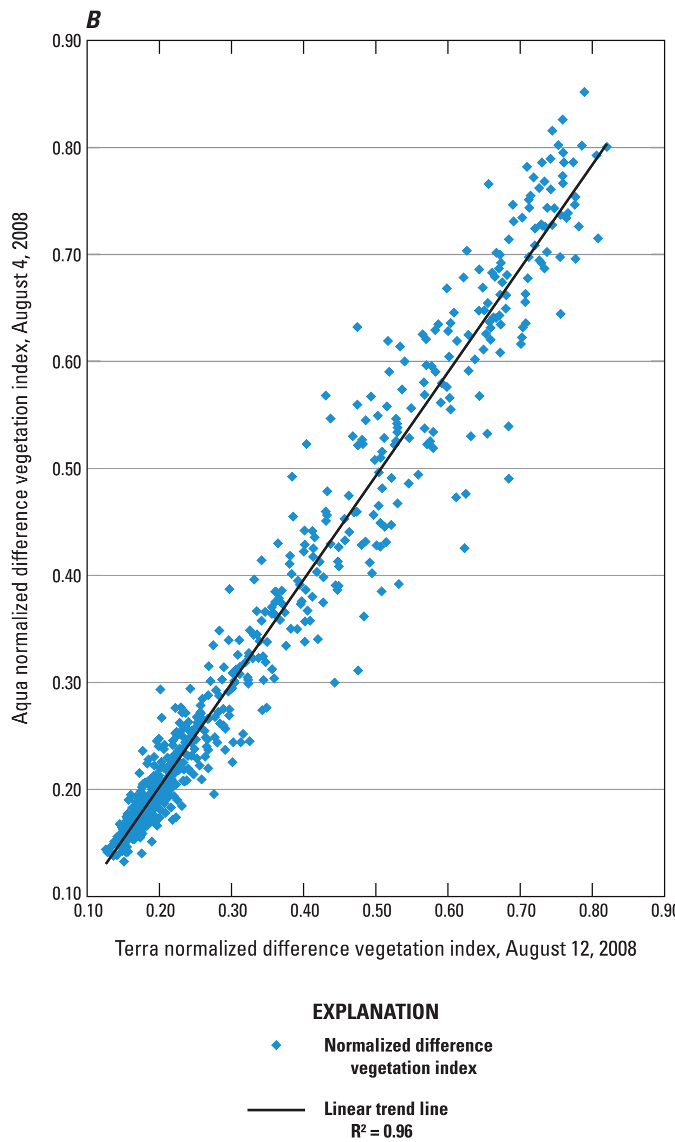


Figure 3. Aqua and Terra satellite correlations for land-surface temperature (LST) and Normalized Difference Vegetation Index (NDVI), Escalante Valley focus area near Enterprise, Utah. (*A*) Aqua and Terra LST, August 4, 2008; (*B*) Aqua and Terra NDVI, August 4 and August 12, 2008, respectively.

Summary

A strong correlation between actual evapotranspiration (ET_a) and Normalized Difference Vegetation Index (NDVI) is required to downscale 1-kilometer-resolution Simplified Surface Energy Balance (SSEB) ET_a data to 250-meter-resolution data. ET_a-maximum monthly NVDI (NDVImax) correlations calculated for this study do not meet this criterion. A 1–2-kilometer eastern shift in Terra Moderate Resolution Imaging Spectroradiometer land-surface temperature (MODIS LST) data negatively influences this relation and translates to a 2–3-kilometer shift in SSEB ET_a. However, it is uncertain how much the ET_a-NDVImax correlation could improve if only Aqua LST data are used in the SSEB model (in the Columbia Plateau, the Aqua LST-NDVI correlation is only slightly greater than the Terra LST-NDVI correlation). Correlations between ET_a and NDVImax possibly could improve, but not enough to be sufficient for downscaling. Further study is needed to delineate the Terra LST shift, its effect on SSEB ET_a, and the relation between ET_a and NDVI.

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