ELSEVIER

Remote Sensing of Environment

Jornada Experimental Range: A Unique Arid Land Location for Experiments to Validate Satellite Systems

K. M. Havstad, W. P. Kustas,† A. Rango,† J. C. Ritchie,† and T. J. Schmugge†*

The Jornada Experimental Range (Jornada) in southern New Mexico provides a unique opportunity to use remote sensing techniques to study arid rangeland and the responses of vegetation to changing hydrologic fluxes and atmospheric driving forces. Research by the United States Department of Agriculture Forest Service and Agricultural Research Service at Jornada has been continuous since 1912. The Jornada has been a National Science Foundation Long-Term Ecological Research site since 1981. These long-term investigations have provided ground data on vegetation characteristics, ecosystem dynamics, and vegetation response to changing physical and biological conditions. To complement the programs of ground measurements, a campaign called JORNEX (JORNada EXperiment) began in 1995 to collect remotely sensed data from aircraft and satellite platforms to provide spatial and temporal data on physical and biological states of the Jornada rangeland. A wide range of ground, aircraft, and satellite data have been collected on the physical, vegetative, thermal, and radiometric properties of three ecosystems (grass, grass/shrub transition, and shrub) typical of the Jornada rangeland and of southwestern U.S. deserts. Spatial surface energy balance estimates were made from a combination of parameters and state variables estimated from aircraft and ground data. Landscape surface roughness was evaluated with the laser altimetry data and used to estimate aerodynamic roughness. Data from different platforms allowed the evaluation of the landscape at different scales. These measurements are being used to quantify hydrologic budgets and plant responses to change in components in the water and energy balance at the Jornada. Published by Elsevier Science Inc.

INTRODUCTION

Arid lands, semiarid grasslands, and woodlands occupy about one-half the Earth's land surface (Holecek et al., 1998; FAO, 1982). Semiarid and arid rangelands cover much of the southwestern United States. Because arid and semiarid regions are sensitive to climate variations, much research has been devoted to identifying changes in rangeland vegetation and vegetation patterns and attempting to link such changes to environmental factors. Change in the boundaries between semiarid and arid lands, the expansion of arid lands, and changes in the relative proportions of bare soil, grass, and shrub are candidate indices of environmental change due to either human impacts or regional climatic changes. Monitoring changes in these vast areas, which often have limited access, are difficult using conventional techniques. Remote sensing tools offer a unique capability to study and monitor these vast areas for changes and to assess rangeland health.

The United States Department of Agriculture (USDA) Agricultural Research Service (ARS) Jornada Experimental Range (Jornada) in southern New Mexico has a long history of research, experimentation, and monitoring (Ares, 1974), making it a unique location to study the effects of climate change on the interface between desert grassland and desert shrub ecosystems and to test different remote sensing techniques and systems

* USDA Agricultural Research Service, Jornada Experimental Range, Las Cruces, NM

† USDA Agricultural Research Service, Hydrology Laboratory, Beltsville, MD

Address correspondence to Jerry C. Ritchie, USDA ARS Hydrology Laboratory, BARC-West, Beltsville, MD 20705, USA. E-mail: jritchie@hydrolab.arsusda.gov

Received 19 November 1999; revised 15 February 2000.

0034-4257/00/$–see front matter
PII S0034-4257(00)00118-8

for monitoring and detecting these changes. The Jornada Experimental Range was established in 1912 under the jurisdiction of the USDA Bureau of Plant Industry. In 1915 the USDA Forest Service assumed control at Jornada and began collecting climate and vegetation data. Some research plots and data records have been maintained since 1912 (Ares, 1974). The management of Jornada was transferred from the Forest Service to the Agricultural Research Service in 1954. In 1977 the site was selected as a Biosphere Reserve as part of the United Nation's International Man and the Biosphere program. In 1981 the National Science Foundation selected Jornada as a Long-Term Ecological Research (LTER) site. These different programs and research efforts at Jornada have produced an 87-year history of long-term ecological research on processes related to vegetation change, desertification, and range management. These historic and ongoing investigations have produced a wealth of ground data on vegetation characteristics, ecosystem dynamics, and vegetation responses to hydrologic, atmospheric, and human inputs (Havstad and Schlesinger, 1996).

A campaign named JORNEX (the JORNada EXperiment) was begun in 1995 to collect remotely sensed data from ground, airborne, and satellite platforms to complement the ongoing long-term research at Jornada and to provide spatial and temporal data on the physical and biological state of the rangeland. The objectives of JORNEX were to develop remote sensing techniques to assess rangeland conditions, to quantify rangeland vegetation and landscape characteristics, and to measure plant/atmosphere interactions. These measurements are being used to quantify physical, hydrological and vegetational responses to changes in components in the water and energy balance at different scales and to evaluate techniques of scaling data. Coupling a mechanistic understanding of hydrological and ecosystem processes is a key to the development of principles for proper range management practices.

In 1997, Jornada was selected as EOS and ASTER validation sites. This paper discusses data collected at Jornada and presents selected examples of results from the JORNEX measurement campaigns.

STUDY AREA

The Jornada Experimental Range (783 km^2) lies 37 km north of Las Cruces, New Mexico on the Jornada del Muerto Plain in the northern part of the Chihuahuan Desert (Fig. 1) (Schmidt, 1979). It is located between the Rio Grande floodplain (elevation 1,186 m) on the west and the crest of the San Andres mountains (2,833 m) on the east. Jornada is part of the larger Jornada del Muerto basin and is typical of the Basin and Range physiographic province of the American Southwest and the Chihuahuan Desert.

The climate of Jornada is characteristic of the northern region of the Chihuahuan desert with abundant sunshine, low relative humidity, wide ranges of daily temperature, and variable precipitation both temporally and spatially. The average monthly maximum temperature ranges from 13°C in January to 36°C in June. The frost-free period averages 200 days, but the effective growing season, especially for perennial grasses, is limited to the summer months. Precipitation, which averages 241 mm yr^{-1}, mainly occurs as localized thunderstorms during July, August, and September. Droughts (<75% of average annual precipitation) have occurred in 18 years between 1915–1995. Potential evaporation is approximately 10 times the average precipitation.

Jornada is on the La Mesa geomorphic surface of middle Pleistocene age (>400,000 YBP). The ancestral Rio Grande River deposited sediments on this plain. Soil development was strongly influenced by topographic position, parent material, and climatic fluctuations during the Quaternary (Gile et al., 1981). Wind in this region commonly modifies these gently sloping surfaces to form coppice dunes. Most dunes are less than 4 m in height and 12 m in diameter and are less than 100 years old (Gile, 1966; Gile and Grossman, 1979). The study sites for the JORNEX, PROVE, EOS, and ASTER are located on Typic Haplargid and Paleargid soils that have developed from alluvium in level basins below the Piedmonts. The soils are loamy to fine loamy and are moderately deep with calcic horizons of varying thicknesses close to the surface. Most of the carbonate content of these soils originated from atmospheric additions. Surface colors are typically light brown and reddish brown, and were called Desert and Red Desert soils in earlier soil classifications (Gile et al., 1981).

Jornada is the most arid North American grassland. The vegetation is characteristic of a subtropical ecosystem in the hot desert biome. Grasses are entirely C4 plants on the plains. The principal grasses include black grama [*Bouteloua eriopoda* (Torr.) Torr.], mesa dropseed [*Sporobolus flexuosus* (Thurb. Ex Vasey) Rydb.], and three awn [*Aristida purpurea* Nutt. and *Aristida pansa* Wooton & Standl.]. Shrubs and suffrutescents are commonly C3 plants and include honey mesquite [*Prosopis glandulosa* Torr.], fourwing saltbush [*Atriplex canescens* (Pursh) Nutt.], broom snakeweed [*Gutierrezia sarothrae* (Pursh) Britton & Rusby], and soaptree yucca [*Yucca elata* (Engelm.) Engelm.]. Seasonal rains trigger flushes of both annual and perennial forbs such as spectaclepod [*Dithyrea wislizenii* Engelm.], desert baileya [*Baileya multiradiata* Harv. & Gray ex. Torr.], and leatherweed croton [*Croton pottsii* (Klotzsch) Muell. Arg.]. More than 490 plant species have been identified on Jornada.

Grass communities of black grama, which once dominated the landscape, have been susceptible to encroachment by shrubs during the last century. Vegetation surveys made in 1858, 1915, 1928, and 1963 show that total area dominated by grass had decreased from 90% in

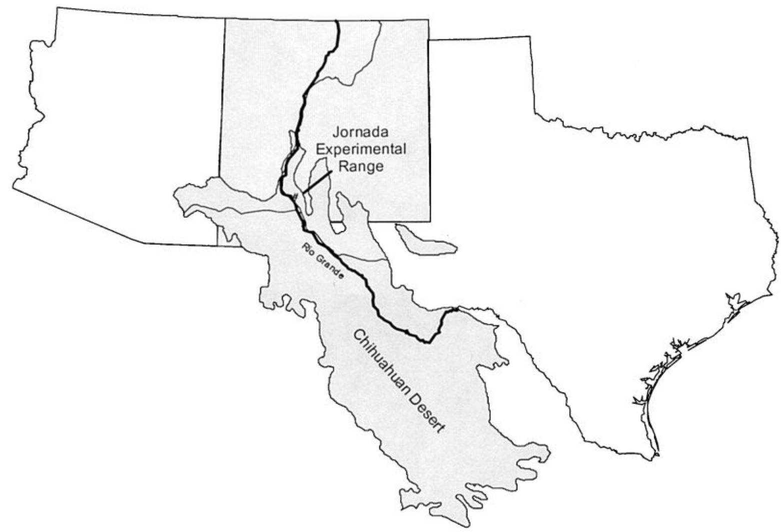


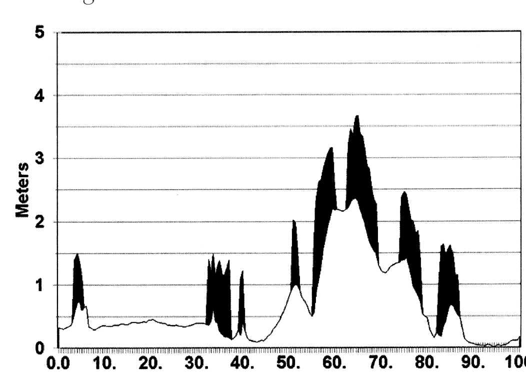
Figure 1. Chihuahuan Desert as delineated by Schmidt (1979). Marked area of about 350,000 km^2 is based on an aridity index of ≤10 (where $I = P$ mm/T°C+10; I=aridity index, P=precipitation in mm, and T=temperature). Region includes scattered mountain masses not classified as desert.

1858 to 23% in 1963 (Buffington and Herbel, 1965). Droughts, grazing by livestock and native fauna, and shrub seed dispersal by livestock have all contributed to the spread of shrubs (Grover and Musick, 1990). Conversion from grass-dominated to shrub-dominated vegetation on these deep coarse texture soils characteristically has resulted in the formation of coppice dunes (Buffington and Herbel, 1965), resulting in increased spatial heterogeneity of critically limited nutrients (especially N) required for plant growth (Schlesinger and Pilmanis, 1998) and increased wind erosion (Gibbens et al., 1983). These changes have significant effects on flux of dust and surface albedo from desert ecosystems, with resulting strong effects on global climates (Schlesinger et al., 1990). The JORNEX study area encompasses remnant black grama semiarid grassland, a honey mesquite-dominated shrub coppice duneland that developed in the past 80 years, and an ecotone between these two areas.

Not only has the vegetation cover changed, but also the surface landscape has changed with the development of coppice dunes. The coppice dunes have more relative relief and vegetation is concentrated on the tops of dunes. A 100-m engineering survey cross section through the coppice dunes shows the dune topography and mesquite vegetation on the dunes (Fig. 2). Dunes in this 100-m transect range from 0.32 m to 2.20 m high with an average dune height of 0.84 m. The mesquite is clumped on the tops of the dunes, and when the vegetation height is added to the dune height, the height range is from 1.13 m to 3.51 m, with an average total dune plus mesquite height of 1.80 m. Landscape roughness, wind flow characteristics, albedo, and nutrient distributions are considerably changed when compared to the desert grassland site (Schlesinger and Pilmanis, 1998).

A Thematic Mapper (TM) image of June 1995 (Fig. 3) shows the western boundary of Jornada, the PROVE sites, the Rio Grande River, and the general vegetation patterns. Three specific sites in Jornada were chosen for intensive studies for the JORNEX. JORNEX sites were selected to represent grass (Figs. 4 and 5), grass-shrub ecotone (transition) (Figs. 6 and 7), and shrub (mesquite) (Figs. 8 and 9) ecosystems. The grass and transition sites were part of the Grassland PROVE study area in May 1997. The grass site is on a level area where black grama dominates and encompasses an enclosure where grazing has been excluded since 1969. The transition site has vegetation components of both the grass and shrub sites. Dunes are developing at the transition site but are usually less than 1 m in height. Honey mesquite on coppice dunes dominates the shrub site. Bare soil with almost no vegetation dominates the areas between these coppice dunes. The sites will be referred to as grass, transition, and shrub in this paper. Data in support of the JORNEX experiments have been collected at these sites in May 1995, September 1995, February 1996, May 1996, September 1996, May 1997, September 1997, April 1998, September 1998, May 1999, and September 1999 (Table 1).

Figure 2. Surveyed cross section (100 m) through coppice dunes at the shrub site with heights of vegetation superimposed. Ground is shown as light and vegetation as dark.



DATA COLLECTION[1]

Long-Term Jornada Data Collection[2]

A wide range of data sets on climate, hydrology, soils, plants, and animals are maintained by the Jornada Experimental Range and the Jornada LTER data management programs. Data sets with unrestricted access include climate, plant, and soil data. Climate data sets include climatological data, dryfall and wetfall deposition chemistry, pan evaporation, and precipitation. Plant data sets include summaries of annual and seasonal aboveground net primary production (g m^{-2} $year^{-1}$) for each of the five major plant community types in the Jornada basin: mesquite, creosote [*Larrea tridentata* (Sesse & Moc. ex DC.) Coville]-dominated shrublands; tarbush (*Flourensia cernua* DC.)-dominated shrublands; black grama upland grasslands; and tobosa [*Hilaria mutica* (Buckley) Benth.]-dominated playa grasslands. Soil data sets include N volatilized as ammonia, monthly soil water content, and soil surface erosion since 1935. Data are georeferenced and supported by typical ancillary data layers (elevation, soils, geology, hydrology and general physical features, livestock grazing history, and vegetation types in 1915, 1927, and 1998) characteristic of a geographic information system.

Restricted data sets require release authorization by the responsible investigator.[3] Restricted animal data sets include arthropod and small mammal inventory data. Restricted hydrology data sets include surface runoff, water chemistry, sediment concentration, and percent organic carbon. Restricted soil data sets include mass flux data and threshold friction velocity data. Restricted plant data sets include basal cover by species at permanently marked locations established in 1915, and species cover changes since 1939 in response to rabbit exclusion and shrub removal. Data management and access follow standardized LTER protocols.

JORNEX Data Collection[4]

Ground Data

Vegetation measurements were made by species, cover, height, and standing litter along 150-m permanent transects established at each site using vertical line point intercept techniques (Canfield, 1941; Eberhart, 1978). Along each 150-m transect, three 30-m segments were measured for vertical line point intercepts at 10-cm intervals for a total of 900 point measurements per transect. At 1-m intervals along these 150-m transects, a survey noting the presence or absence and form of vegetation was conducted.

Surface landscape (soil and vegetation) temperatures were measured with an Everest thermal infrared radiometer (IRT) with a band pass of approximately 8 μm to 13 μm during each JORNEX campaign at the grass and shrub sites. Temperatures were measured at transition site for selected campaigns. Temperature measurements were collected at 5-m intervals over preestablished grid patterns of 25 m^2 or 30 m^2.

Radiance measurements were made using an Exotech four-band radiometer with filters corresponding to the first four bands of the Landsat TM. A backpack-type apparatus (called a "yoke") equipped with an Exotech and IRT was used to make measurements at 5-m intervals between center points of a grid of 16 30-m squares at the grass site in September 1995, May 1996, and September 1996. The yoke-mounted Exotech looked nadir, and a second (stationary) Exotech was mounted near the site looking upward. A standard reference panel was also measured.

Radiometric plant canopy and soil reflectance measurements were made with a Barnes modular multispectral radiometer at the grass, transition, and shrub sites in September 1995 and September 1996 (Everitt et al., 1997). Reflectance measurements consisted of 15 randomly selected plant species and soil. Measurements were made in the green (0.52–0.60 μm), red (0.63–0.699 μm), and near-infrared (0.76–0.90 μm) spectral bands with a 15° field-of-view sensor placed 1 to 1.5 m above each canopy/soil surface. Reflectance measurements were made between 1100 and 1400 hr under sunny conditions. Radiometric measurements were converted to reflectance for a common solar irradiance reference condition (Richardson, 1981).

Radiometric plant canopy and soil reflectance measurements were also made using an Analytical Spectral Devices (ASD) full-range (0.35–2.5 μm) spectroradiometer at 5-m intervals along the 150-m vegetation transects and at the temperature measurement grids at the grass, shrub, and transition in May 1997, September 1997, April 1998, September 1998, May 1999, and September 1999. Separate radiometric measurements were made for the dominant plant species, litter, and bare soil (10 measurements of each selected type) at each site. A standard reference panel was also measured.

Leaf area index (LAI) measurements were made with a LICOR LAI-2000 instrument along the 150-m vegetation transects. Measurements were made at 1-m

[1] Trade names are included for the benefit of the reader and do not imply an endorsement of or a preference for the product listed by the U.S. Department of Agriculture.

[2] Information on access to all long-term ARS Jornada Experimental Range and LTER data sets can be found on the Jornada home page at HTTP://jornada.nmsu.edu. Inquiries regarding data and their availability should be directed to the Jornada LTER office through the Jornada home page.

[3] Information on access to restricted ARS Jornada Experimental Range and LTER data sets can be found on the Jornada Home page at HTTP://jornada.nmsu.edu. Inquiries regarding data and their availability can be directed to responsible investigator and the Jornada LTER office through the Jornada home page.

[4] Data collected in support of the JORNEX Experiments are complied at the USDA ARS Hydrology Laboratory at Beltsville, MD 20705.

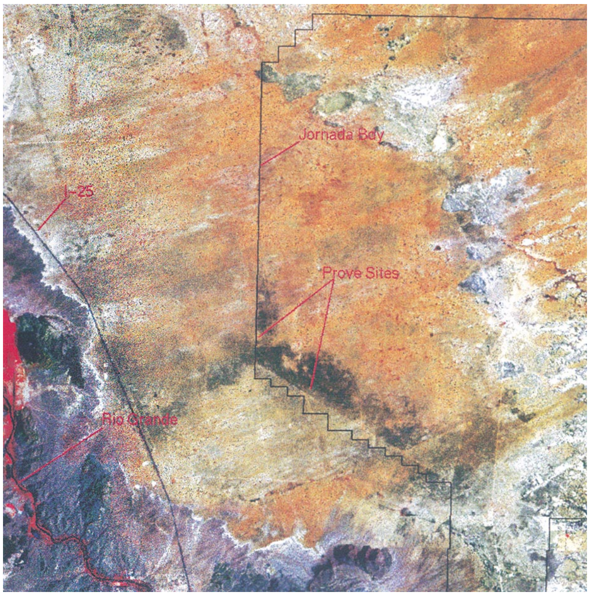


Figure 3. Landsat TM image (bands 4, 3, and 2) June 5, 1995 showing the Jornada basin with west boundary of the Jornada Experimental Range, Rio Grande river, and the PROVE study sites.

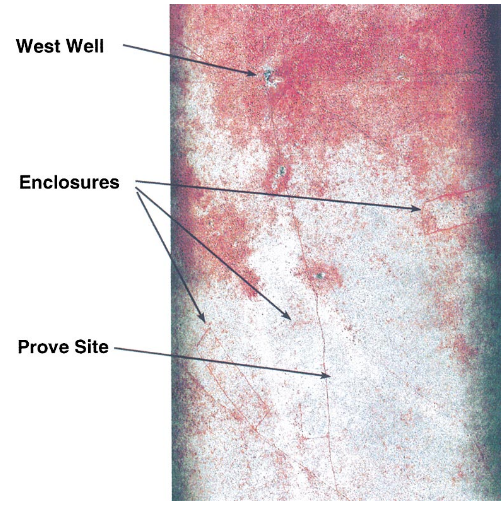


Figure 5. TIMS image of grass site at 4-m resolution for June 19, 1997). Channels at 10.6 μm, 9.0 μm, and 8.4 μm were used in the RBG channels, respectively.

intervals for three 30-m sections of the 150-m transects at the grass, shrub, and transition sites for all campaigns.

Surface energy fluxes were monitored continuously from May 1995 to January 1997 using the Bowen ratio-energy balance method and periodically (during intensive field campaigns) with eddy correlation systems at the grass, transition, and shrub sites. Net radiation, air and soil temperature, vapor pressure differences, wind speed and directions, and atmospheric pressure were measured and recorded every 30 seconds, with 15-min and 30-min means recorded on a Campbell Scientific CR10 data logger. A site with a 25-m tower at the transition site and a site with a 10-m tower at the shrub site was monitored during the September 1996 campaign. Eddy correlation instruments were positioned at two heights on the towers. One-dimensional sonic and krypton hygrometer sensors were deployed at 3 m and 5 m on the 10-m tower at the shrub site and at 5 m and 25 m on the 25-m tower at the transition site in 1996. An IRT pointed at a 45° angle was used to monitor surface temperature from the top of a 10-m (shrub site) and 25-m (transition site) tower (Kustas et al., 1998; Ritchie et al., 1998).

Aircraft Data

An ARS aircraft stationed at Weslaco, Texas was used to collect airborne spectral (Exotech), thermal, three-band multispectral video and laser altimeter data. Airborne campaigns for JORNEX were scheduled to make measurements for 3 days centered on the date (Table 1) of an overpass of Landsat-5. Aircraft flight lines crossed the three sites where ground measurement were being made.

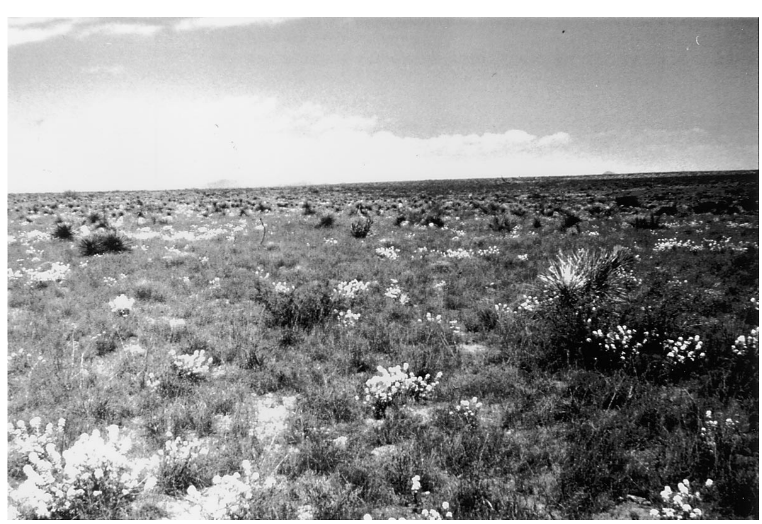


Figure 4. Ground level photograph of the grass site at the Jornada Experimental Range.

Figure 6. Ground-level photograph of transition site at the Jornada Experimental Range.

Global Positioning System (GPS) navigation (Trimble Transpack II) was integrated with the systems on the airplane to measure the flight direction (bearing), altitude, time, ground speed, and latitude and longitude coordinates. GPS data were collected by a computer. A video insertion system (Compos model LP-701) annotated the GPS data directly to all video systems. Data collections from all instruments on the aircraft were synchronized to the GPS time.

Video imagery was obtained with a three-camera multispectral digital video imaging system (Everitt et al., 1995). The three cameras are visible near-infrared (0.4–1.1 μm) equipped with yellow-green (0.555–0.565 μm), red (0.623–0.635 μm), and near-infrared (0.845–0.857 μm) filters. A computer with an RGB image-grabbing board (640×480 pixel resolution) captured digital images. In addition, the signals of cameras were also subjected to a color encoder that provided an analog color infrared composite, which was collected continuously on the S-VHS recorder. Imagery was acquired at altitudes between 300 m and 3,000 m AGL between 1000 and 1400 hours local time under clear conditions during each campaign.

Airborne measurements of surface temperature were made with an Everest thermal sensor with a 15° field of view. An Exotech four-band radiometer was used to make radiance measurements corresponding to the first four bands of the Landsat TM. The IRT and Exotech were mounted looking nadir. A second Exotech was placed on the ground looking upward to measure irradiance. A color video camera, borehole-sighted with the IRT and Exotech, recorded color images of the flight line. Each video frame was annotated with GPS data. Airborne data from these instruments were collected for two north–south flight lines that passed over the grass, shrub, and transition sites. Each flight line was approximately 10-km long. Flights were made at altitudes of approximately 125 m and 300 m AGL with passes in opposite direction at each altitude on each flight line. Flights were made on the three days centered on a Landsat TM overpass (Table 1). Morning (0915–1015 hours local time) and early afternoon (1230–1430 hours) flights were made on each day, weather permitting.

Laser profile altimetry measurements were made on four north–south and four east–west flight lines designed to cross the three study sites. Laser altimetry flights were made in May 1995, September 1995, February 1996, and May 1997. Flights were made at an altitude of approximately 200 m AGL. The altimeter was a pulsed gallium-arsenide diode laser, transmitting and receiving 4,000 pulses per second at a wavelength of 0.904 μm. The field of view of the laser was 0.6 milliradians, which gives a "footprint" on the ground that was approximately 0.06% of the altitude. The timing electronics of the laser receiver allowed a vertical resolution of 5 cm for each measurement. Digital data (distance from the airplane to the landscape surface) from the laser receiver along with data from a gyroscope and an accelerometer mounted on the base of the laser platform were recorded with a portable computer. A video camera, borehole-sighted with the laser, recorded an image of the flight line. Sixty video frames were recorded per second, annotated with consecutive numbers, clock time, and GPS data. Landscape surface elevation was calculated for each laser measurement based on known ground elevations along a laser transect (Ritchie, 1996).

A scanning laser altimeter was flown over the sites in February 1998 by Aerotec of Bessemer, Alabama. An airborne thermal scanner was flown over the sites in September 1997 by Agrometrics of Tucson, Arizona. An aircraft under contract to NASA and DOE flew the two north–south flight lines on June 19, 1997, September 30, 1997, and June 1999. The aircraft carried the Thermal Infrared Multispectral Scanner (TIMS) and a 12-channel Daedelus multispectral scanner [Thematic Mapper Simulator (TMS)] with bands from the visible to the thermal infrared. TIMS collected data in six channels in the 0.8-μm to 12-μm thermal band (Schmugge et al. 1998; Pallu-

Figure 7. TMS image of transition site at 4-m resolution for June 19, 1997. Near-infrared, red, and green channels were used in the RBG, respectively.

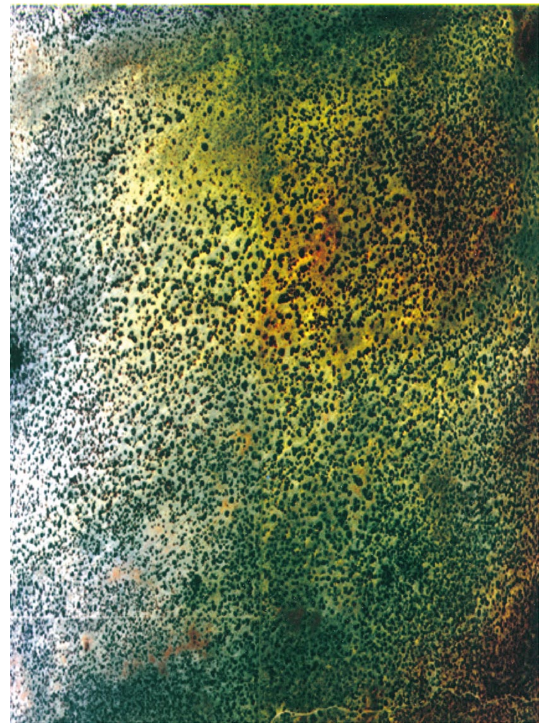


Figure 9. TMS image of shrub site at 4-m resolution for June 19, 1997. Near-infrared, red, and green channels were used in the RBG, respectively.

Figure 8. Ground-level photograph of mesquite-dominated coppice dune site at the Jornada Experimental Range.

Table 1. Dates of Data Collection for the JORNEX Experimental Campaigns

Date	*Sky Conditions*
May 19–21, 1995	Partly cloudy
September 24–26, 1995	Clear
February 15–17, 1996	Clear
May 5–7, 1996	Clear
September 10–12, 1996	Heavy rains on September 11, 1996
May 24–26, 1997	Partly cloudy
September 29–30, 1997	Partly cloudy
April 25–27, 1998	Partly cloudy
September 16–18, 1998	Clear
May 30–31, 1999	Partly cloudy
September 27–28, 1999	Clear

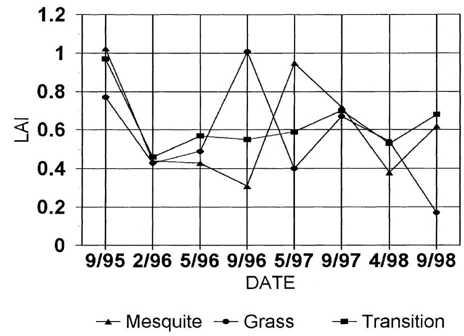


Figure 10. Spatial LAI measurement made using a LICOR LAI-2000 for the grass, transition, and shrub sites. Measurement made at 1-m intervals along vegetation survey transects.

coni and Meeks, 1985). Both instruments have 2.5 milliradian IFOV and approximately 40° swaths. For the June 1997 flight, the altitudes were 1,500 m and 5,000 m AGL, affording 4-m and 12.5-m resolution data, respectively. On the September 1997 flight, the altitudes were 750 m and 5,000 m AGL, producing 2-m and 12.5-m resolution data. A flight of the MASTER (MODIS/ASTER Airborne Simulator) instrument was made on September 17, 1998 and June 1, 1999. The MASTER collected data in 50 channels in the 0.4-μm to 13-μm range. NASA provided flights of the AVIRIS (Airborne Visible InfraRed Imaging Spectrometer) instrument on May 27, 1997, May 15, 1998, and September 13, 1998.

Satellite Data

Landsat TM scenes were acquired for the cloud-free days during the campaigns of June 1995, September 1995, February 1996, May 1996, and September 1998 to be used for scaling ground and aircraft measurements to larger areas. AVHRR and GOES data were also available to make inferences about larger areas and to assess the value of different resolution data.

RESULTS

Vegetation measurements at the three study areas in 1997 (Table 2) show the present plant composition. To illustrate the dynamic nature of these areas, the vegetation compositions as estimated by USDA scientists (unpublished data) in 1915 for each of these areas are also presented in Table 2. Detailed vegetation surveys were conducted for the entire Jornada Range in 1915, and their georeferenced records allow direct comparison to current study locations. The grassland site has maintained black grama dominance since 1915, though other perennial grasses are now more evident. The shrub site completed conversion to mesquite-dominated coppice dunes during the past 82 years. The transition site exhibits transitional vegetation dynamics characteristic of the northern Chihuahuan Desert. In 1915 three awn, a short-lived perennial grass species, dominated the transition study area. Other Jornada studies have documented the rapid establishment of mesquite into sandy upland sites once black grama was lost from the plant community

Table 2. Vegetation composition (%) of Study Sites in the Jornada basin Measured in 1997 (Vertical Line Point Intercept Transect Method) and in 1915 (Ocular Reconnaissance Method)

	Grass		*Transition*		*Shrub*	
	1997	*1915*	*1997*	*1915*	*1997*	*1915*
Perennial grasses						
Black grama	58	75	1	13	0	15
Red three awn	3	0	1	54	0	35
Mesa dropseed	11	5	0	13	0	5
Other	0	0	1	0	0	0
Total	72	80	3	85	0	55
Perennial and annual forbs	14	5	26	10	1	35
Perennial shrubs and suffrutescents						
Mesquite	trace	5	60	0	99	4
Yucca	3	5	7	5	0	0
Snakeweed	11	5	4	0	trace	5
Other	0	0	0	0	0	1
Total	14	15	71	5	99	10

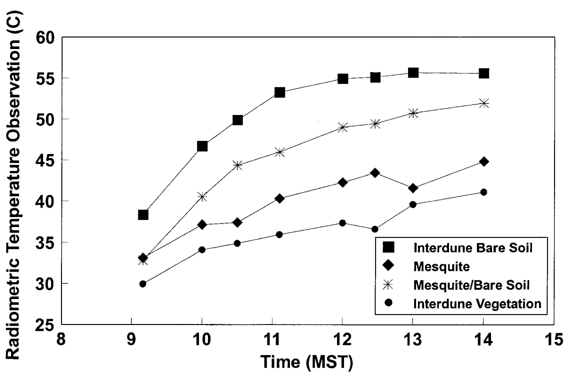


Figure 11. Handheld radiometric temperature observations at the shrub site of vegetation, bare soil and mixtures of bare soil and mesquite (mesquite/bare soil), May 1996.

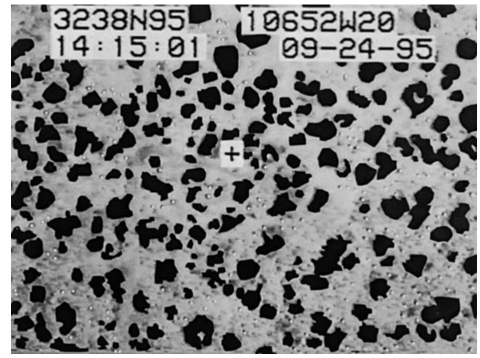


Figure 12. Aerial video imagery near the shrub site modified to highlight mesquite dunes (i.e., dark features). This image was used to calculate the fractional cover.

(Buffington and Herbel, 1965). It is expected that the transition site will undergo further vegetation change to a shrub-dominated site over the next few decades.

Estimates of LAI have been made during all campaigns using the LICOR LAI-2000. Figure 10 shows the LAI measured over the time period. These are spatially based LAI, calculated using all data collected along a 150-m transect including measurements $\geqslant 0$ rather than making LAI measurement under individual plants. These LAI values probably represent trends in the cover over the time period rather than actual LAI values since the LAI-2000 was not designed to estimate LAI under sparse vegetation. September 1995 was the wettest study campaign and had the most visible vegetation cover, and this was reflected in the high LAI found at all sites. The fact that LAI values changed little from the baseline measurements made in February 1996 through September 1996 at the shrub site indicated that only a small amount of green leaf vegetation was present for May and September 1996 and that the mesquite branches/stems were mainly responsible for attenuating radiation. Low LAI values at the grass site in 1998 probably were the result of grazing at the site in the summer of 1998, which had not occurred in previous years. We have no explanation for the large changes in LAI at the grass and shrub sites between September 1996 and May 1997.

Handheld IRT measurements of mesquite, interdune vegetation, bare soil, and mixtures of mesquite and bare soil indicated that temperature differences between vegetation and bare soil can reach 15°C to 20°C (Fig. 11). Similar patterns have been measured at the grass and transition sites between vegetation and bare soils along with large diurnal changes in temperature.

Aerial video imagery modified to contrast the mesquite dunes from the interdune areas indicated fractional cover (f_c)≈0.3 (Fig. 12). The clumped nature of the vegetation was quite apparent, which probably requires modifying LAI values for use in modeling efforts with ΩLAI where Ω is a clumping factor (Chen and Cihlar, 1995). This pattern of clumps was evident in all the aircraft images (Fig. 9) of the shrub site and to some extent at the transition site (Fig. 7). The influence of these large bare area between dunes and their effects on albedo and surface temperature need to be understood to use remotely sensed data (aircraft of satellite) to estimate large-scale evapotranspiration and to address concerns of scaling data.

By weighting the radiances of canopy and soil temperatures from handheld observations with the estimate of f_c, a composite observed temperature [$T_R(\theta)$] at the shrub site was estimated and compared to $T_R(\theta)$ measured from the 10-m tower ($\theta \approx 45°$ with ≈35-m pixel) and from the aircraft with a 30-m to 80-m pixel size depending on aircraft altitude. Differences in $T_R(\theta)$ between the tower and handheld observations gave a root-mean-square error (RMSE) of 0.9°, while for the aircraft, which had higher $T_R(\theta)$ values, RMSE≈3°. Larger differences and higher $T_R(\theta)$ values from aircraft sensors compared to the ground-based observations may be due to a combination of factors that include: (a) nadir observations are primarily influenced by sunlit bare soil and vegetation temperatures; and (b) a bias in the composite temperature estimated with the ground-based measurement is caused by the an overestimate of f_c. A regression equation forced through the origin between the average of north and south viewing $T_R(\theta)$ from the tower and the handheld observations resulted in a slope of 0.99. The high correlation between tower $T_R(\theta)$ and the handheld measurements may indicate that for these sparsely clumped vegetated surfaces, off-nadir observations may provide composite temperatures that include a contribution of shaded as well as sunlit soil and vegetation temperatures. Although off-nadir observations might "see" more vegetation, this effect is probably minor relative to observing shaded temperatures caused by the clumpiness of the vegetation and the microtopography of the dunes.

Spectral measurements from the airborne TIMS sensor for the grass site indicated that there are emissiv-

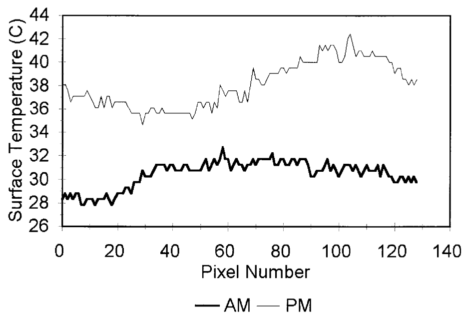


Figure 13. Ground surface temperature measured in the morning (lower line) and afternoon (upper line) from 300 m AGL on October 9, 1997 with an infrared thermometer mounted on an airplane.

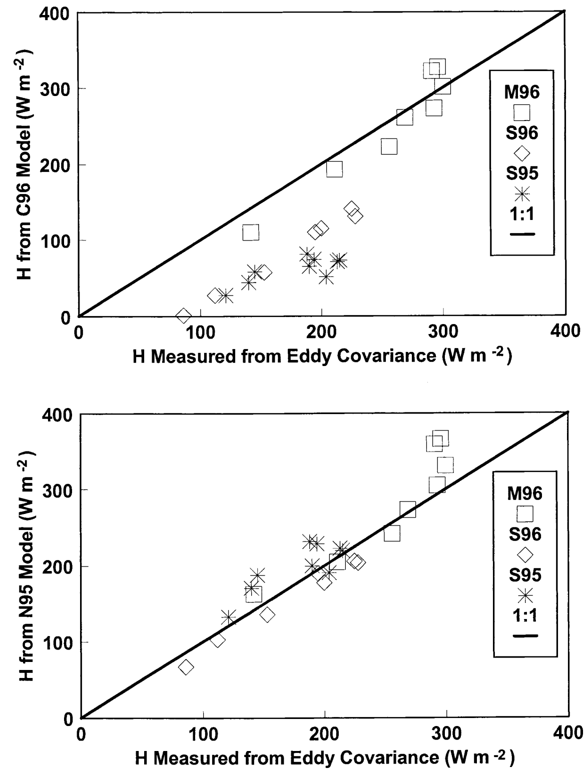


Figure 14. Comparison of H predicted by C96 (Chehbouni et al., 1996) and N95 (Norman et al., 1995) models versus H measured by EC technique for May 1996 (M96), September 1996 (S96), and September 1995 (S95) campaigns.

ity differences over the 8-μm to 13μm spectral range (Fig. 5). Brightness temperatures of the 10.8-μm, 9.3-μm, and 8.5-μm channels were applied to the RGB channels of the display. Thus the redness in Fig. 5 indicates that the 10.8-μm channel had a higher brightness than the shorter wavelength channels. This was a result of the SiO_2 present in the soils. The silicates have a broad reflectance peak in 8-μm to 9.5-μm region that causes a significant decrease in the emissivity (Salisbury and D'Aria, 1992). Calculated emissivities for the 10.8-μm, 9.3-μm, and 8.5-μm channels are 0.97, 0.92, and 0.91 based on laboratory measurements of the emissivity for a sample of the soil from the grass site (Salisbury, private communication). These spectral differences were also observed in field measurements made with a multispectral handheld radiometer. For dead vegetation a temperature of 31°C was observed for all channels, while for bare soil the broadband channel read 36°C, the 10.8-μm channel read 37.2°C, the 9.3-μm channel read 33.1°C, and the 8.5-μm channel read 34.7°C. These measurements were made on September 17, 1998 at about 9 A.M. (MST) and indicated the emissivity variations over the 8-μm to 12-μm window. The differences among the channels would be larger at the time of the TIMS overflight at 12 P.M.

October 9, 1997 morning (10:30 A.M. MDT) and afternoon (1:30 P.M. MDT) measurements along the same transect of radiometric ground surface temperature from a nadir-viewing IRT with a 15° field of view onboard the ARS aircraft showed the daytime increase in temperature (Fig. 13). The aircraft flew at nominal height of 300 m AGL and yielded an IRT sensor footprint diameter of 80 m. These data were georeferenced to allow direct comparison of the surface features causing the spatial and temporal variation in the observations. In both transects the surface temperatures were relatively high due to the sparse vegetation cover and dry soil surface conditions. The transect began over the grass site, passed over a transition area, and ended over a mesquite dune area. Temperatures are in the same range as those measured on the ground the same day.

Remotely sensed radiometric temperature observations were available from weather satellites and provide a unique spatially distributed boundary condition for surface energy balance modeling at regional scales. Recent studies have shown that single-source approaches can lead to large uncertainties in surface flux predictions over heterogeneous surfaces. More reliable results have been obtained using two-source models that consider separately the contributions of soil/substrate and vegetation to the radiometric temperature observation and to the turbulent fluxes and thus accommodate differences between aerodynamic and radiometric temperatures.

Recent efforts in the application of surface energy balance modeling with remotely sensed surface temperatures (Norman et al., 1995; Chehbouni et al., 1996) accommodate differences between radiometric and aerodynamic temperatures. These approaches would be more applicable to heterogeneous surfaces like those at the shrub site. Models developed by Norman et al. (1995) (referred to as N95) and Chehbouni et al. (1996) (referred to as C96) were applied to the data from the shrub site (Kustas et al., 1998) for preliminary assessment of these approaches using data for September

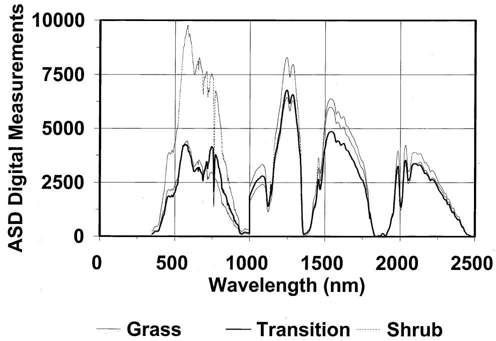


Figure 15. ASD digital measurements made along the shrub, transition, and grass site vegetation transects in May 1997. Each trace is an average of 10 measurements made at 5-m intervals along the first 50-m in each transect.

1995, May 1996, and September 1996. Comparisons between H [sensible heat flux (W m^{-2})] predicted by C96 and N95 and measurements of H using the eddy covariance (EC) techniques are shown in Fig. 14. The N95 model performed well for all three periods, while C96 underestimated September 1995 and September 1996 periods. The poorer performance with C96 could be due in part to the canopy architecture affecting the model coefficient used in adjusting radiometric temperature values. The N95 model also predicts latent heat (LE). In the case of LE, the N95 model tends to overpredict LE for most of the observations in May 1996 and September 1995. This preliminary study indicates that the accuracy of C96 and N95 model predictions of H and LE fluxes for this ecosystem largely depends on how LAI is defined, and for N95, estimating the appropriate fractional green cover (f_g) or fraction of LAI that is green or actively transpiring. Although remotely sensed vegetation indices (VIs) are related to LAI, VIs are strongly affected by soil background and canopy structure, making these indices difficult to use in desert environments (Anderson et al., 1993). However, approaches to obtain reliable LAI estimates from vegetation index data over arid and semiarid regions are being developed (van Leeuwen et al., 1997).

ASD digital measurements made along the vegetation transects for the grass, transition, and shrub sites are shown in Fig. 15. The data in this figure are an average of 10 ASD digital measurements made at 5-m intervals for the first 50 m of each transect. The grass and transition sites have similar patterns in the visible-near-infrared wavelengths (0.4–1.0-μm), while the shrub site has a much higher digital readings. ASD digital measurements made at wavelengths greater than 1.0 μm are similar for all sites. The higher readings in the visible-near-infrared at the shrub site are probably due to the bare soil along this transect (see Figs. 9 and 12). Large areas of bare soil at the shrub site would increase the albedo of the site. Reduction of total vegetative cover accompanies changes of vegetation from grass to mesquite at Jornada. These changes have significant effects on the albedo and the surface temperatures (Figs. 11 and 13) measured at the different sites.

Laser altimeter-measured transects at the grass, shrub, and transition sites show differences in surface topography and roughness at the sites (Pachepsky et al., 1997). The grass site is relatively uniform in surface roughness with an occasional shrub or taller vegetation. Laser data from the shrub site has evidence of dunes present on the underlying landscape with vegetation on top of the dunes. The transition site shows evidence of both the grass and shrub sites with the beginning of what appears to be small dunes. Fractional vegetation cover and vegetation heights measured from the laser altimeter were comparable to the measurement made on the ground.

Fractal analysis of laser altimetry data from the grass, shrub, and transition sites (four transects at each site for February, May, and September) supports the possibility of distinguishing between these landscapes using fractal properties of the laser data to quantify landscape roughness (Pachepsky and Ritchie, 1998). The fractal dimensions tend to increase in a sequence from grass to transition to shrub sites in this range of scales. Results show that the fractal dimension is subject to seasonal changes and spatial variation in any specific range of scales. However, the pattern of the dependence of fractal dimensions on scale is specific to the land cover. A fractal technique for estimating cover type from laser altimeter data represents a new technique to quantify landscape roughness (Pachepsky et al., 1997; Pachepsky and Ritchie, 1998).

Menenti and Ritchie (1994) estimated effective aerodynamic roughness at the shrub using high-resolution laser altimeter measurements of land surface roughness. Investigations by De Vries et al. (1997) show that estimations of the effective aerodynamic roughness of the complex terrain consisting of coppice dunes with bare interdunal areas at Jornada are plausible using simple terrain features computed from high-resolution laser altimeter data. The estimates of aerodynamic roughness compare well with estimates made using wind profiles measured at the site (De Vries et al., 1997). The availability of high-resolution altimeter data of the land surface would make it possible to estimate aerodynamic roughness for other landscapes where wind flow data are not available.

CONCLUSIONS

The ARS Jornada Experimental Range is well suited for EOS validation because of its long history of ground-based studies and ongoing repetitive remote sensing missions. The ground measurements associated with the rangeland research began in 1912 and have intensified since 1981 when Jornada was designated an LTER site.

Twice-a-year remote sensing missions were initiated in 1995 and continue through the present. The remote sensing measurements are being used to establish areal evapotranspiration, rangeland conditions, vegetation change, and the effects of scale. The ground and remote sensing data supported the intensive PROVE campaign. The extensive logistical support available at Jornada is a key component of successful field programs such as JORNEX and PROVE.

The authors express appreciation to the USDA-ARS Integrated Farming and Natural Resources Unit, Subtropical Agricultural Research Laboratory, Weslaco, TX for the use of their Aerocommander and Twin Cessna as platforms for flying the instruments. Special appreciation goes to M. R. Davis, pilot, USDA-ARS, Weslaco, TX, who flew the airplanes and to Dr. Frank Schiebe, who designed systems and aided in the collection of the airborne radiation and thermal data. Sincere appreciation is due to the staffs of the USDA-ARS Jornada Experimental Range, Las Cruces, NM; USDA-ARS Hydrology Laboratory, Beltsville, MD; USDA-ARS Integrated Farming and Natural Resources Unit, Subtropical Agricultural Research Laboratory, Weslaco, TX; USDA-ARS National Tilth Laboratory, Ames, IA; and the USDA-ARS Grazingland Research Laboratory, El Reno, OK, who provided logistical and ground support before, during, and after the airborne campaigns. Support for the TIMS, TMS, and MASTER flights was provided by the ASTER project of NASA's Earth Observing Satellite program. Thanks also goes to the Hydrological Sciences Branch at NASA Goddard Space Flight Center for the use of their ASD instrument for ground spectral measurements.

REFERENCES

Anderson, G. L., Hanson, J. D., and Haas, R. H. (1993), Evaluating Landsat Thematic Mapper derived vegetation indices for estimating above-ground biomass on semiarid rangelands. *Remote Sens. Environ.* 45:165–175.

Ares, F. N. (1974), *The Jornada Experimental Range: An Epoch in an Era of Southwestern Range Management.* Range Monograph No. 1, Society for Range Management, Denver, CO.

Buffington, L. C., and Herbel, C. H. (1965), Vegetational changes on a semidesert grassland range from 1853 to 1963. *Ecol. Monographs* 35:139–164.

Canfield, R. H. (1941), Application of the line intercept method in sampling range vegetation. *J. Forestry* 39:388–394.

Chehbouni, A., Lo Seen, D., Njoko, E. G., and Monteney, B. M. (1996), Examination of the difference between radiative and aerodynamic surface temperatures over sparsely vegetated surfaces. *Remote Sens. Environ.* 58:177–186.

Chen, J. M., and Cihlar, J. (1995), Quantifying the effect of canopy architecture on optical measurements of leaf area index using two gap size methods. *IEEE Trans. Geosci. Remote Sens.* 33:777–787.

De Vries, A. C., Ritchie, J. C., Menenti, M., and Kustas, W. P. (1997), Aerodynamic roughness estimated from surface features for a coppice dune area using laser altimeter data. In *12th Symposium on Boundary Layers and Turbulence,* Vol. 12, pp. 289–290.

Eberhart, L. L. (1978), Transect methods of population studies. *J. Wildlife Manag.* 42:–31.

Everitt, J. H., Alaniz, M. A., Davis, M. R., Escobar, D. E., Havstad, K. M., and Ritchie, J. C. (1997), Light reflectance characteristics and video remote sensing of two range sites on the Jornada Experimental Range. In *ASPRS 16th Biennial Workshop on Videography and Color Photography in Resource Assessment,* pp. 485–495.

Everitt, J. H., Ecobar, D. E., Cavazos, I., Noriega, J. R., and Davis, M. R. (1995), A three-camera multispectral digital video imaging system. *Remote Sens. Environ.* 54:333–337.

Food and Agricultural Organization (FAO) (1982), *Production Yearbook.* United Nations FAO Statistics Series No. 47. Rome, Italy.

Gibbens, R. F., Tromble, J. M., Hennessey, J. T., and Cardenas, M. (1983), Soil movement in mesquite duneslands and former grasslands of southern New Mexico from 1933 to 1980. *J. Range Manag.* 36:145–148.

Gile, L. H. (1966), Coppice dunes and the Rotura soil. *Soil Sci. Soc. Amer. Proc.* 30:657–660.

Gile, L. H., and Grossman, R. B. (1979), *The Desert Project Soil Monograph.* USDA Soil Conservation Service Document No. PB 80–135304, National Technical Information Service, Springfield, VA.

Gile, L. H., Hawley, J. W., and Grossman, R. B. (1981), *Soils and Geomorphology in the Basin and Range Area of Southern New Mexico—Guidebook to the Desert Project.* Memoir 36, NM Bureau of Mines and Mineral Resources, Socorro, NM.

Grover, A. C., and Musick, H. B. (1990), Shrubland encroachment in southern New Mexico, U.S.A.: An analysis of desertification process in the American southwest. *Climate Change* 17:305–330.

Havstad, K., and Schlesinger, W. (1996), Reflections on a century of rangeland research in the Jornada Basin of New Mexico. In *Proceedings Shrubland Ecosystem Dynamics in a Changing Environment* (J. R. Barrow, E. D. McArthur, R. E. Sosebee, and R. J. Tausch, Eds.), USDA Forest Service General Technical Report INT-GTR-338, pp. 10–15.

Holechek, J. L., Pieper, R. D. and Herbel, C. H. (1998), *Range Management Principles and Practices.* 3d ed. Prentice Hall, New Jersey.

Kustas, W. P., Prueger, J. H., Ramalingham, K., Schmugge, T. J., Rango, A., Ritchie, J. C., Hipps, L. E., and Hatfield, J. L. (1998), Utility of radiometric temperatures for surface energy flux estimation of a heterogeneous desert ecosystem. Preprint Volume of *American Meteorological Society Special Symposium* on Hydrology, Phoenix, AZ, pp. 67–72.

Menenti, M., and Ritchie, J. C. (1994), Estimation of effective aerodynamic roughness of Walnut Gulch watershed with laser altimeter measurements. *Water Resourc. Res.* 30(5): 1329–1337.

Norman, J. M., Kustas, W. P., and Humes, K. S. (1995), A two-source approach for estimating soil and vegetation energy fluxes from observations of directional radiometric surface temperature. *Agric. For. Meteorol.* 77:263–293.

Pachepsky, Y. A., and Ritchie, J. C. (1998), Seasonal changes in fractal landscape surface roughness estimated from airborne laser altimetry data. *Int. J. Remote Sens.* 19(13):2509–2516.

Pachepsky, Y. A., Ritchie, J. C., and Gimenez, D. (1997), Fractal modeling of airborne laser altimetry data. *Remote Sens. Environ.* 61:150–161.

Palluconi, F. D., and Meeks, G. R. (1985), *Thermal Infrared Multispectral Scanner (TIMS): An investigator's guide to TIMS data.* Jet Propulsion Laboratory Publ. 85–32.

Richardson, A. J. (1981), Measurement of reflectance factors under daily and intermittent irradiance variations. *Appl. Opt.* 20:1336–1340.

Ritchie, J. C. (1996) Remote sensing applications to hydrology: Airborne laser altimeters. *Hydrol. Sci. J.* 41(4):625–636

Ritchie, J. C., Rango, A., Kustas, W. P., Schmugge, T. J., Havstad, K. M., Everitt, J. H., Hipps, L. E., and Ramalingham, K. (1998), JORNEX: A remote sensing campaign to study plant community response to hydrologic fluxes in desert grasslands. In *Rangeland Management and Water Resources* (D. F. Potts, Ed.), American Water Resources Society, Herdon, VA, pp. 65–74.

Salisbury, J. W., and D'Aria, D. M. (1992), Emissivity of terrestrial materials in the 8–14 μm atmospheric window. *Remote Sens. Environ.* 42:83–106.

Schlesinger, W. H., and Pilmanis, A. M. (1998), Plant-soil interactions in deserts. *Biogeochem.* 42:169–187.

Schlesinger, W. H., Reynolds, J. F., Cunningham, G. L., Huenneke, L. F., Jarrell, W. M., Virginia, R. A., and Whitford, W. G. (1990), Biological feedbacks in global desertification. *Sci.* 247:1043–1048.

Schmidt, R. H. (1979), A climatic delineation of the "real" Chihuahuan Desert region. *J. Arid Environ.* 2:243–250.

Schmugge, T. J., Hook, S. J., and Coll, C. (1998), Recovering surface temperature and emissivity from thermal infrared multispectral data. *Remote Sens. Environ.* 65:121–131.

van Leeuwen, W. J. D., Huete, A. R., Walthall, C. L., Prince, S. D., Begue, A., and Roujan, J. L. (1997), Deconvolution of remotely sensed spectral mixtures for retrieval of LAI, fAPAR and soil brightness. *J. Hydrol.* 188–189:697–724.