MEASURING THE EFFECT OF OVERGRAZING IN THE SONORAN DESERT

NEVIN A. BRYANT[1], LEE F. JOHNSON[1], ANTHONY J. BRAZEL[2], ROBERT C. BALLING[2], CHARLES F. HUTCHINSON[3], and LOUISA R. BECK[3]
[1] *Jet Propulsion Laboratory, California Institute of Technology, Pasadena CA, 91109, U.S.A.*
[2] *Arizona State University/Laboratory of Climatology, Tempe AZ, 85287-1508, U.S.A.*
[3] *University of Arizona/Office of Arid Lands Studies, Tucson AZ, 85719-4896, U.S.A.*

Abstract. Long term overgrazing in Mexico has caused a sharp discontinuity in vegetative cover along the international border in the semi-arid Sonoran Desert. The United States side, protected from overgrazing by the Taylor Act since 1934, exhibits longer, more plentiful grasses and less bare soil than adjoining Mexican lands. Satellite- and ground-based datasets were used in a multi-scale examination of the differential radiative and reflective characteristics of the two regimes. The more exposed Mexican landscape dries more rapidly than the United States following summer convective precipitation. After about three days, depletion of soil moisture evokes a period of higher surface and air temperatures in Mexico. Good correspondence was found between remote and *in situ* measures of surface temperature and biomass.

Introduction

The Problem

Approximately 35% of the earth's land surface is characterized as arid to semi-arid, based either on vegetation or climate (White, 1956). In these regions, surface moisture and thermal energy are in a delicate balance; vegetative cover change resulting from overgrazing is recognized as an important contributor to potential changes in local and regional climate. The debate regarding the impact of vegetation changes on local and regional climates in desert regions has received considerable attention in the literature since the mid-1970s. On the one hand, several investigators have suggested that vegetation removal, often by overgrazing, leads to increased albedo, decreased surface and near-surface temperatures, and decreased convective precipitation (Otterman, 1974; Charney, 1975, Berkofsky, 1976; Ellsaesser *et al.* 1976; Sud and Fennessey, 1982). On the other hand, a variety of theoretical arguments and empirical measurements by other investigators have raised serious questions concerning direct relationships between vegetation, temperature and rainfall patterns in desert areas (Jackson and Idso, 1975; Ripley, 1976; Idso, 1977; Idso and Deardorff, 1978; Wendler and Eaton, 1983; Courel *et al.*, 1984). Many of these investigators have found that a decrease in vegetation cover reduces evapotranspiration thereby evoking an increase in local air temperature. The purpose of

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this research was to clarify the impact of overgrazing on the land surface climatology of a semi-arid grassland.

The low amount of vegetative cover available for thermal inertia contributes to wide diurnal temperature fluctuations and dramatic changes in evaporative cooling after precipitation events in arid and semi-arid regions. Temperature changes over short time periods may have a large-scale forcing effect on regional energy budgets. As such, measurement and monitoring of surface temperatures and hydrologic cycling in arid and semi-arid zones is useful for scientific investigation of desertification processes. In the past, the large areal scale and sporadic weather episodes associated with these regions has made assessment of causal relationships difficult. The growing archive of satellite data, with its timely and synoptic coverage, promises to alleviate this difficulty.

Study Site Characterization

Experiments designed to measure arid land surface variables and their possible effect on climate have been hampered by the inability to establish 'matched pairs' of study sites (Reining, 1979). Ideally, site pairs should be located on either side of a boundary marking profound differences in land surface conditions, usually resulting from differing land management practices, in otherwise comparable environments. The border between the United States and Mexico in the Sonoran Desert presents such a boundary. The border has been marked by a fence since 1920, and the U.S. side has been protected from overgrazing since the Taylor Grazing Act of 1934. Over time, marked differences in land surface parameters have evolved in response to differing land management practices. Bahre and Bradbury (1978) estimated that Mexico has 5% (absolute) higher albedo and 29% more bare soil than adjoining United States lands. The spatial variations found along the border may be viewed as an analog to the temporal changes observed in recent years in other desert areas throughout the world, including the Sahel.

The use of paired sites has been useful for three reasons: (a) differences in soil type, vegetation species composition, topography, and geology are minimized; (b) the close proximity of both sites minimizes meterological differences attributable to time lags in air mass movement; and (c) the close proximity of the sites enables instantaneous assessment of relative differences in satellite sensor measurements without undue concern for absolute calibration and correction. The combination of these three points has made us confident that the significance of any observed differences are not attributable to exogenous variables, but rather associated with precisely observed differences in plant cover and absolute biomass.

A 40 km border swath extending from Nogales to Lochiel was chosen for investigation. In addition, three paired sites along the swath were selected for intensive *in situ* analysis (Figure 1):

(1) an oak-woodland community, located on a series of northeast/southwest-trending ridges west of Nogales;

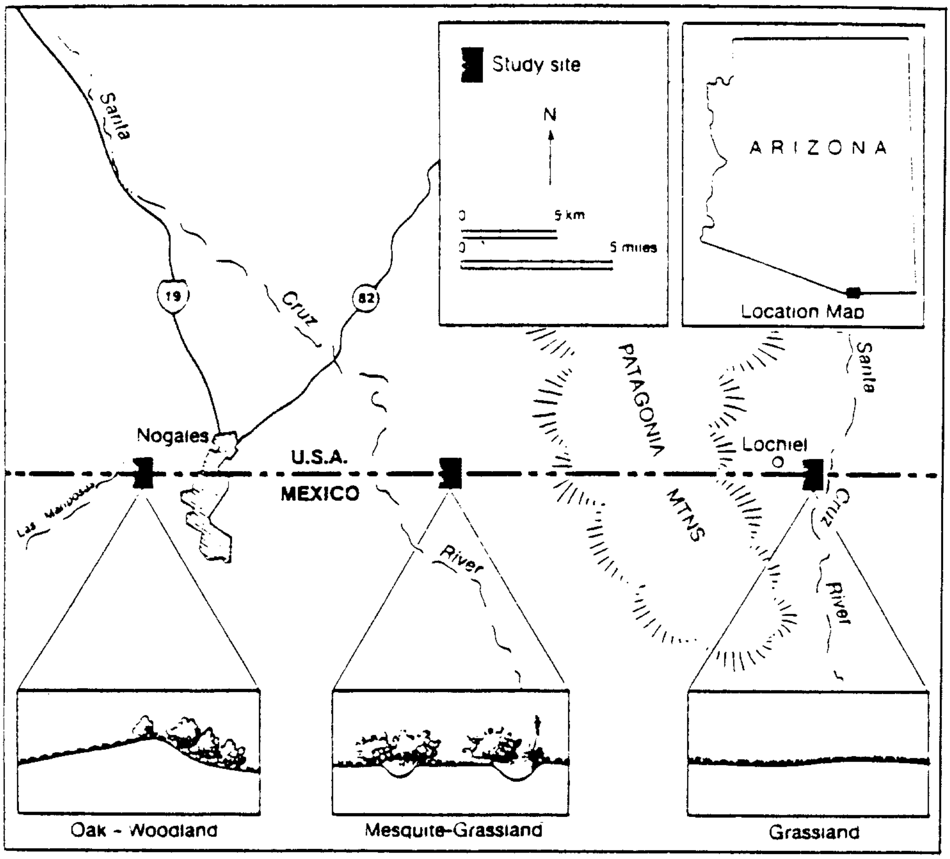

Fig. 1. Study area map.

(2) a topographically dissected mesquite-grassland community near Kino Springs, Arizona; and

(3) a relatively level grassland community, located immediately east of Lochiel, within the San Rafael Valley.

Within each of the three communities, paired sites were identified on either side of the border. These site-pairs were selected on the basis of similar vegetation, topography, soils, and land use.

Nogales

These sites were located just west of the twin border towns of Nogales. This is an area of oak-woodland, with wooded northwest slopes separated by grassland. The dominant species include Grama, *Trichachne californica* (Arizona Cottontop), *Bothriochloa barbinodis* (Cane Bluestem), *Quercus arizonica* (Arizona White Oak), *Q. emoryi* (Emory Oak), *Q. oblongifolia* (Mexican Blue Oak), and *Prosopsis fuliflora* (Mesquite). The average elevation is 1270 m.

Kino Springs

Kino Springs is part of the old Maria Santisima del Carmen land grant, bordered on the east by the Patagonia Mountains and on the west by the Santa Cruz River. The region is a finely-dissected, semi-desert grassland, with several invader species. The dominant species include Mesquite, *Bouteloua eriopoda* (Black Grama), *Eragrostic lehmanniana* (Lehmann Lovegrass), *Aristida* spp. (Three-awn), *Opuntia* spp. (Prickly Pear and Cholla), and *Yucca* spp. The average elevation is 1200 m.

Lochiel

These sites were located near the old Lochiel border crossing, in the southern end of the San Rafael Valley. The dominant species here include Black Grama, Arizona Cottontop, *Bouteloua curtipendula* (Sideoats Grama), *B. hirsuta* (Hairy Grama), *B. rothrockii* (Rothrock Grama), and *Sporabolus wrightii* (Wright Sacaton). The average elevation is 1400 m.

The Lochiel site offered a number of advantages over the other sites. There, the topography and flora were the least complex, thereby facilitating understanding of land surface parameters. The Lochiel site was also superior with regard to vehicular access and landowner cooperation, and was therefore chosen as the primary site for field investigation.

Regional Climate

A decision was made to focus the investigation on summer months based on long-term climate studies (Neilson, 1986, 1987 and Carleton, 1987) which characterized the regional weather circulation and climatic variation for the Sonoran Desert. In late June or early July the northwest corner of the Bermuda High airmass breaks over the Rocky Mountain/Sierra Madre Oriental axis, diverting moisture originating over the Gulf of Mexico away from Texas and into the Sonoran Desert. The occurrence of precipitation episodes in Sonora is triggered by pulses in the subtropical jet stream, mixing moist air masses originating over the eastern Pacific or Gulf of Mexico with thermal lows or occasional cold fronts from the north. During late-August or early-September, the air mass tends to shift back to Texas. The onset of the summer monsoon is quite regular, but the number and spacing of precipitation events varies widely from year to year.

The Tucson weather statistics for the past 120 years were analyzed by Neilson (unpublished research results) to characterize rainfall patterns in the winter season and summer monsoon since 1972, when satellite observations became available. The statistics reveal a bimodal precipitation pattern. Most rainfall occurs in the summer monsoon season; a lesser amount of precipitation is associated with winter frontal systems. It has been possible from this analysis to select specific years of precipitation stress for retrospective analysis, and to characterize the weather for the summer field observations in 1987 and 1988.

There appear to be at least three hierarchical scales of control on convective events during the summer monsoon season. First, there are regional controls of moisture tracks associated with jet streams and general circulation around the Bermuda High which mark the onset of the large-scale precipitation events of interest. Second, and nested within the first, are local, orographic controls on convective activity. The field sites were selected to minimize topographic differences and associated orographic effects. Thirdly, there is a stochastic component to the spatial and temporal distribution of convective events at the spatial scale associated with the size of the event itself. For these reasons, emphasis was placed on (1) monitoring drying episodes subsequent to summer storms producing more than 0.5 inch precipitation within 24 hours, and (2) characterizing aggregate weather over the entire season to determine if there were either positive or negative feedbacks from the land surface to the regional climatology.

Experimental Approach

The investigation consisted of three separate, but related, studies aimed at isolating variables that would explain the land surface climatology of the region. First, U.S. and Mexican weather station data collected over a number of years were examined to discern differences (if any) in temperature and precipitation and their significance. Second, *in situ* monitoring of microclimate and vegetation was conducted to characterize the nature and intensity of land surface interactions for sites on the vigorous U.S. and overgrazed Mexican landscapes. Third, analyses of satellite data (Landsat MSS, AVHRR, GOES, and SMMR) were undertaken to determine both seasonal and short term precipitation event-driven responses.

Supporting Investigation

Historical Weather Data Analysis

Balling (1988) analyzed 30 years of archival records from the U.S. and Mexican weather stations in the study region, and found summertime monthly mean maximum air temperatures significantly warmer in Mexico by about 2.5 °C after accounting for elevation and latitude. Controlling only for elevation, the difference increased to 4 °C. Evidence of warming in arid regions experiencing decreased vegetative cover agrees with classical agricultural meteorology and rangeland management literature (Dregne, 1983, Penman, 1956). No significant difference in precipitation amount was found between the two countries.

Balling (1989) noted that differences in archival daily maximum air temperatures appeared to be more associated with differential evapotranspiration rates than with albedo differences along the U.S./Mexico border. On a seasonal time scale, ΔT (T_{MEX}-$T_{U.S.A.}$) increased during wet years, probably due to a vegetative response on the U.S. side of the border. On a daily scale, ΔT was negligible immediately after rainfall, above average during days 3–7 of drying episodes, and again negligible by day 10.

In Situ Meteorological Data Analysis

For brief periods in the summer of 1987, meteorological stations were established on both sides of the border, 200 m from the fence line near Lochiel, during daylight hours. The sites were situated on a relatively level surface with similar soil types on each side. This preliminary meteorological analysis showed: (a) no direct correlation between albedo differences and surface temperature differences; (b) no direct correlation between net radiation differences and surface temperature differences; and (c) an apparent correlation between surface temperature differences and the time since the last precipitation. Result (c) indicated that the sparser canopied Mexican sites have soils which dry out more quickly after a rain. Continuous monitoring at the site-pair during the summer of 1988 focused on differences arising during drying episodes following major precipitation events.

An eleven-day sample (Table I) illustrates the radiation and energy budgets at these sites throughout summertime pre-monsoon and monsoon conditions. The samples are 31 May 1987 (day 151) prior to greenup, 21–23 July 1988 (203–205) during a drying period following monsoon rains, 9–13 August 1988 (222–226) during a similar drying period, 27 August 1987 (239) after rain, and 22 September 1987 (265) after a long dry spell. The equivalent daily total evapotranspiration (ET) values shown were estimated after techniques employed by Jackson *et al.* (1983), whereby near solar noon instantaneous fluxes were used together with seasonal and latitudinal correction factors to approximate daily totals of ET.

On average, subtle differences between the two sites are evident. Solar absorption was only 10 W m^{-2} less in Mexico, thermal emission was only 10 W m^{-2} greater, and the subsurface heat flux was 30 W m^{-2} higher. Latent heat flux (LE) was 50 W m^{-2} less in Mexico (the equivalent of 0.62 mm/day ET). This represents only a 10% lower ET rate in Mexico.

However, these means mask important short term temporal differences during drying phases of the respective soils, between monsoon rain events. During drying phases which were investigated, Mexico averaged about 34% less ET than on the U.S. Much of this lower ET rate was balanced by higher sensible heat flux, thermal emission, and subsurface heat flux. Only 11% resulted from lower solar absorption rates in Mexico. The lower ET rates in Mexico were associated with air temperatures 2 °K higher, and surface temperatures 7 °K higher, than in the U.S. This finding is in agreement with an error analysis of ET rates at nearby Patagonia, AZ, by Ben-Asher (1981), who showed a 35% reduction in ET by an increased air temperature of 2 °K using a Penman and Priestley Taylor combination method.

TABLE I: Key energy budget parameters derived by field measurement at Lochiel during summers 1987, 1988. All data taken at 1100 local time

Julian Date	151 (1987)	203 (1988)	204 (1988)	205 (1988)	222 (1988)	223 (1988)	224 (1988)	225 (1988)	226 (1988)	239 (1987)	265 (1987)
AD	>30	2	3	5	2	3	4	5	6	1	15
α (US)	0.16	0.17	0.17	0.17	0.14	0.14	0.14	0.14	0.14	0.15	0.13
α (Mex)	0.15	0.18	0.18	0.18	0.16	0.16	0.16	0.16	0.16	0.13	0.17
L ↑ (US)	579.2	531.0	549.2	536.3	505.2	522.6	505.2	520.5	533.8	482.0	479.3
L ↑ (Mex)	576.4	519.8	535.2	585.6	497.5	526.1	524.0	532.4	547.0	476.5	563.8
G (US)	14.6	17.0	19.1	19.0	19.9	19.1	19.2	20.0	18.6	17.5	16.6
G (Mex)	40.5	45.4	51.3	45.5	52.2	49.2	48.2	50.7	47.2	48.4	35.4
H (US)	315.8	186.6	196.0	70.8	102.2	121.8	91.0	125.8	148.6	54.8	61.5
H (Mex)	257.2	135.0	150.9	126.6	84.9	85.3	83.1	115.1	151.8	43.0	233.5
LE (US)	157.1	362.2	422.0	543.5	541.5	495.6	529.3	519.8	453.6	509.7	475.5
LE (Mex)	208.7	387.5	439.4	397.0	515.8	480.5	471.6	468.3	391.0	514.1	173.7
ET (US)	2.20	5.00	5.80	7.40	7.50	6.80	7.30	7.20	6.20	7.00	6.60
ET (Mex)	2.90	5.30	6.00	5.50	7.10	6.50	6.50	6.40	5.40	7.10	2.40
T_{air} (US)	298.5	299.6	300.7	303.9	298.5	299.2	298.5	299.5	299.4	298.2	297.2
T_{air} (Mex)	300.6	300.8	301.3	307.8	298.5	302.0	301.8	301.7	301.1	298.2	299.5
T_{surf} (US)	318.0	311.1	313.7	311.1	307.3	309.9	307.3	309.6	311.6	303.7	303.3
T_{surf} (Mex)	317.6	309.5	311.8	318.8	306.1	310.4	310.1	311.3	313.5	302.7	315.9

AD = Antecedent Dryness (days since $\geqslant$13 mm precip.)
H = Sensible Heat Flux (W m^{-2})
LE = Latent Heat Flux (W m^{-2})
ET = Evapotranspiration (mm day^{-1})

α = albedo (0.3–3.0 μ)
G = Soil Heat Flux (W m^{-2})
L ↑ = Longwave Outgoing (W m^{-2})
T = Temperature (°K)

Balling (1989) noted cooler air temperatures in Mexico than in the U.S. during the first few post-rainfall days. It is hypothesized that lower surface resistance to evaporation from overgrazed lands caused a higher initial ET rate, explaining the slightly cooler temperatures occurring immediately after rainfall in Mexico. After a few days, depletion of soil moisture in Mexico evokes higher surface and air temperatures than are found in the U.S.

This hypothesis was explored with the results of the energy budget comparisons for two drying spells during 1988: 21–24 July (Figure 2) and 9–13 August (Figure 3). For the first 2 days of the three day sequence in July, LE values were 4% to 7% higher in Mexico. However, this difference is not expressed with a high degree of confidence, as estimates can only be resolved within 10% due to instrumentation limitations and methods used. Calculations show that a 5% higher LE rate should evoke a 1.5 °K cooling effect on surface temperature, which approximates the measured differential during the first two days of the drying phase. Clear-sky LE measurements were precluded by cloud cover on day-3 of this sequence. By the fourth day, LE values were 37% lower in Mexico than in the U.S. surface temperatures were higher in Mexico by 7.7 °K and more energy was transferred to the atmosphere as sensible heat flux.

The first day of the August sequence showed a cooler surface temperature in Mexico (by 1.2 °K) accompanied by a lower LE rate, contrary to the July period. A higher rate of subsurface heat flux occurred on this day in Mexico, resulting in slightly less (within detectable limits) LE flux to the atmosphere. The cooler temperature in this case may be attributed to a slightly higher surface albedo in association with a more rapid heat flux to lower soil levels. Subsequent days in the sequence illustrate the effect of rapid drying in Mexico accompanied by higher surface temperatures and substantially lower LE than in the U.S.

Soil moisture block measurements indicated that the U.S. side draws on increased moisture storage at depths below 10 cm in the grassland root zone. The 0–10 cm soil moisture observations showed little difference between the U.S. and Mexico shortly after rainfall, with a large differential developing in the extreme upper levels of the soil as the drying spells progressed (George, 1989).

Similar results were found by Enz *et al.* (1988) in a study of soil moisture retention, energy balance, and radiative surface temperature changes of bare soil and wheat stubble during a drying period. The Enz study showed that LE is greater from bare soil than from wheat stubble because of lessened surface resistance to the movement of water vapor to the atmosphere. As the bare soil dried, LE differences diminished and ultimately resulted in greater LE from the stubble.

Analysis of these two drying spells indicates the complexity of energy partitioning during initial soil drying phases, with the relatively similar end product of warmer surface temperatures in Mexico during later stages of drying spells. These findings from limited field sampling explore the subtle relationships between antecedent precipitation and aerodynamic, radiative, and subsurface properties of the

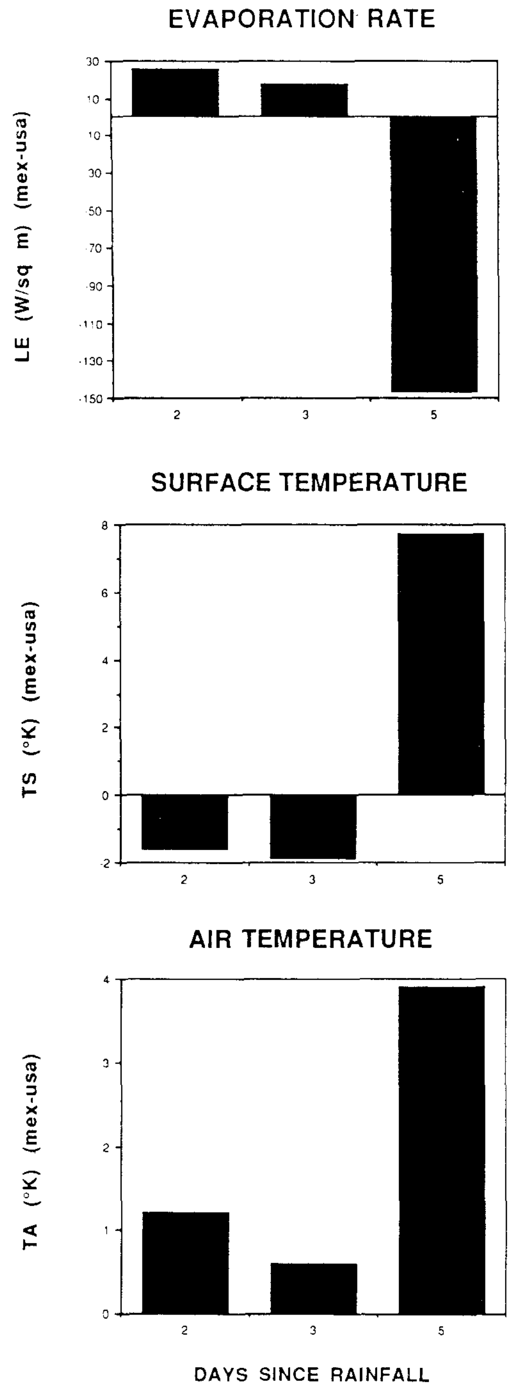

Fig. 2. LE, T_S, and T_A measured at Lochiel, 21–24 July 1988.

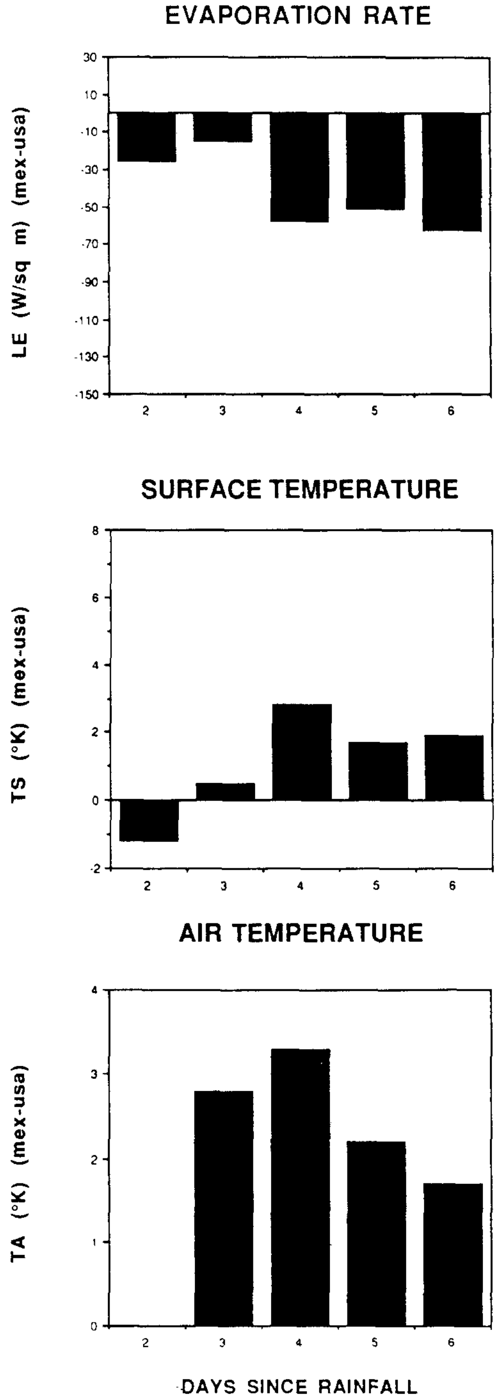

Fig. 3. LE, T_S, and T_A measured at Lochiel, 9–13 August 1988.

two landscapes in developing resultant surface and air temperature differences in this semi-arid environment.

In Situ Vegetation Analysis

A block sample design was used to measure total biomass, green biomass, percent cover, and percent green at Lochiel during the 1988 growing season (Hutchinson and Beck, 1989). The paired sites, each centered a few hundred meters from the border, were situated on a broad piedmont plain dissected by shallow drainage channels. The major soil was White House loam on the U.S. side, and White House gravelly loam and gravelly, sandy loam on the Mexican side. Slopes were predominantly flat to 10%. Runoff was slow to medium on both sites.

The block consisted of twelve samples for each of four dates. For each sample, a 70 × 70 cm quadrat was placed on the ground at a randomly chosed location within the study site. A nadir-view 35-mm photograph was taken to determine percent cover and percent green within the quadrat. The vegetation was then clipped, oven-dried, separated into green and non-green components, and weighed to estimate green- and total-biomass in kg ha^{-1}.

Results showed that the U.S. samples significantly (95% confidence level) exceeded the Mexican samples throughout the growing season in terms of green biomass, total biomass, and percent cover (Table II). Green biomass accumulation during the season was suppressed on the Mexican side by grazing pressure. Measured vegetation amount and vigor was moderate in the spring, minimal in early summer, and maximumal in autumn, a progression which corresponds well with the precipitation regime in the area.

TABLE II: Field estimates of biomass at Lochiel

	Total biomass (kg ha^{-1})	Green biomass (kg ha^{-1})	Percent cover	Percent green
4/26/88				
U.S.A.	1027.7	98.1	77.9	11.3
Mex	180.6	47.3	52.3	29.8
6/22/88				
U.S.A.	1006.2	180.5	67.1	21.0
Mex	105.6	42.3	42.1	43.6
7/2/88				
U.S.A.	577.9	107.7	67.1	21.6
Mex	80.6	43.9	44.6	55.6
10/15/88				
U.S.A.	1414.1	514.5	85.8	36.5
Mex	299.2	120.6	62.1	40.4

Satellite Data Analyses

Several satellite data products, both archival and coincident with the 1988 summer field work, were investigated for their ability to distinguish significant land surface climatology components. Digital AVHRR (Advanced Very High Resolution Radiometer) thermal band data were analyzed for their ability to assess surface temperature differences along the border. Landsat MSS (Multi-Spectral Scanner) visible and near-infrared data were analyzed seasonally for selected years to determine the predictability of relationships between spectral signature, seasonal precipitation, and vegetative growth. SMMR (Scanning Multichannel Microwave Radiometer) passive microwave data were used to estimate soil moisture fluctuations observed after major summer precipitation events. GOES (Geosynchronous Observational Environmental Satellite) visible-channel data were studied in an attempt to discern differential summer convective activity on either side of the border. The results of each satellite data investigation are described below.

Surface Temperature

A surface temperature gradient along the border was observed in several AVHRR (Kidwell, 1986) scenes. The AVHRR, flown aboard the NOAA polar-orbiting satellites, provides thermal data on a daily basis in two channels (10–11 μ, and 11–12 μ) with ~1 km spatial resolution. Sequential AVHRR datasets were acquired for the drying period following several rainfall events identified by Balling (1989). The data were calibrated (Lauriston *et al.*, 1979), subjected to a split-window atmospheric correction (Strong and McClain, 1984), corrected for emissivity (Price, 1984; Cooper and Asrar, 1989), and geo-registered.

Paired sites (5 km square, centered ~4000 m from the border) were chosen in relatively flat terrain at Lochiel. First order trend surfaces were fit through the

TABLE III: AVHRR-derived estimates of surface temperature for 3 major drying episodes

Date	Days since rain	$T_{S\,(\text{Mex-U.S.A.})}$	
		Lochiel	Swath
07/09/82	3	1.0	–0.5[a]
07/10/82	4	0.7	–0.3[a]
09/22/85	5	1.3	0.8
09/24/85	7	2.0	0.7
09/26/85	9	1.7	0.4[a]
09/23/88	3	2.5	1.1
09/29/88	9	2.1	1.6
10/01/88	11	2.2	1.7
10/02/88	12	2.2	1.4

[a] ΔT_S not significant @ 0.01 level.

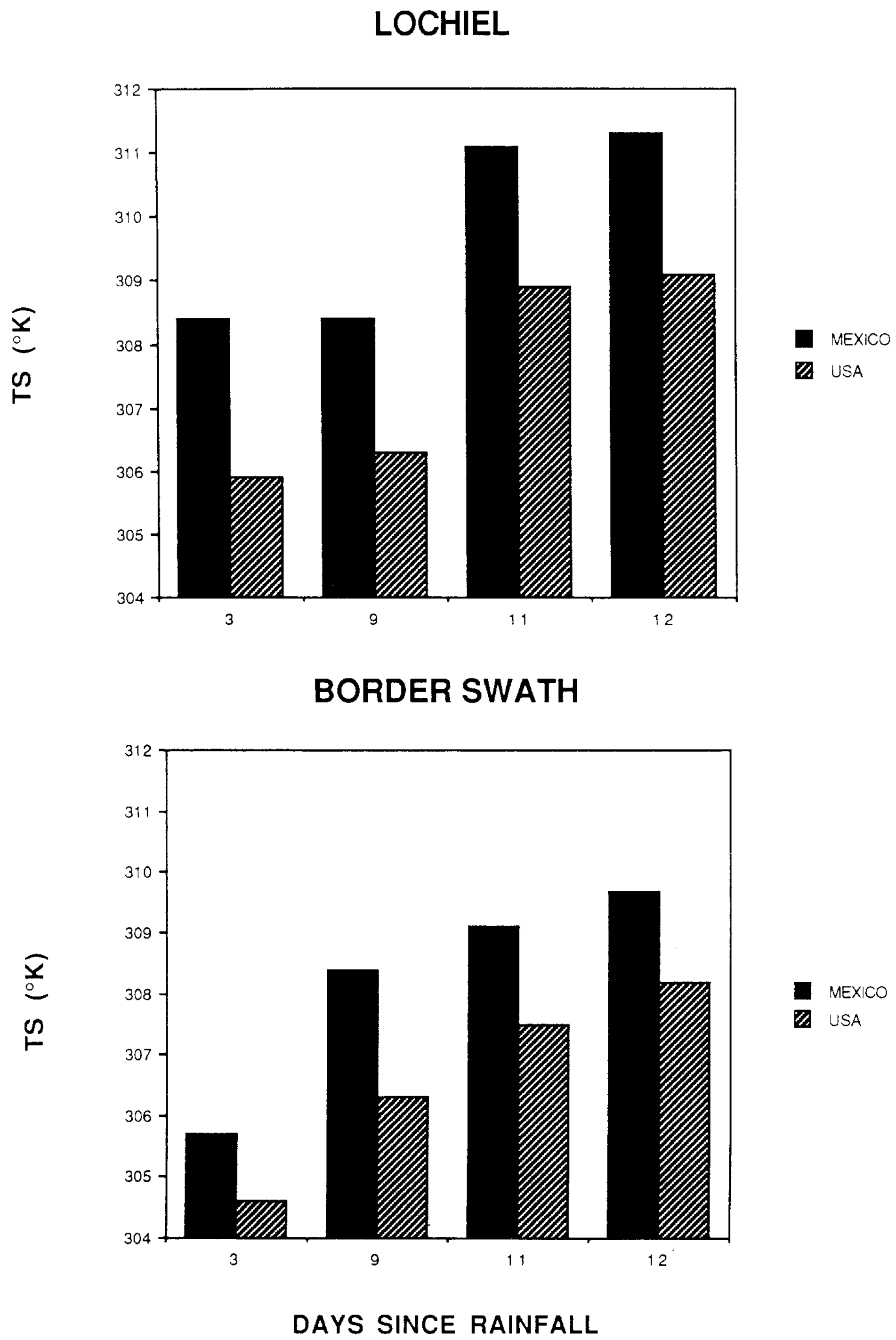

Fig. 4. AVHRR-derived estimates of surface temperature at Lochiel and along border swaths during a drying episode 23 September to 2 October 1988.

topography (@: 50 000 scale) of these sites, and a model (after Outcalt, 1972) was used to simulate surface temperatures based on boundary conditions observed in the field measurements. Simulation results suggested that the influence of topography on surface temperature differences for the site-pair should be on the order of 10%. In addition, a pair of swaths extending from Nogales to Lochiel, 5 km deep, was defined.

Estimated surface temperature in Mexico, both at Lochiel and throughout the border swaths, was found to be consistently and significantly (99% confidence level) warmer than in the U.S. (Table III). Temperature differences from 1 to 3 K were observed beginning three days after rainfall and continuing for at least twelve days. These findings, along with the estimated absolute temperatures, are in reasonable agreement with the *in situ* measurements. Figure 4 shows the temperature gradient during a drying episode in September 1988. Prevailing cloudy conditions and other data acquisition difficulties prevented analysis of satellite data during the first two days of the drying cycle after any major rainfall event, thus precluding satellite corroboration of the initially cooler temperatures in Mexico shown in the field data.

NDVI

Data from the Landsat MSS were used to formulate a normalized difference vegetation index (NDVI) (Tucker, 1979). The NDVI has been described by many investigators as an indicator of vegetative quantity and vigor, particularly in agricultural or other heavily vegetated regions. Investigators have used AVHRR-derived NDVI (Tucker *et al.*, 1985; Townsend and Justice, 1986) to monitor biomass in arid and semi-arid regions, including the Sahel.

MSS digital counts were converted to absolute radiance values using published post-launch coefficients (Malila and Anderson, 1986). An MSS NDVI, $[(L_7 - L_5)/(L_7 + L_5)]$, was then formulated with data from the red and near-infrared MSS channels. Topographically similar paired sites, approximately 1280 m square (16 × 16 pixels), were identified within a few thousand meters of the border near Nogales and Lochiel.

NDVI was calculated at these sites for the years ('79, '82, '86, '87) using spring, early summer, and autumn observations. Consistently higher NDVI's were observed in the U.S. as a result of differential grazing load. NDVI in both countries was greatest in autumn (coincident with the annual vegetative maximum) and least in early summer (Figure 5). These findings are consistent with green biomass amounts measured at Lochiel in the vegetation sampling study (Table 2).

NDVI observations at the Nogales and Lochiel sites were compared with the 45-day antecedent precipitation recorded at the nearby Nogales and Canelo weather stations, respectively. An apparently strong relationship was found between the NDVI observations and antecedent precipitation on both a seasonal (Figure 5) and annual (Figure 6) basis. This finding is similar to that found by Justice and Hier-

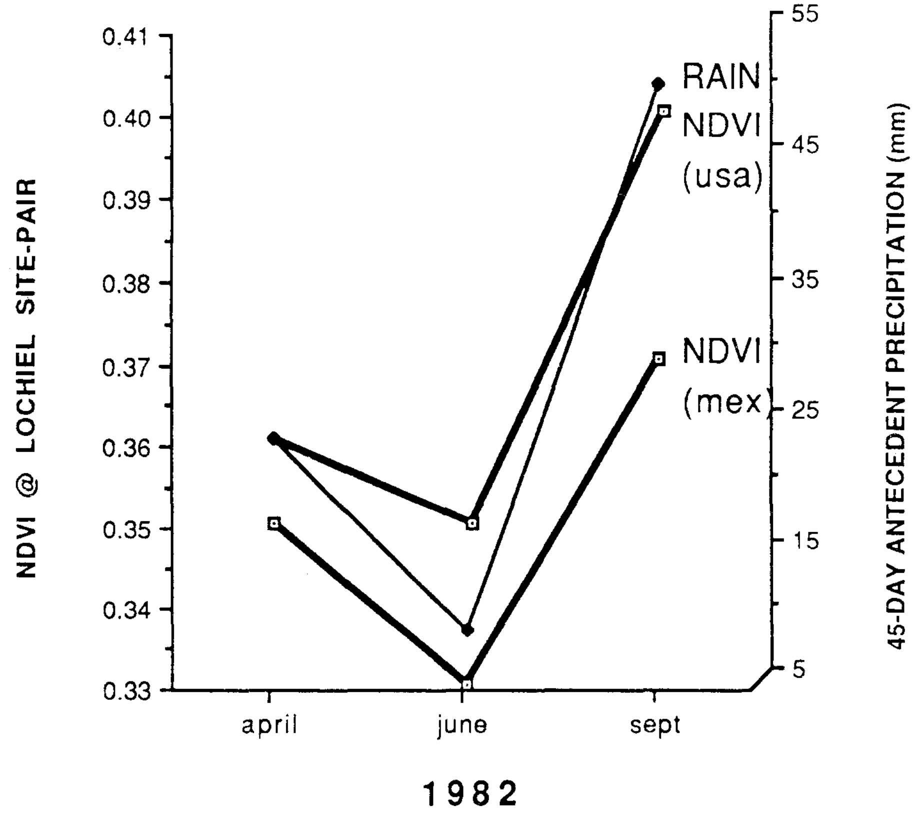

Fig. 5. Comparison of MSS-derived NDVI, with antecedent precipitation for 3 seasons in 1982; Lochiel site-pair.

naux (1986) in a study of AVHRR-derived NDVI in the Sahel, the implication being that the potential exists for combining biomass models with seasonal precipitation history and end-of-season NDVI to estimate biomass production. Further work is needed to better define the relationship between NDVI, cumulative precipitation, and vegetation cover in semi-arid regions. However, despite the presence of such confusion factors as bare soil and senescent vegetation, the index appears to respond to green biomass in an encouraging fashion.

Soil Moisture

Data from the SMMR (Njoku *et al.*, 1980) were processed to estimate soil moisture content in broad swaths (ie: 0.5 × 2 degrees) on either side of the border. The SMMR is a five frequency, dual polarized radiometer with spatial resolution ranging from 30 km at 37 GHz to 150 km at 6.6 GHz. The SMMR Temperature Calibrated Tape (TCT) product, binned in 0.5 degree latitude by 0.5 degree longitude cells, was used to construct polarization ratios at 6.6 GHz. The 6.6 GHz ratio

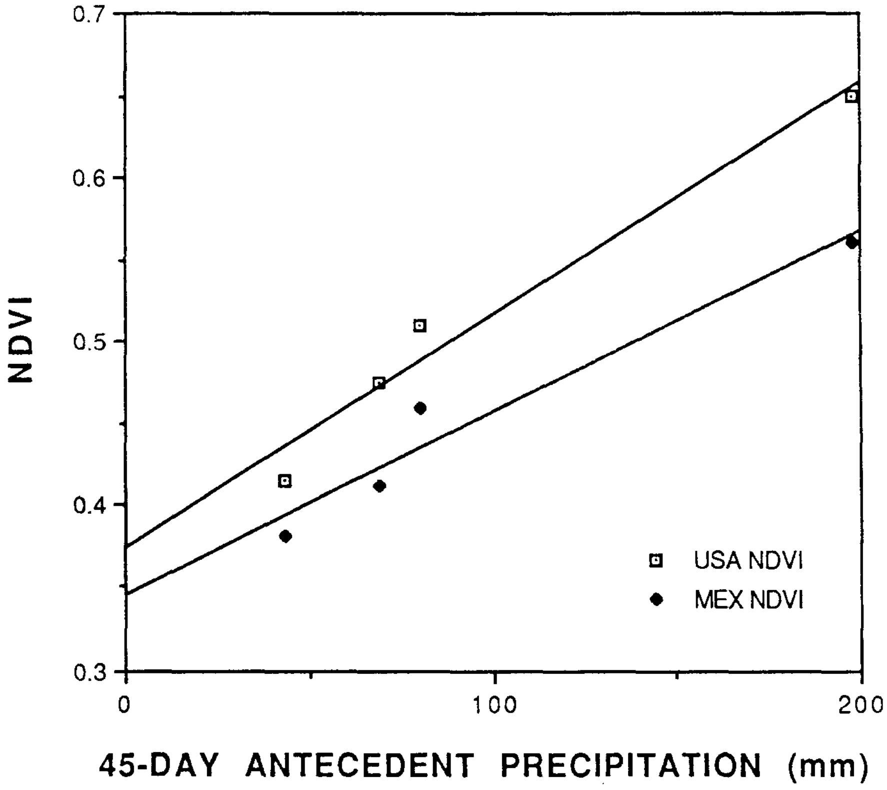

Fig. 6. Comparison of MSS-derived NDVI with antecedent precipitation at the vegetative maximum (late summer/early autumn); 1979, 1982, 1986, 1987; Nogales site-pair.

[(V − H)/(V + H)] has been shown to be sensitive to soil moisture, particularly in areas of sparse vegetation (Kerr and Njoku, 1988). The polarization ratio in the border region varied with weekly precipitation for several rainfall events in 1982 (e.g. Figure 7).

It is believed that differences in polarization ratios from several SMMR channels may be convolved to yield large-area estimates of soil moisture content, surface roughness, and integrated atmospheric water content (Kerr, 1988, personal communication). Such a model applied to TCT data showed a more rapid soil moisture depletion in Mexico for drying episodes in July and December 1982 (Figures 8, 9).

Convective Cloud Formation

Miller (1989 and unpublished research results) assessed the impact of the Sonoran border discontinuity on summertime convective cloud development. Unusually heavy spring and summer rainfall in 1980 produced a high contrast in vegetative cover along the border. During the period June–August 1980, 22 days were asso-

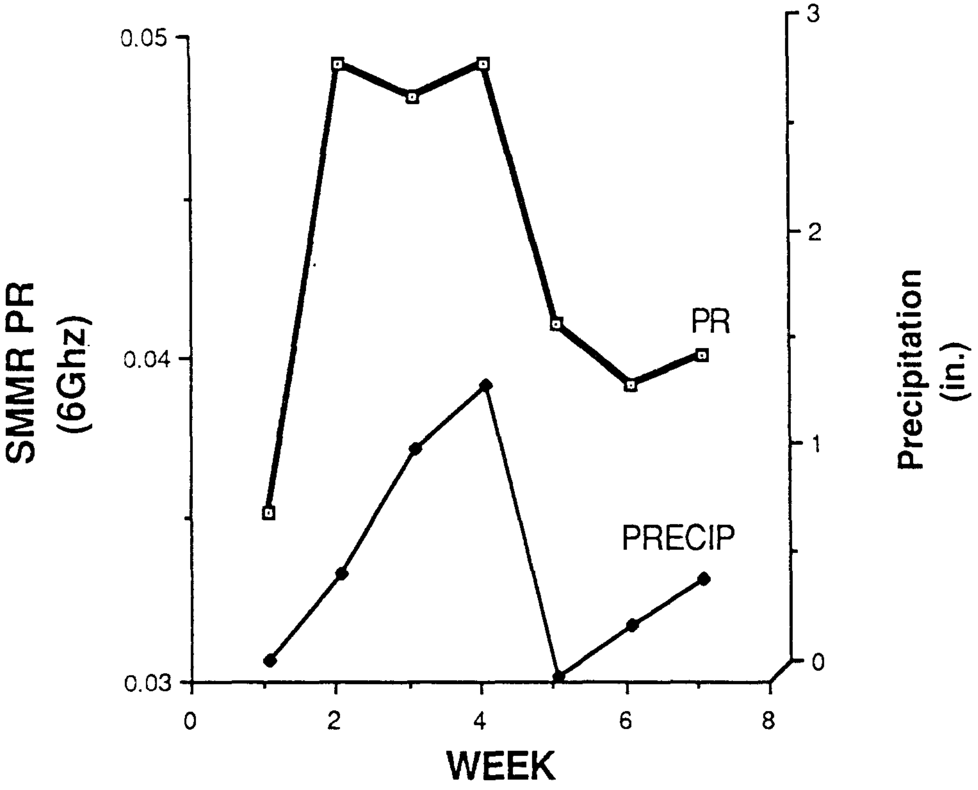

Fig. 7. Comparison of SMMR polarization ratios with weekly rainfall totals; November–December 1982; U.S.A.

ciated with widespread cumulus activity. For these days, early- and late-afternoon GOES visible-band film products were video-digitized and convective cloud formations identified. Each image pair was compared quantitatively to calculate the rate of convective cloud formation. Growth rates over Mexico were found to be from 50 to 177% higher (most results significant @ 99% confidence level) than over the U.S. These preliminary findings suggest that the higher surface and air temperatures of the overgrazed Mexican landscape may increase atmospheric instability and thereby support a higher growth rate of afternoon cumulus than on the U.S. side of the border. While the impact of topographic variation cannot be neglected, the observed increase in convective activity is consistent with other studies of differentially heated surfaces (Mahfouf *et al.*, 1987; Anthes, 1984; Lugt and Schwiderski, 1966).

Conclusions and Future Study

Several disparate datasets were used to detect and monitor, at a variety of scales,

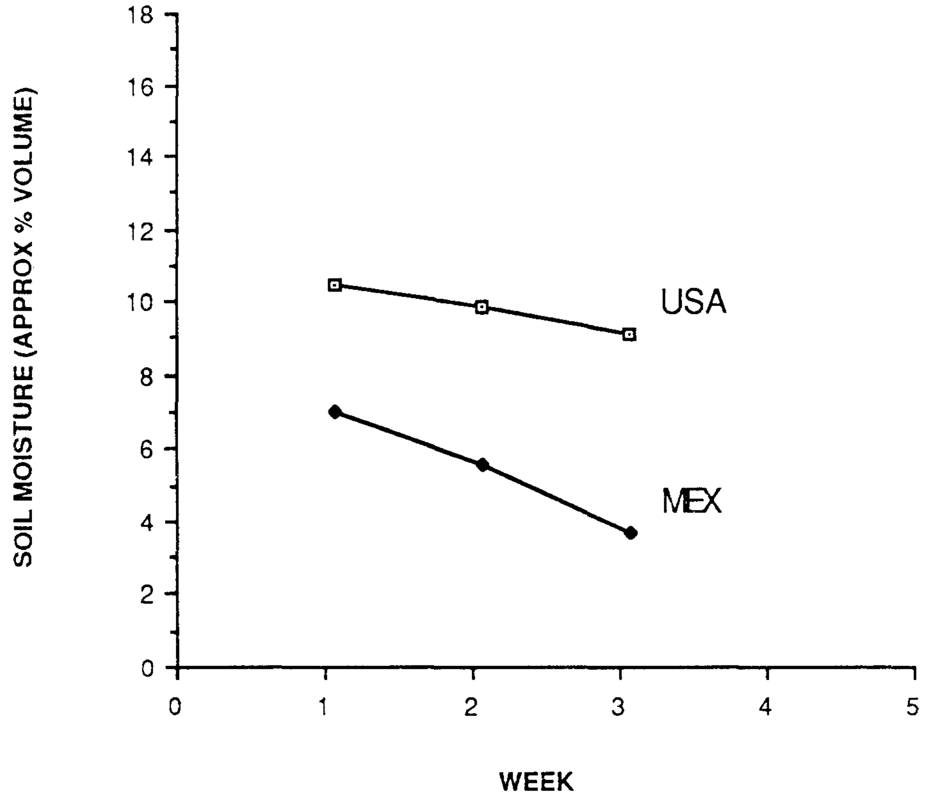

Fig. 8. SMMR estimates of soil moisture content during a drying episode in July 1982.

land surface climatology response to rainfall in controlled and overgrazed semi-arid grassland regimes along the U.S./Mexico border. *In situ* micro-meteorological monitors showed that higher rates of latent heat flux on overgrazed Mexican lands lessen the amount of soil moisture available for vegetative growth during the main growing season. In addition, differential soil moisture depletion evokes higher surface- and air-temperatures in Mexico, a gradient which endures for several days following major precipitation events. These findings are in agreement with the classical agricultural meteorology and range management literature (Branson,1976; Thornthwaite, 1948).

Archival records from a number of weather stations throughout the region were studied. Summertime monthly mean maximum air temperatures in Mexico were found significantly warmer than in the U.S., after appropriate corrections. Daily temperature differences, apparently driven by the amount of moisture available for evapotranspiration, were found subsequent to major precipitation events.

Satellite data in several wavelengths were used to monitor land surface variables both locally and regionally. Visible/near-infrared band Landsat MSS data were used to estimate green biomass, which in turn provides a means for establishing

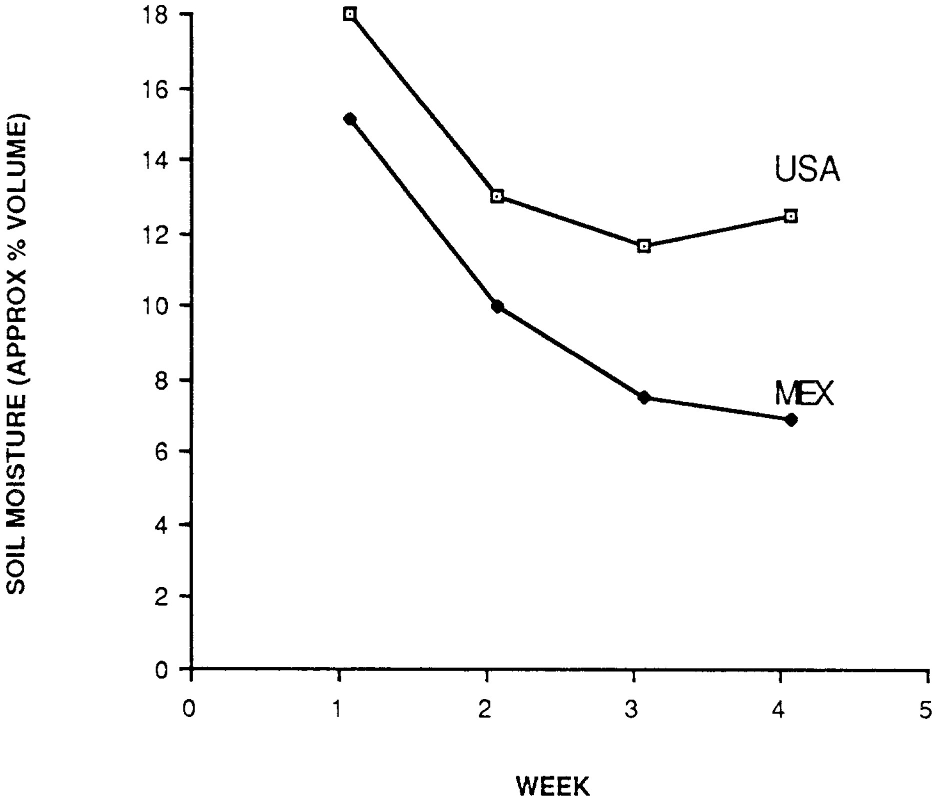

Fig. 9. SMMR estimates of soil moisture content during a drying episode in December 1982.

and monitoring the health of the floral community. These results corresponded well with antecedent precipitation amount and with ground-based biomass measurements. Thermal-infrared AVHRR data were used to observe the surface temperature gradient along the border. The measured temperatures and differentials corresponded well with ground-based observations. Finally, SMMR microwave data showed promise in providing large-scale estimates of soil-moisture content. It would appear that satellite data analysis provides a viable means of monitoring critical land surface variables on a large scale in the semi-arid regime.

Further work is needed to quantify the meteorological effect, if any, of the observed surface processes on regional convection. Toward this end, empirical results of this study may be incorporated into a general land surface climatology model of biosphere-atmosphere interactions similar to that of Verstraete (1988). Input of remotely sensed data may provide such models with information of finer spatial and temporal resolution than is currently available from existing meteorological and other point data sources.

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