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ABSTRACT

This study provides a baseline quality check on provisional Landsat Surface Reflectance (SR) products as generated by the U.S. Geological Survey (USGS) Earth Resources Observation and Science (EROS) Center using Landsat Ecosystem Disturbance Adaptive Processing System (LEDAPS) software. Characterization of the Landsat SR products leveraged comparisons between aerosol optical thickness derived from LEDAPS and measured by Aerosol Robotic Network (AERONET), as well as reflectance correlations with field spectrometer and Moderate Resolution Imaging Spectroradiometer (MODIS) data. Results consistently indicated similarity between LEDAPS and alternative data products in longer wavelengths over vegetated areas with no adjacent water, while less reliable performance was observed in shorter wavelengths and sparsely vegetated areas. This study demonstrates the strengths and weaknesses of the atmospheric correction methodology used in LEDAPS, confirming its successful implementation to generate Landsat SR products.

1. Introduction

This study provides a baseline quality check on provisional Landsat Surface Reflectance (SR) products as generated by the U.S. Geological Survey (USGS) Earth Resources Observation and Science (EROS) Center. In 2010, the USGS integrated Landsat Ecosystem Disturbance Adaptive Processing System (LEDAPS) algorithms into an initial operating capability for generating and distributing provisional, atmospherically adjusted Landsat SR products for community and internal evaluation. A number of previous studies have examined the efficacy of the LEDAPS approach by comparisons with independent data sources (Ju et al., 2012; Masek et al., 2006; Ouaidrari & Vermote, 1999; Vermote et al., 1997a, 1997b). To perform a baseline quality check, the spatial and temporal reach of these studies is increased by leveraging an extensive sample of Aerosol Robotic Network (AERONET), field spectrometer, and Moderate Resolution Imaging Spectroradiometer (MODIS) data to further characterize the current generation of LEDAPS SR products.

The USGS processing system was built to help address the agency's Climate Data Record (CDR) Science Strategy "… to develop science-quality, applications-ready time-series of key terrestrial variables using historical and current Landsat data on an operational basis" (Dwyer et al., 2011). One of the fundamental, high priority CDRs identified in the strategy is SR. USGS adopted the LEDAPS approach for scene-based atmospheric correction for four main reasons. First, the algorithm basis has been well-established and documented (Kaufman et al., 1997; Ouaidrari & Vermote, 1999; Vermote et al., 1997a, 1997b). Second, routine production of LEDAPS SR matured demonstrably during the mid-2000s (Masek et al., 2006; User Guide for L7ESR, 2007; Vermote & El Saleous, 2007; Wolfe et al., 2004). Third, SR products have found a substantial community of users, mainly through the distribution of stand-alone code from the LEDAPS project. Examples of such applications include multi-sensor data fusion (Gao et al., 2006; Zhu et al., 2010), mapping of growing degree days (Hassan et al., 2007), disturbance mapping (Huang et al., 2009; Masek et al., 2006; Song et al., 2001; Thomas et al., 2011), monitoring of crop gross primary productivity (GPP) (Gitelson et al., 2008), impervious surface mapping (Powell et al., 2008), forest leaf area index (LAI) and albedo variation (McMillan & Goulden, 2008), biomass dynamics (Powell et al., 2010), and drought effects on carbon balance (Rocha & Goulden, 2010). And fourth, while marginal improvements to the correction scheme have been demonstrated using MODIS atmospheric profiles (Ju et al., 2012), the Landsat scene-based approach at the core of LEDAPS remains crucial for correcting data from the pre-MODIS era.

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Table 1
Percent pixel loss for each test site due to Scan Line Corrector (SLC) failure in Enhanced Thematic Mapper Plus (ETM+) scenes.

Site	Percent pixel loss
Bondville	29.30%
Ft. Peck	38.60%
Mead-2	9.60%
Mead-3	19.20%
Average	24.20%

In general, the LEDAPS correction scheme is applied to reflective bands to adjust for the effects of molecular scattering and absorption due to ozone, water vapor, aerosols, and other particles, as well as for Rayleigh scattering (Ouaidrari & Vermote, 1999). In the processing flow, standard Landsat 5 or 7 Level-1 data are first converted to top of atmosphere (TOA) reflectance and brightness temperature using published calibration coefficients (Chander et al., 2009). Then, as with standard MODIS SR processing, the Second Simulation of a Satellite Signal in the Solar Spectrum (6S) radiative transfer model (Vermote et al., 1997a, 1997b; Kotchenova et al., 2006) is used to derive lookup tables for application of the correction. LEDAPS relies heavily on independent auxiliary data sources for air pressure, air temperature, ozone, and topography, and also uses a scene-dependent dense dark vegetation (DDV) approach (Kaufman et al., 1997) for aerosol retrieval. A fixed continental aerosol model is also used in estimating the aerosol optical thickness (AOT) parameter used for final correction. The LEDAPS algorithms do not correct for bidirectional reflectance distribution function

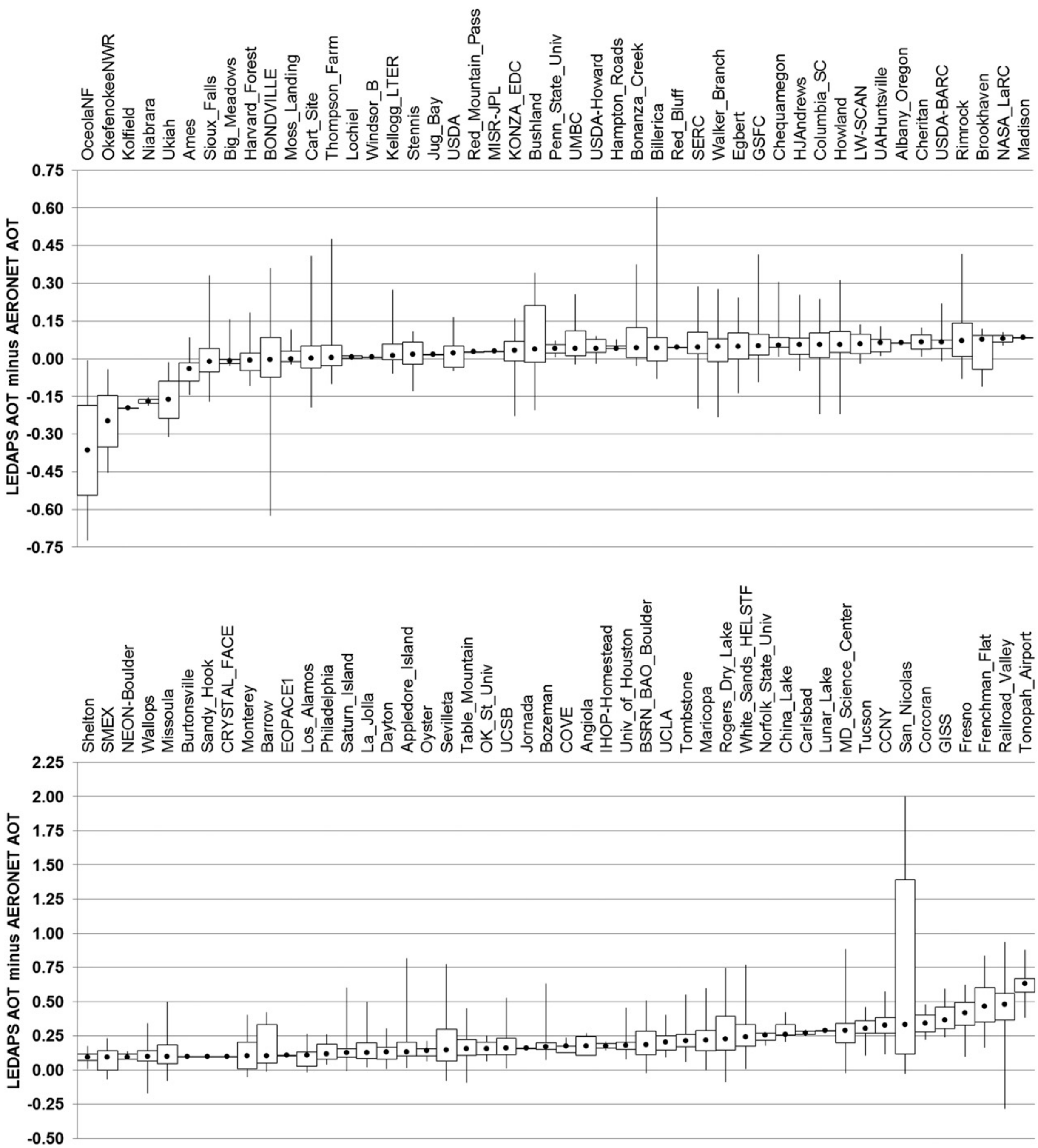


Fig. 1. Boxplots of the difference between LEDAPS and AERONET AOT arrayed by median difference at each of the 95 sites in the comparison dataset.

(BRDF), adjacency, or phenology effects. The quality of the output SR retrievals from Landsat are expected to approach MODIS SR products (Masek et al., 2006), with known issues related to scenes lacking sufficient DDV for optimal aerosol estimation.

2. Data and methods

Three sets of comparisons were conducted, each based on a unique set of samples and contrived to cover a range of independent data sources and SR retrieval conditions (i.e., AERONET, field spectrometer, and MODIS data). Specific data and methods used for each set of comparisons are described in detail below.

2.1. LEDAPS SR products

All Landsat-based SR products characterized in this study were generated by the USGS on-demand processing system using the February 2011version of the LEDAPS code. The system generates the full suite of LEDAPS-based parameters, including TOA reflectance, AOT, SR, and pixel-level quality flags. Access to and full descriptions of the products can be found on-line through the USGS Provisional Landsat Surface Reflectance Products Web portal (http://landsat.usgs.gov/PLSRP.php).

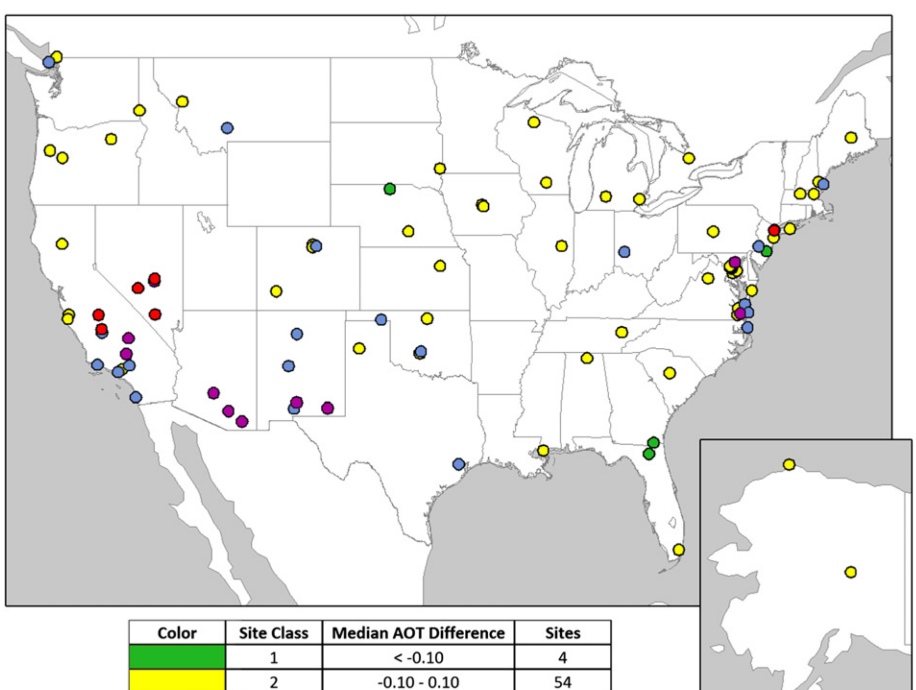
2.2. AERONET AOT comparisons

In the first comparison, AERONET data (Holben et al., 1998) were used to characterize the quality of LEDAPS AOT retrievals. AERONET is a network of ground-based sun photometers that measure the properties of atmospheric aerosols and provide quality screening for its distributed data. As described before, LEDAPS algorithms rely on a scene-dependent DDV approach to retrieve AOT. Comparisons with AERONET cloud-screened and quality-assured AOT provides indirect characterization of LEDAPS SR products, with poorly retrieved aerosols generally indicating reduced algorithm performance. Comparison methods follow from similar studies of aerosol retrieval quality from Landsat and other spaceborne sensors (Ju et al., 2012; Liu et al., 2004; Masek et al., 2006; Ouaidrari & Vermote, 1999; Slater et al., 1987).

The samples for AOT comparison were selected by the intersection of Landsat scene acquisitions with available AERONET data for the Continental U.S. and Alaska. The Landsat bulk metadata service (http://landsat.usgs.gov/consumer.php) was queried to generate a list of all available Landsat 5 Thematic Mapper (TM) and Landsat 7 Enhanced Thematic Mapper Plus (ETM+) scenes in the USGS archive covering the AERONET sites. Then, all Level 2.0 AERONET data (cloud screened and quality assured) for the study area were downloaded from the AERONET Web site (http://aeronet.gsfc.nasa.gov/). Site records were extracted where AERONET and Landsat scene center times were within 30 min of each other, yielding a database of 5245 unique AERONET samples across 110 sites.

The requisite Landsat SR products were acquired from the USGS on-demand system, and a 300×300 pixel region of interest (ROI) centered on each AERONET sample was extracted from the products. The LEDAPS-based AOT parameter was then filtered by conservative quality flag criteria such that only valid, cloud-free, and snow-free pixels over land not affected by cloud shadow or adjacent clouds were used in the comparison. The filtering reduced the number of coincident LEDAPS/AERONET samples to 3514 across 95 sites for analysis.

The temporal range of the comparison dataset spanned July 5, 1993 to January 24, 2011, with 55% of samples coming from Landsat 5 and 45% percent from Landsat 7. The difference between LEDAPS DDV-based AOT (450 nanometers (nm)–520 nm) and AERONET AOT (440 nm) was calculated for each of the paired sample locations. Outlier and error grouping analyses were conducted, using the median AOT difference to group the AERONET locations into five site classes based on magnitude and direction of the differences. The relationships between AERONET and LEDAPS AOT were graphed, and summary statistics were also generated to characterize bias and variability of LEDAPS AOT with respect to the independent AERONET measurements.



Color	Site Class	Median AOT Difference	Sites
	1	< -0.10	4
	2	-0.10 - 0.10	54
	3	0.11 - 0.20	20
	4	0.21 - 0.30	10
	5	> 0.30	7

Fig. 2. Spatial distribution of 95 sites categorized into five classes based on magnitude and direction of median AOT differences.

2.3. Vicarious field spectrometer comparisons

The second set of comparisons in this study used field spectrometer measurements to characterize LEDAPS SR quality. Field spectrometer measurements provide a more direct characterization of SR quality than AERONET data, but sample sizes are small due to limited availability of locations where vicarious data have been collected. Three test sites were used for direct comparison between LEDAPS SR and field data, and a temporal stability analysis of LEDAPS TOA and SR was conducted for two different, spectrally invariant sites. All analyses used field measurements made with an Analytical Spectral Devices (ASD) FieldSpec spectrometer (Helder et al., 2012) calibrated to meet National Institute of Standards and Technology (NIST)references for wavelength, absolute reflectance, downwelling and upwelling radiances. Since the ASD data are hyperspectral in nature, measurements were convolved to match the reflective bands of Landsat5 or 7 imagery, as indicated by the appropriate prelaunch Relative Spectral Response curves.

The first test site used in the direct comparisons was the South Dakota State University (SDSU) grassland site located near Brookings, South Dakota. The second and third were more arid, spectrally brighter sites: Railroad Valley Playa (RVP) in Nevada and Ivanpah Playa (IP) in California. ASD measurements covering a footprint of approximately 150 × 250 meters (m) have been made regularly at

Site Class	1	2	3	4	5
Number of sites	4	54	20	10	7
Number of observations	7	1774	752	526	412
Correlation	0.87	0.86	0.73	0.79	0.63
RMSD	0.50	0.29	0.43	0.52	0.65
Bias	0.25	-0.06	-0.19	-0.27	-0.42

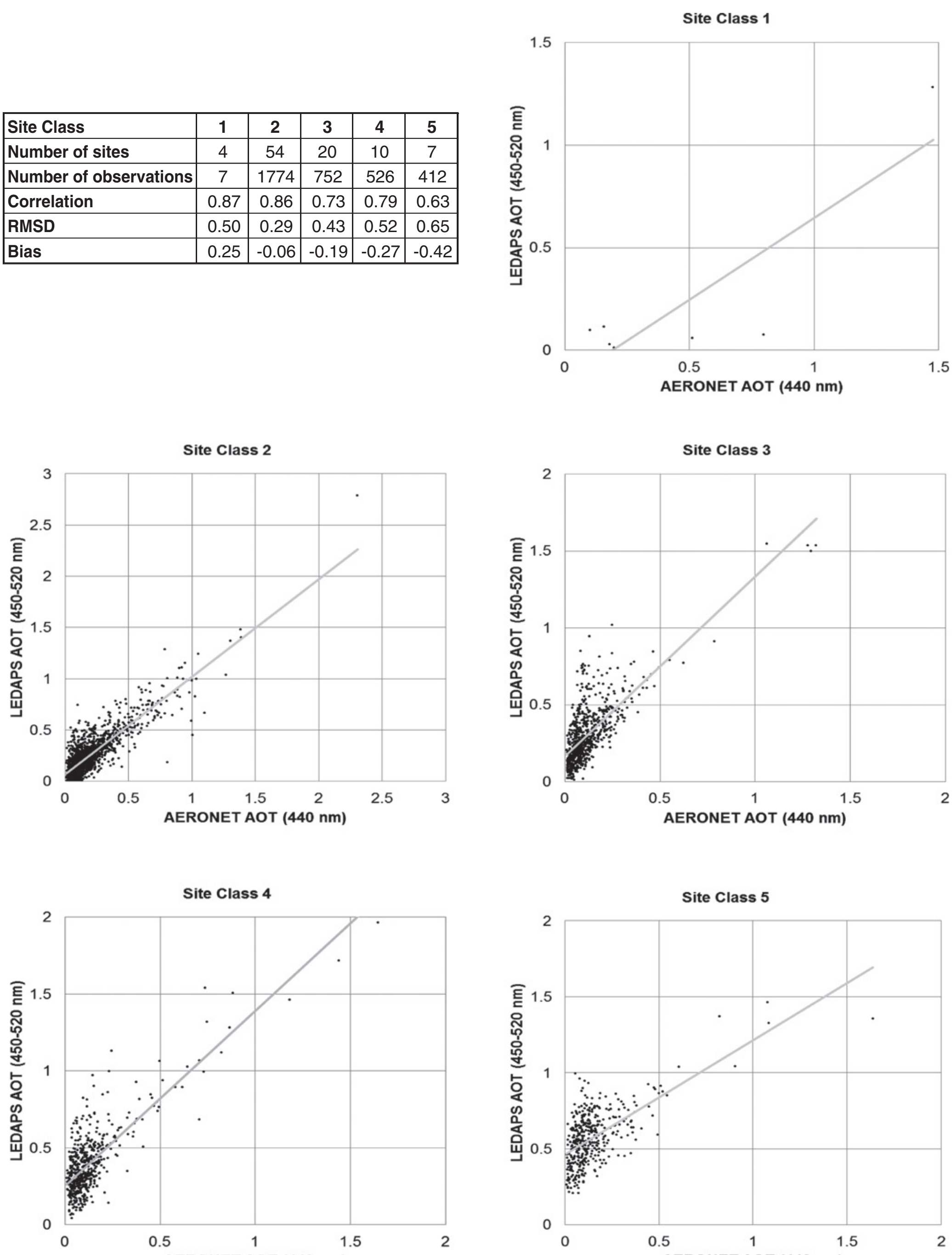


Fig. 3. Relationships between LEDAPS and AERONET AOT by site class.

the SDSU site for over ten years. The reflectance of the SDSU site is low (less than 0.10 reflectance units) in the blue through red portions of the spectrum, but it does represent a site for which the LEDAPS algorithms are expected to perform adequately (i.e., contained within a vegetated scene, and not adjacent to extensive water). The RVP and IP sites are Committee on Earth Observation Satellites (CEOS) Reference Standard Test Sites, and are extensively used for the purpose of vicarious calibration by the Remote Sensing Group (RSG) at the University of Arizona. They are both dry lake playas in a geographical region with reasonably high expectations of clear weather and typically low levels of aerosol loading. These sites have a higher reflectance signal and a lower amount of atmospheric noise, and represent targets for which LEDAPS is not optimized because of the lack of DDV.

For the SDSU grassland site, a total of eleven Landsat 5 and 7 scenes were matched to coincident ASD data. LEDAPS SR products for these scenes were acquired from the USGS on-demand system, and a 3×5 pixel ROI centered on the SDSU site was extracted from the corresponding products. The LEDAPS SR values were averaged over each ROI to find the mean reflectance of the study site for each band and scene, and then compared with the field-measured ASD samples. At RVP and IP, a total of five scenes were matched with coincident ASD data provided courtesy of the University of Arizona. LEDAPS SR products for these scenes were acquired from the USGS on-demand system. These desert sites tend to cover more area and be more uniform than grassland, so University of Arizona RSG characterized a larger region than was used for the SDSU site. This allowed larger 5×5 pixel ROIs centered on the RVP and IP site locations to be extracted from the products. As with the SDSU grassland site, the LEDAPS SR values were averaged over each ROI to find the mean reflectance of the study sites for each band and scene, and then compared with the field-measured ASD samples.

The temporal stability analysis of LEDAPS TOA and SR was conducted for two of the CEOS Pseudo Invariant Calibration Sites (PICS), Algodones Dunes and Libya 4. Due to their predominately invariant surface reflectance, PICS are routinely used to check the overall temporal stability of satellite radiometric calibration. For LEDAPS SR products, an atmospheric correction is being performed: if the correction is reliable, the temporal stability should be increased in the non-atmospherically corrected PICS data that have minimal spatial spectral variability. For Algodones Dunes, 83 Landsat 5 TM scenes spanning2002 to 2010 and a representative ROI of 145×130 pixels were used. For Libya 4, 57 Landsat 5 TM scenes spanning 2000 to 2010 and a larger homogenous ROIof 4750×4720 pixels were used. For both Algodones Dunes and Libya 4, the requisite LEDAPS SR products were acquired from the USGS on-demand system. Mean SR and TOA values were calculated from the site ROIs, and the temporal trends were plotted. The uncertainties associated with the LEDAPS products for the PICS were quantified as the ratio of the standard deviation of each date to the mean of the time series.

2.4. MODIS comparisons

The third set of comparisons in this study used MODIS as an independent data source for LEDAPS product characterization. MODIS comparisons were conducted to describe cross-sensor consistency in SR and the derivative normalized difference vegetation index (NDVI). Because of the common 6S radiative transfer model at the base of LEDAPS and MODIS atmospheric correction schemes (Masek et al., 2006) the respective SR and derived products are expected to be similar. The methods used for LEDAPS/MODIS comparisons in this study are based on earlier studies which compare analogous products from different sensors (Brown et al., 2006; Feng et al., 2012; Opoku-Duah et al., 2008; Roy et al., 2008).

Two cropland sites from Mead, Nebraska (Mead-2, Mead-3), one cropland site from Bondville, Illinois, and one grassland site from

Table 2
Comparison between Landsat Ecosystem Disturbance Adaptive Processing System (LEDAPS) surface reflectance (SR) and Analytical Spectral Devices (ASD) SR for the South Dakota State University (SDSU) grass site.

SDSU Grass Site Comparison																			
Date		Band 1			Band 2			Band 3			Band 4			Band 5			Band 7		
		LEDAPS	Ground	Difference	LEDAPS	Ground	Difference	LEDAPS	Ground	Difference	LEDAPS	Ground	Difference	LEDAPS	Ground	Difference	LEDAPS	Ground	Difference
08/26/2003	L7	0.050	0.045	−0.004	0.076	0.075	−0.002	0.085	0.086	0.001	0.285	0.277	−0.008	0.304	0.319	0.015	0.171	0.172	0.001
06/15/2006	L7	0.053	0.054	0.000	0.092	0.092	0.000	0.101	0.106	0.005	0.312	0.312	0.000	0.294	0.317	0.023	0.165	0.170	0.005
07/20/2007	L7	0.054	0.051	−0.003	0.086	0.085	−0.001	0.106	0.110	0.003	0.263	0.259	−0.005	0.318	0.344	0.025	0.192	0.197	0.005
06/12/2008	L5	0.066	0.072	0.007	0.108	0.114	0.007	0.111	0.123	0.012	0.305	0.328	0.023	0.294	0.317	0.023	0.166	0.174	0.008
07/14/2008	L5	0.054	0.056	0.002	0.090	0.086	−0.004	0.104	0.108	0.004	0.282	0.246	−0.036	0.310	0.335	0.025	0.180	0.203	0.022
08/23/2008	L7	0.051	0.051	−0.001	0.075	0.080	0.005	0.085	0.093	0.007	0.280	0.280	0.000	0.309	0.335	0.026	0.173	0.183	0.009
09/16/2008	L5	0.053	0.037	−0.016	0.081	0.059	−0.023	0.096	0.068	−0.028	0.249	0.236	−0.013	0.287	0.277	−0.010	0.174	0.148	−0.026
05/30/2009	L5	0.054	0.052	−0.001	0.090	0.087	−0.003	0.084	0.084	0.000	0.295	0.307	0.012	0.285	0.295	0.011	0.164	0.159	−0.005
08/05/2010	L5	0.037	0.030	−0.007	0.064	0.057	−0.007	0.055	0.052	−0.003	0.317	0.315	−0.002	0.226	0.233	0.007	0.109	0.109	−0.001
08/21/2010	L5	0.035	0.030	−0.005	0.064	0.059	−0.006	0.056	0.054	−0.002	0.332	0.339	0.007	0.225	0.236	0.011	0.100	0.106	0.006
10/30/2010	L7	0.040	0.034	−0.006	0.063	0.067	0.004	0.068	0.071	0.004	0.307	0.324	0.018	0.249	0.273	0.025	0.125	0.130	0.006
Average				−0.003			−0.003			0.000			0.000			0.016			0.003

Ft. Peck, Montana were used for the MODIS comparisons. These AmeriFlux (http://ameriflux.ornl.gov) sites were selected to represent spatially homogenous but temporally variable land cover types for analysis. Forty-eight Landsat 7ETM+ scenes were selected based on visual examination of the images for clear-sky conditions over the sites during snow-free months, covering one year of acquisition using an operational Scan Line Corrector (SLC; 2002) and two years of SLC-off data.

Daily Terra MODIS 500 m SR data (MOD09GA) were obtained from the Land Processes Distributed Active Archive Center (LPDAAC) for each date of the LEDAPSSR data. The MODIS Reprojection Tool (MRT) Web Interface (MRTWeb; https://lpdaac.usgs.gov/get_data/mrtweb) was used to transform the data to the Lambert Azimuthal Equal Area map projection (sphere 6370997 centered at −100° longitude and −45° latitude) and to subset the tiles to 3000 square meter (m^2) blocks centered on the coordinates of the Ameriflux sites.

LEDAPS SR was delivered at a 30 m resolution in the Universal Transverse Mercator (UTM) projection, and was reprojected to conform with the projection and geographic subset applied to the MODIS data. The visible Red (MODIS Band 1, Landsat Band 3) and near-infrared (NIR; MODIS Band 2, Landsat Band 4) SR data were averaged across the area of interest to represent the reflectance value for each site at each time step.

Saturated pixels and fill values in the ETM+ image gaps due to SLC failure were excluded, which reduced the number of points used to compute the averages computed for LEDAPS images. MODIS images consistently included values for every pixel in the subset areas of interest, but the effects of the SLC in ETM+ data from 2005 and 2006 reduced the number of points available from the LEDAPS images by an average of 24%. Table 1 shows the percentage of pixels lost to SLC failure for each of the analysis sites. The Mead, NE location was least affected due to its fortunate position near the center of Path 28/Row 31.

The NDVI was computed from the reflectance averages in standard fashion ((NIR − Red) / (NIR + Red)). Time series of the LEDAPS and MODIS SR values were plotted for each site, followed by basic linear regression analyses and evaluation of the derived statistical indicators.

3. Results and discussion

3.1. AERONET AOT comparisons

Boxplots of the differences between LEDAPS and AERONET AOT are shown in Fig. 1. Median site differences (the dot in each box) between LEDAPS and AERONET AOT ranged from −0.36 (Oceola National Forest) to 0.63 (Tonopah Airport). The AOT values for the majority of sites (82 of 95) were higher in LEDAPS calculations than in AERONET measurements.

The median AOT difference by site was used to group the AERONET locations into five site classes based on magnitude and direction of the differences: 1) underestimated (<−0.10), 2) nearest-zero (−0.10 to 0.10), 3) least overestimated (0.11 to 0.20), 4) overestimated (0.21 to 0.30), and 5) most overestimated (>0.30). The sites were mapped and color coded with respect to the classes specified above (Fig. 2).

The majority of sites (54 of 95) fell in class 2 (yellow), where the median difference between LEDAPS and AERONET AOT observations was within plus or minus 0.1. Only four sites fell in class 1 (green) as locations where LEDAPS underestimated AOT relative to AERONET. Classes 3 (blue), 4 (purple), and 5 (red) represent locations where LEDAPS showed increasing overestimation of AOT compared to AERONET.

Scatterplots and summary statistics by site class are shown in Fig. 3. One outlying site (San Nicolas) was removed from this portion of the analysis. San Nicolas is an island site that showed extreme variability in AOT differences when compared with the other sites (Fig. 1), and so was removed to avoid excessive influence on the relationships in site class 5.

The correlation between LEDAPS and AERONET AOT ranged between 0.63 and 0.87 for the five site classes. The RMSD in AOT ranged between 0.29 and 0.65. In terms of estimation bias, only 4.4% of sites and 0.2% of observations show underestimation by LEDAPS AOT relative to AERONET (site class 1). The remaining site classes all showed

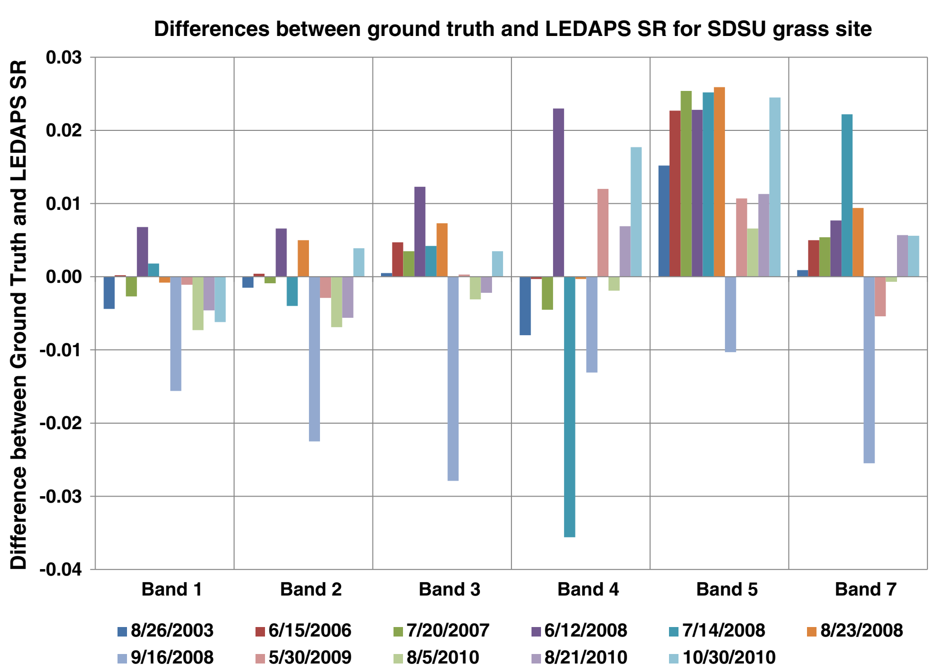


Fig. 4. Differences between ground data and LEDAPS surface reflectance at the South Dakota State University grass site.

Table 3
Comparison between Landsat Ecosystem Disturbance Adaptive Processing System (LEDAPS) surface reflectance (SR) and Analytical Spectral Devices (ASD) SR for the Railroad Valley Playa (RVP) site.

Railroad Valley Comparison																			
Date		Band 1			Band 2			Band 3			Band 4			Band 5			Band 7		
		LEDAPS	Ground	Difference	LEDAPS	Ground	Difference	LEDAPS	Ground	Difference	LEDAPS	Ground	Difference	LEDAPS	Ground	Difference	LEDAPS	Ground	Difference
05/22/2010	L7	0.346	0.327	−0.019	0.438	0.401	−0.037	0.481	0.441	−0.040	0.511	0.471	−0.040	0.504	0.490	−0.014	0.447	0.423	−0.024
07/17/2010	L5	0.285	0.283	−0.002	0.377	0.357	−0.020	0.404	0.391	−0.013	0.439	0.421	−0.018	0.445	0.447	0.003	0.397	0.377	−0.021
10/30/2010	L5	0.250	0.234	−0.016	0.350	0.364	0.013	0.378	0.450	0.072	0.415	0.504	0.089	0.444	0.565	0.122	0.378	0.489	0.111
Average				−0.012			−0.014			0.006			0.010			0.037			0.022

Table 4
Comparison between Landsat Ecosystem Disturbance Adaptive Processing System (LEDAPS) surface reflectance (SR) and Analytical Spectral Devices (ASD) SR for the Ivanpah Playa (IP) site.

Ivanpah Playa Comparison																			
Date		Band 1			Band 2			Band 3			Band 4			Band 5			Band 7		
		LEDAPS	Ground	Difference	LEDAPS	Ground	Difference	LEDAPS	Ground	Difference	LEDAPS	Ground	Difference	LEDAPS	Ground	Difference	LEDAPS	Ground	Difference
09/20/2010	L7	0.202	0.227	0.025	0.322	0.346	0.025	0.449	0.451	0.003	0.519	0.504	−0.015	0.537	0.566	0.029	0.448	0.493	0.045
11/15/2010	L5	0.157	0.204	0.047	0.278	0.326	0.048	0.345	0.406	0.061	0.396	0.456	0.061	0.477	0.530	0.052	0.400	0.440	0.039
Average				0.036			0.036			0.032			0.023			0.041			0.042

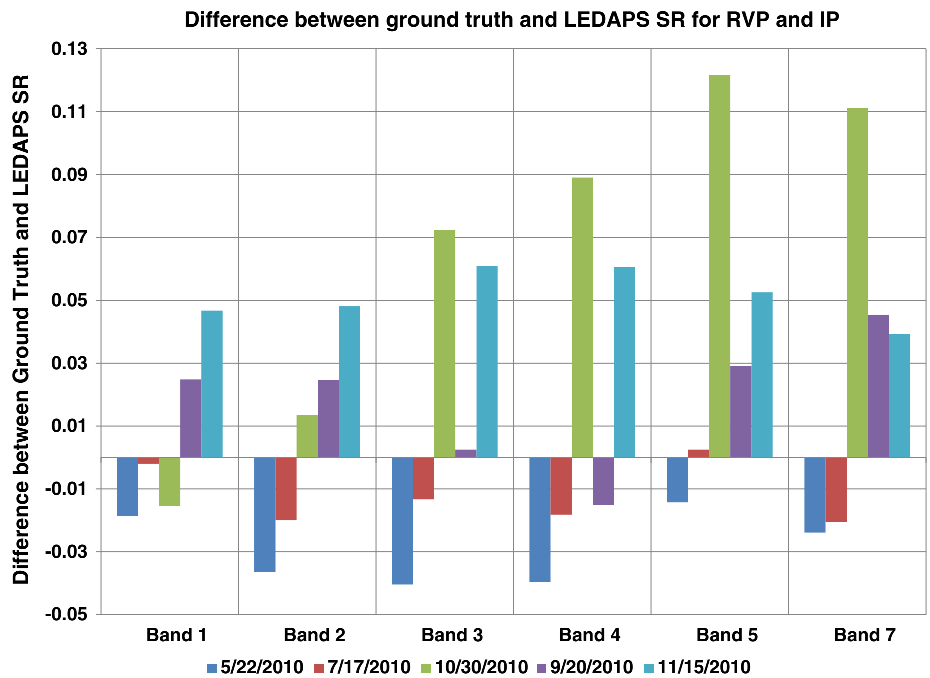


Fig. 5. Differences between ground data and LEDAPS surface reflectance at the Railroad Valley Playa and Ivanpah Playa sites.

LEDAPS AOT overestimation bias (−0.06, −0.19, −0.27, and −0.42 for site classes 2–5 respectively).

3.2. Vicarious field spectrometer comparisons

The comparison statistics between LEDAPS and ASD-measured SR for the SDSU grassland site, which have a 2% uncertainty, are given in Table 2, where the reflectance values from the dates of acquisition for all bands for both data sets are shown along with their differences. Within each band, differences between readings on the same date ranged from zero to 0.036 reflectance units. The average difference between LEDAPS and ASD SR per band was generally plus or minus 0.003, except for Band 5 which had an average difference of 0.016. Fig. 4 is a graphical depiction of the range of differences between ground-based and LEDAPS-produced SR results.

Tables 3 and 4 show the results of the analysis for RVP and IP respectively. For these brighter playa sites, the differences between LEDAPS SR and ground measurements were generally within 0.06 reflectance units

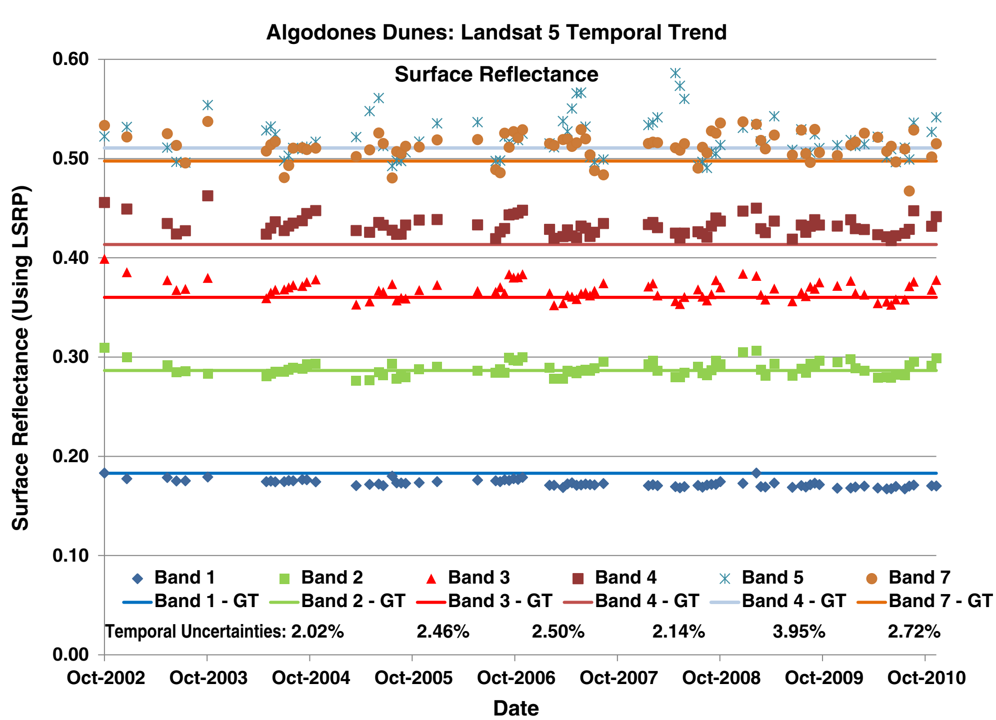


Fig. 6. LEDAPS surface reflectance temporal trend and uncertainty over the Algodones Dunes site.

Table 5
Summary and comparison of uncertainty percentages calculated for temporal trends of Landsat Ecosystem Disturbance Adaptive Processing System (LEDAPS) surface reflectance (SR) and top of atmosphere (TOA) reflectance.

LEDAPS uncertainty percentages across time over selected PICS						
	Algodones Dunes			Libya 4		
	SR	TOA	SR-TOA	SR	TOA	SR-TOA
Band 1	2.02	1.41	0.61	2.43	1.58	0.85
Band 2	2.46	1.25	1.21	2.67	1.05	1.62
Band 3	2.50	1.21	1.29	1.83	1.25	0.58
Band 4	2.14	2.55	−0.41	1.12	1.86	−0.74
Band 5	3.95	6.68	−2.73			
Band 7	2.72	4.17	−1.45	2.24	3.10	−0.86

for all cases except one, which corresponds to a RVP scene from October 30, 2010. For this scene the differences increased to 0.12 reflectance units. The overall difference between the two sets of data is shown in Fig. 5.

The temporal trend of LEDAPS SR over the Algodones Dunes site is shown in Fig. 6. LEDAPS SR values for each band were plotted through time (October 2002–February 2011) against ground measurements collected at the site by a joint team from the SDSU Image Processing Lab and the University of Arizona RSG on February 27, 2011. The ground measurement, representing a single point in time, is depicted for each band as a solid horizontal line. Because the Algodones Dunes site is considered spectrally invariant over time, SR values generated from LEDAPS should maintain proximity to the horizontal lines. This expectation is qualitatively fulfilled in Fig. 6, which shows LEDAPS SR on average to be within 0.01 units of the ground measurements.

The values listed as "Uncertainties" in Fig. 6 are defined as the ratio of the standard deviation to the mean of the temporal data, that is, the variability in the LEDAPS SR data through time over a spectrally stable site. As shown for all bands on Fig. 6 and repeated for clarity in Table 5, the overall LEDAPS SR uncertainty was within 3% of its mean, with the exception of Band 5 which shows a difference of 4%.

LEDAPS includes TOA reflectance with the SR data. LEDAPS TOA was also plotted to examine its temporal trend, and its uncertainty

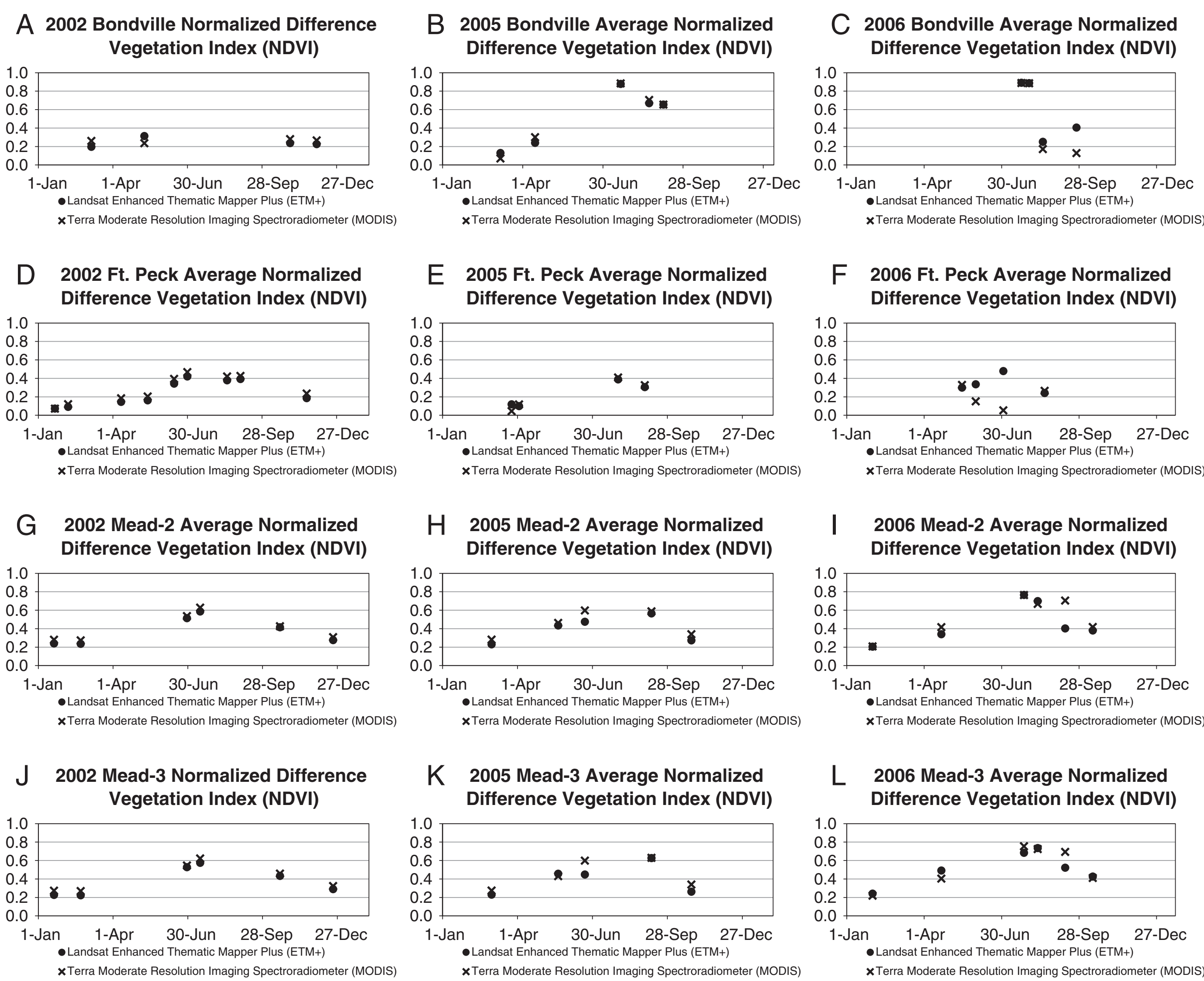


Fig. 7. NDVI averages derived from surface reflectance generated by LEDAPS and MODIS for test sites in 2002, 2005, and 2006: Bondville (A, B, C), Ft. Peck (D, E, F), Mead-2 (G, H, I), and Mead-3 (J, K, L).

was likewise calculated to determine whether atmospheric correction affects long term variability. As summarized in Table 5, TOA uncertainty was lower than SR uncertainty in Bands 1, 2, and 3, and higher in Bands 4, 5, and 7.

The temporal trend was also examined over the Libya 4 site. Results were similar to those obtained for Algodones Dunes. The variability obtained on Libya 4 from the TOA reflectance approach was lower than the LEDAPS SR results by about 0.5 to 1% for Bands 1, 2 and 3. For Bands 4, 5 and 7 the variability was higher than obtained from the LEDAPS SR.

3.3. MODIS comparisons

Time series plots of NDVI values derived from LEDAPS and MODIS Red and NIR data observed over the Ameriflux cropland sites at Mead-2, Mead-3, Bondville, and the Ft. Peck grassland site in 2002, 2005, and 2006 are displayed in Fig. 7. The 2002 plots represent data acquired with a functional ETM + SLC, and the 2005 and 2006 plots include values acquired while the SLC was off. The number of LEDAPS pixels included in the analysis was reduced in 2005 and 2006 due to SLC gaps (by about 24%, see Table 1), but the use of average values for each site mitigated significant impact.

Although the range of dates available over each site was not identically matched between the years used in the analysis, the plots in Fig. 7 indicate the typical green-up and green-down expected in the Central U.S. Mead-2 and Mead-3 best portray the rise and fall in NDVI values between spring and fall. Vegetation cycles in the Bondville site were less obvious because of inadequate cloud-free observations during certain months. Anomalous values are noted in the July 2, 2006 plot for Ft. Peck, which are confirmed to be due to significant cloud cover in the source MODIS image. Overall, slightly larger NDVI values are displayed in the MODIS values compared to the LEDAPS-derived NDVI values.

Figs. 8 and 9 demonstrate the LEDAPS and MODIS Red and NIR reflectance responses, which likewise were similar for all sites, including the cloud effects in the MODIS image over Ft. Peck in July 2006. Otherwise both LEDAPS and MODIS Red SR (Fig. 8) exhibit the general decrease in reflectance response that typically occurs with the increased presence of green vegetation during the summer months. The NIR data (Fig. 9), as typical for observations of a vegetated area, display an increase in values with progressive vegetative growth through the summer season. Generally, the values and trends are similar for both LEDAPS and MODIS Red, NIR, and NDVI data for the sites included in the analysis.

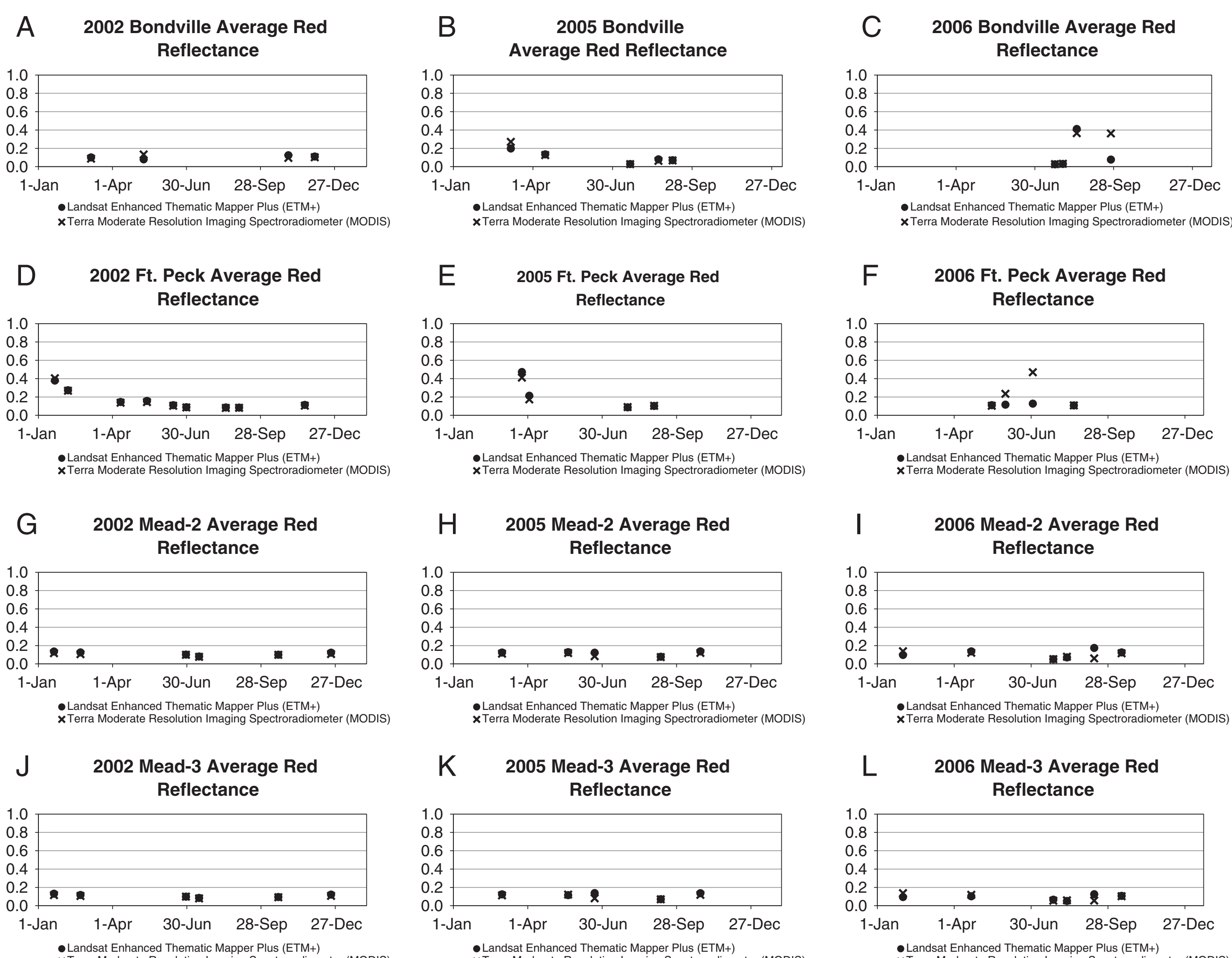


Fig. 8. Red surface reflectance generated by LEDAPS and MODIS for test sites in 2002, 2005, and 2006: Bondville (A, B, C), Ft. Peck (D, E, F), Mead-2 (G, H, I), and Mead-3 (J, K, L).

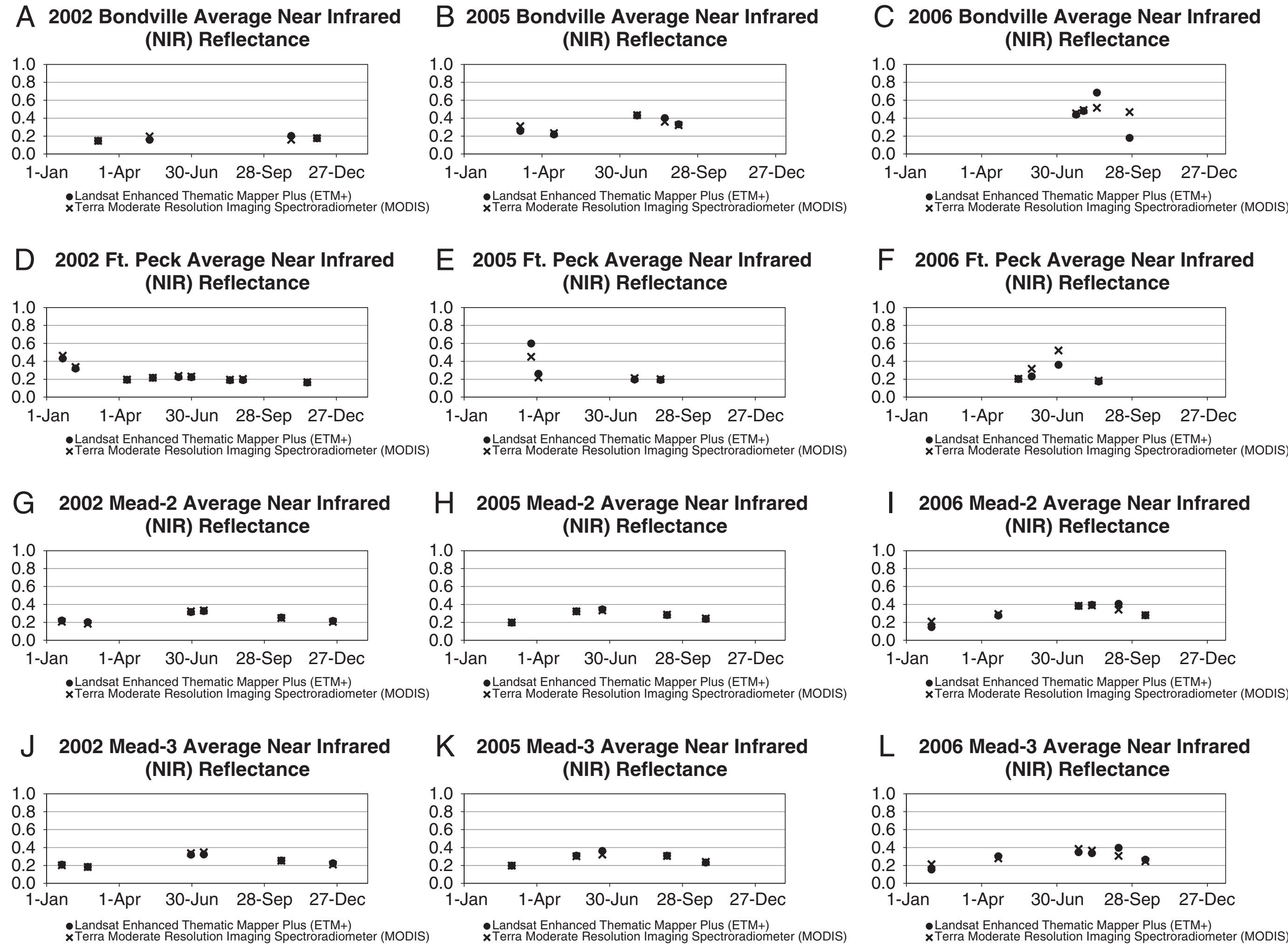


Fig. 9. NIR surface reflectance generated by LEDAPS and MODIS for test sites in 2002, 2005, and 2006: Bondville (A, B, C), Ft. Peck (D, E, F), Mead-2 (G, H, I), and Mead-3 (J, K, L).

The comparison of LEDAPS and MODIS NDVI values derived from SR for all dates at all locations (Fig. 10) generally exhibit linearity between the two data sets, with the exception again of the cloudy July 2006 MODIS acquisition over Ft. Peck. The MODIS NDVI values are slightly but consistently larger than the LEDAPS values, which results in the majority of data point plotting just below the 1:1 trend line along a 0.85 slope. About 80% of the variation in LEDAPS SR NDVI is associated with the MODIS NDVI values, based on R^2 computation (Table 6). The average expected difference between data sets is 0.09 RMSD, and the F-statistic for NDVI is much higher than the maximum critical F-value for a data set this size, confirming significant linearity between LEDAPS and MODIS.

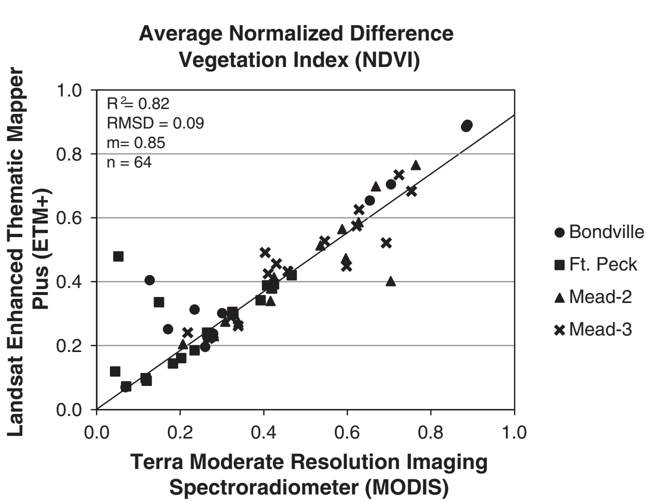


Fig. 10. NDVI averages derived from surface reflectance generated by LEDAPS and MODIS for all dates at all test sites.

The general characteristics of the relationship between LEDAPS and MODIS observed in the NDVI data are iterated in the Red and NIR reflectance data, although to a lesser degree. Fig. 11 shows plots of Red and NIR from all sites in the analysis. Correlation was weakest

Table 6
Statistics for the reflectance and normalized difference vegetation index (NDVI) averaged across all test sites.

Statistic	Near infrared	Red	Normalized difference vegetation index (NDVI)
R^2	0.7165	0.5458	0.8238
Root mean squared deviation (RMSD)	0.0572	0.0542	0.0866
Slope (m)	0.9412	0.6368	0.8467
Intercept (b)	0.0125	0.0433	0.0475
Points (n)	64	64	64

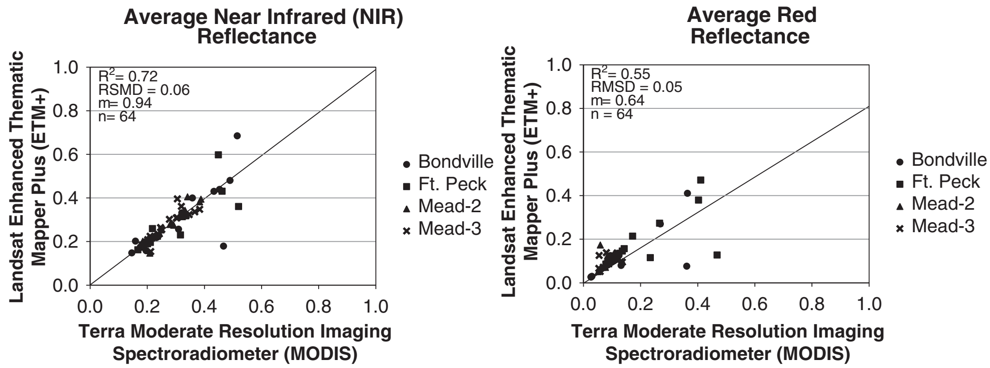


Fig. 11. Red and NIR surface reflectance generated by LEDAPS and MODIS for all dates at all test sites.

between LEDAPS and MODIS in the Red band, and the slopes and R^2 values are less for Red and NIR than those calculated for NDVI (Table 6). The F-statistic for both plots again confirms the linearity between data sets.

4. Conclusions

The characterization of LEDAPS SR by comparison with AERONET, field spectrometer, and MODIS data yielded results consistent with expected algorithm performance. Though available data were limited in this study, LEDAPS SR retrievals demonstrated success in longer wavelengths over vegetated areas with no adjacent water.

Comparisons with AERONET data indicated general overestimation of AOT by LEDAPS where DDV retrieval was problematic (such as in sparse vegetation, arid lands, or near water). For the majority of sites (where DDV targets were present), the LEDAPS estimate of AOT showed little bias relative to AERONET. These observations are consistent with known issues for LEDAPS AOT retrieval in sparsely vegetated regions and in locations where land area is small relative to adjacent water, and confirm the need for caution in using LEDAPS SR data under these conditions.

The expected performance of LEDAPS SR corrections was also supported by comparison of LEDAPS to field spectrometer measurements. LEDAPS values were reasonably corroborated over the grassland test site, which is surrounded by DDV. An exception was found in Band 5, in which LEDAPS was fairly consistent in reporting higher SR values than the field spectrometer. This could indicate that LEDAPS did not sufficiently correct for water vapor in the mid-infrared spectrum, or possibly that the satellite-derived inputs could not discern vegetation stress visible to the field spectrometer (Iacono & Sommer, 2000).

Despite the general success of LEDAPS in the grassland site, its output was not as well matched to field spectrometer measurements in sparsely vegetated, arid regions. This confirms the dependency of LEDAPS corrections on adequate vegetation coverage. In terms of temporal stability, the atmospherically corrected LEDAPS SR had more variability than TOA reflectance in the shorter wavelengths where most aerosol interference occurs. In longer wavelengths where the atmosphere tends to be clearer and only minor water vapor effects are prevalent, LEDAPS is capable of doing a more reliable correction.

The general consistency of LEDAPS SR with AERONET and field spectrometer measurements was repeated in its comparison with MODIS SR. Good agreement was observed between LEDAPS and MODIS SR and NDVI values for data acquired at cropland and grassland locations.

In summary, the expected strengths and weaknesses in LEDAPS were confirmed by the available data used in this study. Results showed reasonable agreement with similar data sets, especially in areas well-suited for DDV methodology. Known issues overestimating AOT in certain conditions, and the observed increase in variability across shorter wavelengths over time, indicate areas for improvement particularly in the LEDAPS aerosol detection and correction components.

LEDAPS represents a consistent method for generating surface reflectance products from the historical Landsat archive. A recent MODIS AOT approach (Ju et al., 2012) could enhance the algorithms' aerosol response, and it should be examined for its applicability to data acquired prior to 2000. New versions of LEDAPS are expected to address some of the known issues and accommodate improved spectral information from Landsat 8 in the future. Such significant LEDAPS enhancements will warrant repeated comparison with the provisional baseline characterization presented here. Users should be aware of the limitations of the approach, and use caution when applying the SR product in areas known to display suboptimal algorithm performance.

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