Title
Preface paper to the Semi-Arid Land-Surface-Atmosphere (SALSA) Program special issue.

Journal
Agricultural and Forest Meteorology., 105(1/3)

ISSN
0168-1923

Authors
Goodrich, DC
Chehbouni, A
Goff, B
et al.

Publication Date
2000-11-01

DOI
10.1016/s0168-1923(00)00178-7

ELSEVIER

Agricultural and Forest Meteorology 105 (2000) 3–20

AGRICULTURAL AND FOREST METEOROLOGY

www.elsevier.com/locate/agrformet

Preface paper to the Semi-Arid Land-Surface-Atmosphere (SALSA) Program special issue

D.C. Goodrich[a,*], A. Chehbouni[b], B. Goff[a], B. MacNish[c], T. Maddock[c], S. Moran[a], W.J. Shuttleworth[c], D.G. Williams[c], C. Watts[l], L.H. Hipps[e], D.I. Cooper[f], J. Schieldge[n], Y.H. Kerr[g], H. Arias[l], M. Kirkland[f], R. Carlos[f], P. Cayrol[g], W. Kepner[q], B. Jones[q], R. Avissar[s], A. Begue[h], J.-M. Bonnefond[o], G. Boulet[b], B. Branan[r], J.P. Brunel[b], L.C. Chen[i], T. Clarke[d], M.R. Davis[m], H. DeBruin[j], G. Dedieu[g], E. Elguero[b], W.E. Eichinger[i], J. Everitt[m], J. Garatuza-Payan[c], V.L. Gempko[c], H. Gupta[c], C. Harlow[c], O. Hartogensis[j], M. Helfert[d], C. Holifield[d], D. Hymer[b], A. Kahle[n], T. Keefer[a], S. Krishnamoorthy[i], J.-P. Lhomme[b], J.-P. Lagouarde[o], D. Lo Seen[h], D. Luquet[h], R. Marsett[a], B. Monteny[b], W. Ni[d], Y. Nouvellon[h], R. Pinker[t], C. Peters[c], D. Pool[p], J. Qi[d], S. Rambal[k], J. Rodriguez[l], F. Santiago[l], E. Sano[c], S.M. Schaeffer[c], M. Schulte[c], R. Scott[c], X. Shao[f], K.A. Snyder[c], S. Sorooshian[c], C.L. Unkrich[a], M. Whitaker[c], I. Yucel[c]

[a] *USDA-ARS, Southwest Watershed Research Center, Tucson, AZ 85719, USA*
[b] *IRD/IMADES, Hermosillo, Sonora, Mexico*
[c] *University of Arizona, Tucson, AZ, USA*
[d] *USDA-ARS Water Conservation Laboratory, Phoenix, AZ, USA*
[e] *Utah State University, Logan, UT, USA*
[f] *Los Alamos National Laboratory, Los Alamos, NM, USA*
[g] *CESBIO, Toulouse, France*
[h] *CIRAD, Montpellier, France*
[i] *University of Iowa, Iowa City, IA, USA*
[j] *AUW, Wageningen, Netherlands*
[k] *CEFE, CNRS, Montpellier, France*
[l] *IMADES, Hermosillo, Sonora, Mexico*
[m] *USDA-ARS, Weslaco, TX, USA*
[n] *Jet Propulsion Laboratory, Pasadena, CA, USA*
[o] *INRA, Bordeaux, France*
[p] *USGS-WRD, Tucson, AZ, USA*
[q] *US-EPA, Las Vegas, NV, USA*
[r] *Audubon Research Ranch, Elgin, AZ, USA*
[s] *Rutgers University, New Brunswick, NJ, USA*
[t] *University of Maryland, College Park, MD, USA*

* Corresponding author.

0168-1923/00/$ – see front matter Published by Elsevier Science B.V.
PII: S0168-1923(00)00178-7

Abstract

The Semi-Arid Land-Surface-Atmosphere Program (SALSA) is a multi-agency, multi-national research effort that seeks to evaluate the consequences of natural and human-induced environmental change in semi-arid regions. The ultimate goal of SALSA is to advance scientific understanding of the semi-arid portion of the hydrosphere–biosphere interface in order to provide reliable information for environmental decision making. SALSA approaches this goal through a program of long-term, integrated observations, process research, modeling, assessment, and information management that is sustained by cooperation among scientists and information users. In this preface to the SALSA special issue, general program background information and the critical nature of semi-arid regions is presented. A brief description of the Upper San Pedro River Basin, the initial location for focused SALSA research follows. Several overarching research objectives under which much of the interdisciplinary research contained in the special issue was undertaken are discussed. Principal methods, primary research sites and data collection used by numerous investigators during 1997–1999 are then presented. Scientists from about 20 US, five European (four French and one Dutch), and three Mexican agencies and institutions have collaborated closely to make the research leading to this special issue a reality. The SALSA Program has served as a model of interagency cooperation by breaking new ground in the approach to large scale interdisciplinary science with relatively limited resources. Published by Elsevier Science B.V.

Keywords: Interdisciplinary; Semi-Arid; Land-Surface-Atmosphere; SALSA; Water balance; Energy balance; Ecological diversity

1. Introduction

The Semi-Arid Land-Surface-Atmosphere (SALSA) research Program seeks to evaluate the consequences of natural and human-induced environmental change in semi-arid regions. The ultimate goal of this multi-agency, multi-national research effort is to advance scientific understanding of the semi-arid portion of the hydrosphere–biosphere interface in order to provide reliable information for environmental decision making. SALSA is accomplishing this goal through a long-term, integrated program of observation, process research, modeling, assessment, and information management, using both existing and innovative technologies, and sustained by cooperation among scientists and information users. A necessary aspect of providing reliable information to decision makers is the publication of peer-reviewed research results. This special issue of Agricultural and Forest Meteorology brings together a number of SALSA research results in a unified format. This presentation is a preface to the SALSA special issue. A synthesis of these results is provided by Chehbouni et al. (2000c) at the end of this issue.

2. SALSA Program background

SALSA grew out of a convergence of several ongoing and proposed efforts to observe, quantify, and model hydrometeorological and ecological processes in semi-arid regions. The experimental component of the program follows the format of earlier land-surface-atmosphere studies, specifically “Monsoon’90” (Kustas and Goodrich, 1994) and “Walnut Gulch’92” (Moran et al., 1993) conducted in southeastern Arizona, USA, in 1990 and 1992; the European Field Experiment in a Desertification-Threatened Area (EFEDA) in Spain (Bolle, 1995); and “Hapex-Sahel,” conducted in Niger, western Africa between 1991 and 1993 (Goutorbe et al., 1994).

Building on the experience of previous field experiments, Goodrich (1994) proposed a multi-year program to evaluate global change processes over a wide range of spatial and temporal scales. The challenge posed by this proposal was to evaluate the water and energy balance for a heterogeneous semi-arid landscape. In July 1995, 65 scientists from nine federal agencies, eight universities, six foreign agencies, and several NASA/EOS science teams representing a broad spectrum of scientific disciplines met in Tucson, AZ to discuss plans for the SALSA effort (Wallace, 1995). A principal outcome of the 1995 workshop was the formulation of the Primary Science Objective to be addressed by SALSA researchers:

> To understand, model, and predict the consequences of natural and human-induced change on the basin-wide water balance and ecological complexity of semi-arid basins at event, seasonal, interannual, and decadal time scales.

It purposefully focuses on two separate but highly interrelated ecosystem components: water balance and ecological complexity. The terrestrial water balance determines water availability, the primary factor limiting human and natural populations in semi-arid regions. Ecological complexity — representing species, habitat, and landscape diversity — is a key indicator of environmental quality and stability in these regions. Water balance and ecological complexity interact at the land-surface-atmosphere interface, making this the primary target for SALSA observations.

River basins comprise well-bounded hydrological systems, and encompass many biological and cultural systems of interest, hence, research focuses on the basin scale. By examining land-surface-atmosphere processes at a basin scale, SALSA results will have direct applicability to environmental management activities based on basin or watershed planning units. Similarly, the range of time scales to be examined by SALSA — from event to decadal — falls within the effective design and planning horizon for most management decisions.

SALSA operates on the principle of voluntary collaboration whereby researchers interact with one another across disciplinary, institutional, and political boundaries to address particular components of the Primary Science Objective. Collaborators are free to pursue their own lines of scientific inquiry in accordance with their institutional needs and resources, and may join or leave the program as they wish. The purpose of the organized SALSA "Program" is to facilitate these interactions and to serve as a platform for research coordination, data assimilation and synthesis, and information exchange. The role of the SALSA researcher is to collaborate with fellow SALSA researchers to gain maximum benefit from the resources used to address the Primary Objective. The ultimate product of the SALSA effort will be a comprehensive "knowledge-base" of data, information, and tools that will aid environmental decision-making in semi-arid regions.

The USDA-Agricultural Research Service (ARS) in Tucson, AZ is the institutional home of SALSA. The ARS provides overall program administration and coordination, and shares leadership and planning responsibilities with Institut de Recherche pour le Développement (IRD, formerly ORSTOM), the French overseas research agency. IRD and its sister agencies CESBIO, INRA and CIRAD bring a global perspective to SALSA that in the future will help extend SALSA research and product applications to semi-arid regions in other parts of the world. Currently, IRD scientists based in Hermosillo, Mexico — in close cooperation with their Mexican counterparts in the Sonoran environmental agency IMADES — have directed and implemented SALSA activities in Mexico. SALSA is linked to several other global change research programs, primarily through its collaborating scientists. Thus SALSA is closely tied to the ARS's National Global Change Program (Agricultural Research Service, 1998), which is guided by the US Global Change Research Program. Similarly, it is closely aligned with the global change research activities of the French agencies IRD and CNRS. SALSA is also associated with various remote sensing technology development efforts including NASA-EOS, ASTER, ERS-2, SPOT4-VEGETATION, ADEOS, and MODIS programs. SALSA will also be a key contributor to the new NSF Science and Technology Center on "sustainability of water resources in semi-arid regions" established at the University of Arizona along with a wide range of partners.

2.1. Semi-arid regions

Over 20 countries worldwide, most of them in arid and semi-arid regions, are considered to be either water-scarce or water-stressed because their growing populations require more water than the hydrological system can provide on a sustainable basis (Watson et al., 1998). Even as the demand for water grows in these countries, the supply is being diminished by human activities that degrade watersheds and threaten natural ecosystems. The "desertification" of drylands negatively affects nearly one billion humans on 35–40 million km^2 of land, or about 30% of the world's land surface (FAO, 1993). While water shortages and desertification affect all dryland areas, developing countries are particularly vulnerable to the economic and social costs associated with the decline of agricultural and natural ecosystem productivity.

The prospect of natural or human-induced global change greatly increases the risks and challenges already faced by these countries. Under current assumptions of global warming, climate models predict major shifts in world precipitation and evaporation patterns over the next century (UNEP, 1997). Semi-arid regions, many of which are already drought-prone, may suffer longer and more severe dry periods, as well as more destructive flooding and erosion caused by higher-intensity rainfall events. The combined effect of these stresses could permanently alter the water balance in some semi-arid regions, further reducing water availability to human and natural ecosystems.

Ecological complexity in semi-arid regions is closely tied to water availability and is threatened by the same unsustainable practices that disrupt the water balance (UNEP, 1997). Many organisms and ecosystems in these regions are already experiencing wide-spread habitat destruction, isolation, and fragmentation (Watson et al., 1998). The loss of native species (drylands are the ancestral home of major crop species such as wheat, barley, and sorghum) increases the vulnerability to agricultural systems worldwide. It is predicted that global change will exacerbate these problems, as the physical barriers and environmental stresses caused by human activity prevent organisms and ecosystems from adapting or migrating (Janetos, 1997).

The adverse effects of natural and human-induced environmental change are already manifest in semi-arid regions worldwide. The failure of communities in these regions to protect their natural resource base is due, in part, to an incomplete understanding of the physical and biological processes operating in semi-arid ecosystems, and the inability to monitor these processes over a broad range of time and space scales. Even in developed countries, policy-makers and resource managers often lack the information and tools needed to detect, predict, and mitigate widespread, incremental, long-term change on water and biotic resources. These inadequacies will be greatly magnified in the event of major shifts in global climate patterns. Consequently, there is a need to better understand the key ecological processes operating in semi-arid environments, and to develop observation, monitoring, and modeling technologies that can be applied to global change problems in these environments worldwide.

SALSA intends to address this societal need through a long-term, integrated program of observation, process research, modeling, assessment, and information management. The program will employ a variety of ground-based and remote sensing techniques to acquire new knowledge on key hydrologic and ecological processes operating within semi-arid river basins. SALSA will use a representative test basin, the Upper San Pedro, as its primary experimental and observational area. However, information from related studies will be incorporated into its “knowledge-base.” SALSA will use airborne and satellite-based remote sensing technologies to help quantify the spatial distribution of land–surface processes and, in turn, will use ground-based measurements to calibrate and validate remote sensing systems. The relationships and technologies developed in the test basin will then be applied to other semi-arid environments.

2.2. Upper San Pedro River Basin

The Upper San Pedro Basin (USPB), located in the semi-arid borderland of southeastern Arizona and northeastern Sonora (Fig. 1), is a broad, high-desert valley bordered by mountain ranges and bisected by a narrow riparian corridor sustained by an intermittent stream. The basin has a variety of characteristics which make it an exceptional outdoor laboratory to address a large number of scientific challenges in arid and semi-arid hydrology, meteorology, ecology, and the social and policy sciences. The area represents a transition between the Sonoran and Chihuahuan deserts with significant topographic and vegetation variation, and has a highly variable climate. It is an international basin with significantly different cross-border legal and land use practices. The upper and middle portions of the basin have a drainage area of 7610 km^2 at the US Geological Survey gaging station at Redington, AZ with approximately 1800 km^2 in Mexico. Elevations within the basin range from roughly 1100 to 2900 m.

The annual rainfall in the USPB ranges from around 300 to 750 mm. Approximately 65% of this typically occurs during the July through September monsoon season from high intensity air – mass convective thunderstorms. Roughly 30% comes from less intense winter frontal systems. Potential evapotranspiration is estimated at more than 10 times annual rainfall at lower elevations (Renard et al., 1993). Interannual climate variability is also high with a demonstrated linkage to the El Niño-Southern Oscillation (Woolhiser et al., 1993). Major vegetation types include desert shrub-steppe, riparian, grasslands, oak savannah, and ponderosa pine. In portions of the basin

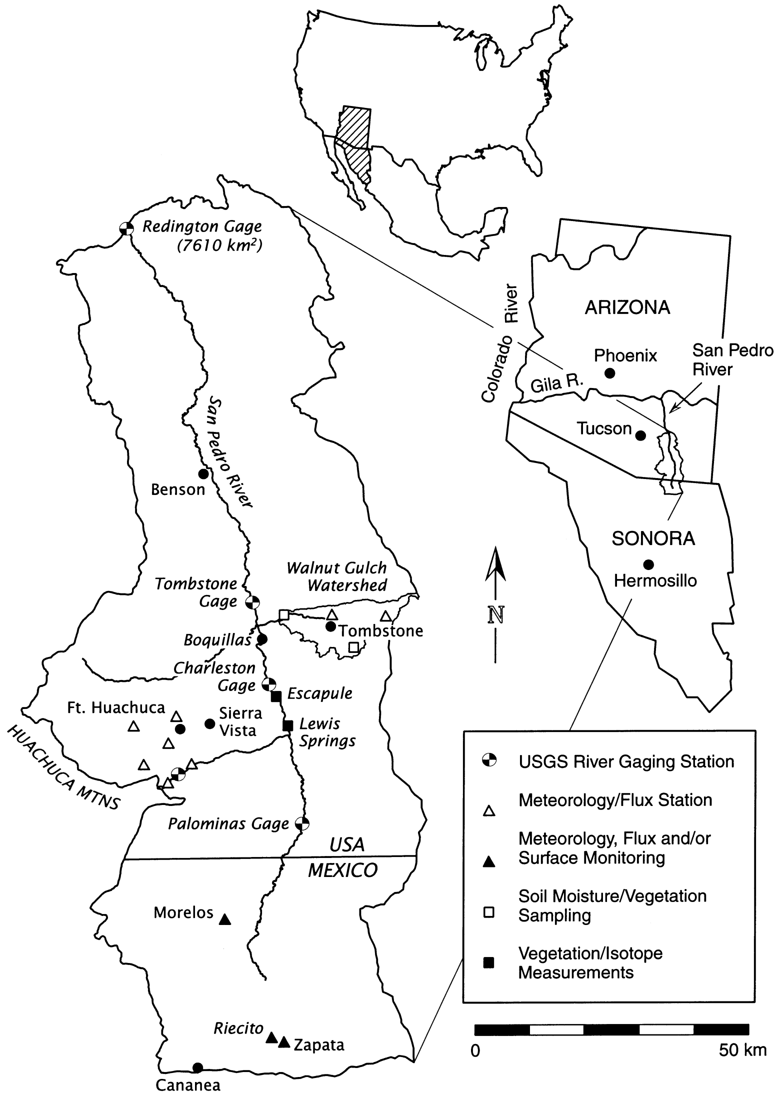


Fig. 1. SALSA study area, Upper San Pedro Basin.

all of these vegetation types are encountered within a span of 20 km. The USPB supports the second highest known number of mammal species in the world. In addition, the riparian corridor provides habitat for more than 400 bird species.

Principal economic drivers in the valley include the US Army Fort Huachuca on the Arizona side of the border and the copper mines near Cananea on the Sonora side (CEC, 1999). Although many view the San Pedro as largely undisturbed wildland, the upland and riparian environments of the valley have been radically altered over the past 100 years by human activities (Bahre, 1991). Despite this past disturbance, the grassland and montane ecosystems at the higher elevations are considered to have great biological significance (DeBano et al., 1995). As noted above, the cottonwood–willow riparian forest supports a great diversity of species — some in danger of extinction — and is widely recognized as a regionally and globally important ecosystem (World Rivers Review, 1997). In 1988, the United States Congress established the San Pedro Riparian National Conservation Area (SPRNCA), the first of its kind in the nation, to protect riparian resources along 60 km of river north of the US–Mexico border (Bureau of Land Management, 1989). The US Bureau of Land Management (BLM) administers the conservation area in a manner that conserves, protects, and enhances its riparian values. A number of factors outside the control of the BLM make protection of the SPRNCA problematic: mine-related pollution, surface diversions, and groundwater pumping in Mexico; potential water-rights claims by downstream users; and increased water use by communities near the conservation area (Jackson et al., 1987; Pool and Coes, 1999). Great concern exists regarding the long-term viability of the San Pedro riparian system and ranching in the face of continued population growth. Groundwater sustains the riparian system in the United States and also much of the ranching industry in the Mexican portion of the San Pedro. The threat of excessive groundwater pumping to this riparian system prompted the first application of international environmental law within US via the North American Free Trade Agreement (CEC, 1999).

Many of the resource management problems in the Upper San Pedro Basin are due to a lack of information about the water and ecological systems being managed. Despite the considerable amount of information already available, more is needed. High priority needs include better quantification of those components of the water balance known with little certainty such as aquifer recharge, groundwater–surface-water interaction, and evapotranspiration from uplands and riparian areas. Research also needs to be conducted on the effect of changing land use and water availability on the ecological complexity of the basin.

For SALSA, the USPB represents an ideal outdoor laboratory, containing diverse topographic, climatic, vegetative, and land use features within a well-defined drainage basin. These characteristics are useful in developing and testing land-surface-atmosphere process models, and calibrating and validating satellite-based Earth observation systems (Wallace, 1995). For over 40 years, a great deal of hydroclimatological research of semi-arid lands has been conducted in a sub-basin of the San Pedro at the USDA-ARS Walnut Gulch Experimental Watershed (Goodrich and Simanton, 1995). This densely instrumented facility provides a foundation and extensive knowledge base for SALSA to expand to the larger USPB. The basin contains riparian and upland ecosystems that show evidence of historic human impact on the vegetation of the region, changes that continue today. Kepner et al. (2000) documented significant land cover and land use change in the San Pedro over a nearly 25-year period using classified Landsat satellite images (see discussion related to objective four for more details).

3. 1997–1999 SALSA scientific objectives

The 1997–1999 SALSA activities were part of a longer term (3–10 year effort) to address the Primary Objective. These secondary objectives were formulated to address the Primary Objective and served to integrate the research of several disciplines. They focus on priorities established at the initial SALSA workshop that were within logistical and monetary constraints. They were:

1. Initiate the development and validation of a coupled soil–vegetation–atmosphere transfer (SVAT) and vegetation growth model for semi-arid regions that will assimilate remotely sensed data with several years of observed data;
2. develop and validate aggregation schemes with data over very highly heterogeneous surfaces;
3. conduct in situ and remote measurements to: (a) quantify and develop models for groundwater, surface water, and evapotranspiration interactions on a seasonal basis; (b) identify plant water sources; and (c) identify plant function and atmospheric controls on a semi-arid riparian system consisting of mesquite, sacaton, and cottonwood/willow vegetation communities; and
4. develop a multi-scale system of landscape pattern indicators using remotely sensed data to estimate current status, trend and changes in ecological condition; and investigate the impact of these changes on water cycle and surface–atmosphere interaction.

The research conducted under these objectives forms the foundation for addressing the SALSA Primary Objective in the following manner. The research associated with the secondary objectives one and two is required to improve our understanding and our ability to model climatic and land use/land cover change impacts on the water and energy balance of large semi-arid regions. This cannot be achieved without an accurate representation of the coupled hydro-ecological processes, and an improvement of the representation of sub-grid scale heterogeneity in atmospheric models. The research associated with the third objective is required because water use by semi-arid riparian systems is a major factor in the semi-arid water balance. Riparian systems support a much higher proportion of the biodiversity than the area they represent in semi-arid regions. Yet there is a great deal of uncertainty in quantifying riparian water use as well as effects that changes in riparian water availability will have on riparian vegetation and the associated species that are supported in this habitat.

The research associated with objective four is required to quantify the changes in land use and land cover over three decades for the entire basin. This provides a foundation for assessing the impacts of these changes on the primary components of the water and energy balance. The spatial size and connectivity of land cover are also a significant indicator of habitat characteristics required to support various species. Changes in these characteristics are often important factors in the survivability or increasing population of various species.

4. Methods

The methods used in the first phase of the SALSA Program spanning roughly the 1996–1999 period are discussed in this section. Existing data collection networks that were either used or expanded upon are briefly mentioned. New experiments and additional data collection to address the objectives noted above are then briefly introduced.

Surface observations were obtained from a variety of existing data collection networks. These included intensive monitoring at the 148 km^2 USDA-ARS Walnut Gulch Watershed (85 raingages, 30 runoff measurement sites, two sites with energy and CO_2 flux, meteorology, vegetation and soil moisture measurements; Renard et al., 1993), meteorological data collection by the US Army at Fort Huachuca, and five USGS stream gaging stations along the Upper San Pedro. In Mexico, four contrasting sites representing different situations with respect to surface degradation have been instrumented (see Fig. 1). These sites ranged from a native and well-managed grassland, representing the pre-degradation conditions in the basin, to a mesquite site representing the ultimate stage of degradation. These sites were equipped with micro-meteorological devices to measure meteorological forcing parameters (precipitation, wind speed and direction, air temperature and humidity, short and long-wave radiation) and fluxes of water, energy and CO_2 (Chehbouni et al., 2000a; Nouvellon et al., 2000b; Cayrol et al., 2000). Soil moisture and temperature were sampled at different depths in the soil. Vegetation characteristics, stomatal conductance, surface reflectance and surface temperature at two different view angles were taken at different sites. In two of the sites (grass and mesquite), runoff measurements were also made. Finally, a set of three large aperture scintillometers (LAS) were used to address the issue of estimating area-average convective flux over heterogeneous surfaces.

4.1. Objective one

A wide variety of in situ and remotely sensed data were collected at these sites to address this objective (Moran et al., 2000; Pinker et al., 2000; Nouvellon et al., 2000b; Qi et al., 2000). A summary of timing, coverage, and sensor specifications of SALSA-related images is presented in Table 1. NOAA-AVHRR data was also acquired and processed during significant portions of the study period. Several soil–vegetation–atmosphere-transfer (SVAT) models, with different degrees of complexity were developed or adapted and successfully validated using multi-year data collected at different sites (Boulet et al., 2000; Nouvellon et al., 2000a; Cayrol et al., 2000; Nouvellon et al., 2000b). Some of these SVATs were coupled to different grass-functioning models (Cayrol et al., 2000; Nouvellon et al., 2000a). These models were also coupled to radiative transfer models so that satellite observations could be assimilated into the process model. This procedure appeared to be very effective in keeping the model on the right track by readjusting some of the unknown and spatially variable model parameters (Nouvellon et al., 2000b; Cayrol et al., 2000). Extensive large scale measurements, on a scale commensurate with the resolution of mesoscale atmospheric models and satellites such as AVHRR,

Table 1
List of the remote sensing information obtained during 1997 SALSA activities

Platform	Sensor	Spectral wavelengths	Overpass time	Coverage
ERS-2	Synthetic aperture radar (SAR)	C-band (5.3 cm)	Monthly, November 1996–October 1997, ∼10:30 a.m.	∼100 km × 100 km, US and Mexico sites
	ATSR2	6 Bands	1997 and 1998	100 km × 100 km window that includes the entire San Pedro Basin
Landsat	Thematic mapper (TM)	6 bands, 0.45–2.35 μm; 1 band, 10.42–11.66 μm	Monthly, November 1996–October 1997, ∼10:30 a.m.	∼180 km × 180 km, US and Mexico sites
DOE Cessna citation	Daedalus–TM simulator	10 bands, 0.42–2.35 μm; 2 bands, 8.5–12.5 μm	April 1996 and August 1997, before 12:00 p.m.	Swath width ∼11 km at 15 m resolution, several US sites and the Mexican border
	TIMS	6 bands, 8.2–12.2 μm		
Agro-metrics 2-engine aircraft	1 band video	8–12 μm	April, June, August, October 1997, before 12:00 p.m.	Swath width 0.25 km at 0.5 m resolution, riparian zone only
USDA-ARS Aero-commander	4 band video	4 bands, 0.45–0.90 μm	August 1997, before 12:00 p.m.	Swath width ∼6 km at 15 m resolution, several US sites and the Mexican border
	Large format camera	Color near-infrared film		
SPOT-4	VEGETATION	4 Bands	1998 and 1999	100 km × 100 km window that includes the entire San Pedro Basin

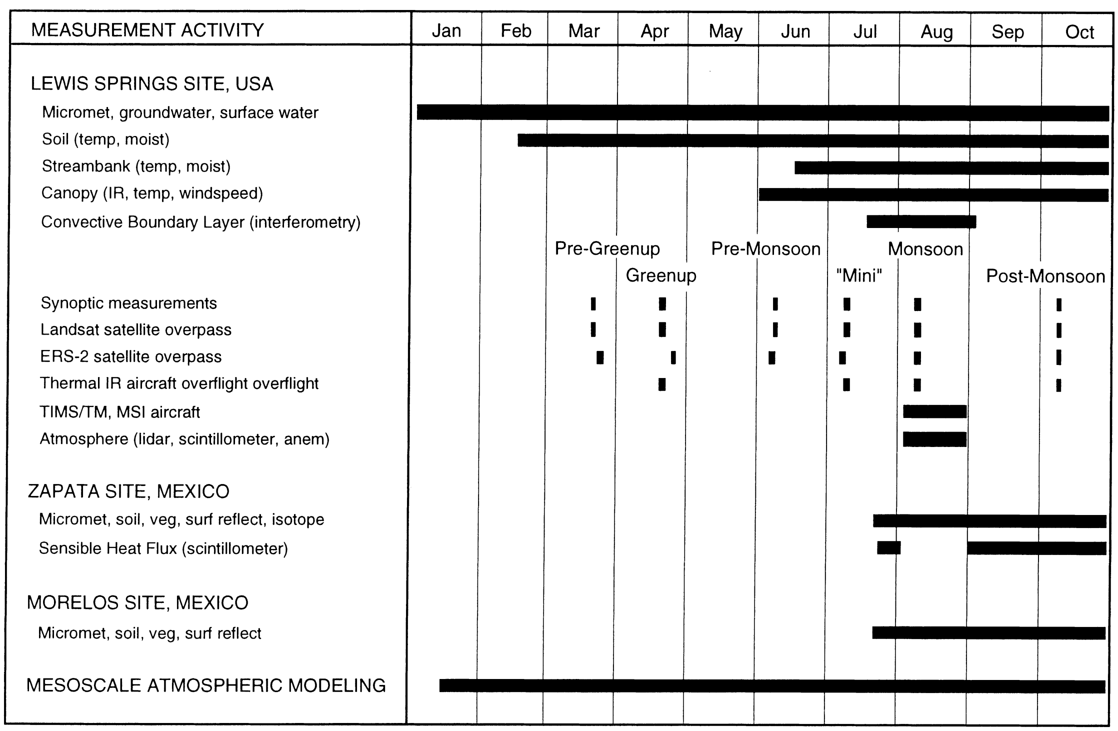
ATSR2 and MODIS, of sensible heat flux were also taken at a relatively uniform site with a scintillometer (Lagouarde et al., 2000). In a study by Watts et al. (2000), sensible heat flux derived from the scintillometer measurements over a 1 km transect compared favorably to an estimate using AVHRR-based surface temperature.

4.2. Objective two

From August 8 to 19 of the 1997 growing season riparian experimental field campaign (discussed in greater detail in Section 4.3) a greater concentration of instrumentation, including two more aircraft, were deployed at the Lewis Springs riparian site. Additional instrumentation deployed at this time included an array of eddy correlation flux instruments (Hipps et al., 1998), a scintillometer (Chehbouni et al., 1999), and the Las Alamos National Laboratory Raman LIDAR (LIght Detection And Ranging) system (Cooper et al., 2000; Eichinger et al., 2000). During the first portion of the August campaign an intercomparison of flux instruments was conducted over a homogeneous region of the sacaton grass while the LIDAR was deployed on the east bank of the San Pedro River. Kao et al. (2000) used this and a variety of measurements in the riparian corridor to do a very high-resolution atmospheric simulation of a portion of the corridor. After several days the LIDAR was moved to the west bank and the flux instruments were redeployed across the highly heterogeneous vegetation types under the path of the scintillometer. Objective two was addressed in part with these data due to the wide variation in vegetation type, height and stress resulting from differential access to groundwater in the compact riparian area. Additional scintillometer data collection was also carried out in Mexico in 1998 and 1999 over a large grass site, mesquite and mixed grass–mesquite transects to address this objective. These data have been used to develop and validate a wide range of aggregation schemes (Chehbouni et al., 2000a,b).

Finally, ground-based remotely sensed observations of atmospheric moisture derived from interferometric methods (Shao et al., 1998) were also taken roughly

Table 2
Schedule of SALSA activities, 1997



400 m south of the Lewis Springs site. Like the scintillometer measurements, these were taken on a scale of several kilometers. The temporal distribution of these measurements and many of those described for 1997 are summarized in the activity/data collection chart (Table 2).

4.3. Objective three

In addition to the broader-scale measurements noted above, an intensive set of groundwater, surface water, isotope, energy flux and plant transpiration measurements were concentrated in the Lewis Springs section of the San Pedro Riparian corridor to address this objective. This stream section is a "gaining reach" where groundwater contributes water to the stream. The vegetation type and structure in the Lewis Springs area was judged to be representative of vegetation throughout the 60 km long SPRNCA. This riparian system typically consists of a narrow (20–100 m) cottonwood/willow forest gallery surrounded on either side by riparian grasses and mesquite thickets. These grow on a flood plain that varies in width from several hundred to between 1 and 2 km. A primary goal of the research and measurements within this corridor was to quantify the surface water, groundwater, and evapotranspiration fluxes into and out of the control volume as depicted in Fig. 2 (Maddock et al., 1998; MacNish et al., 2000; Goodrich et al., 2000). This figure shows a schematic of the Lewis Springs section of riparian corridor geometry and a conceptualization of the types of simultaneous measurements to address this objective. The network of instrumentation installed at Lewis Springs is illustrated in Fig. 3.

Continuous measurements of water levels in the deep wells, meteorology and fluxes (Bowen Ratio) over the riparian grass and mesquite thicket (Scott et al., 2000), and stream stage at section three were made continuously throughout 1997. Measurements of soil gravimetric moisture, temperature, and tension were taken in the near-stream bank trenches to investigate bank storage-stream conductance relationships (Whitaker et al., 1998) for the last half of 1997.

In addition to the continuous measurements, intensive synoptic in situ and remote measurement campaigns of 48–120 h were conducted in March, April, June, August, and October of 1997. These synoptic measurement periods coincided with tree phenologic

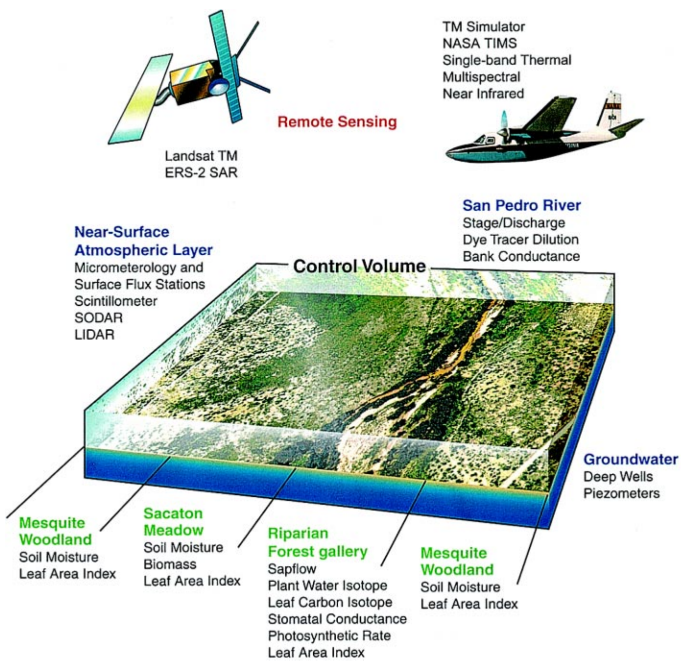


Fig. 2. Lewis Springs section of the San Pedro riparian corridor with a summary of the simultaneous measurements carried out.

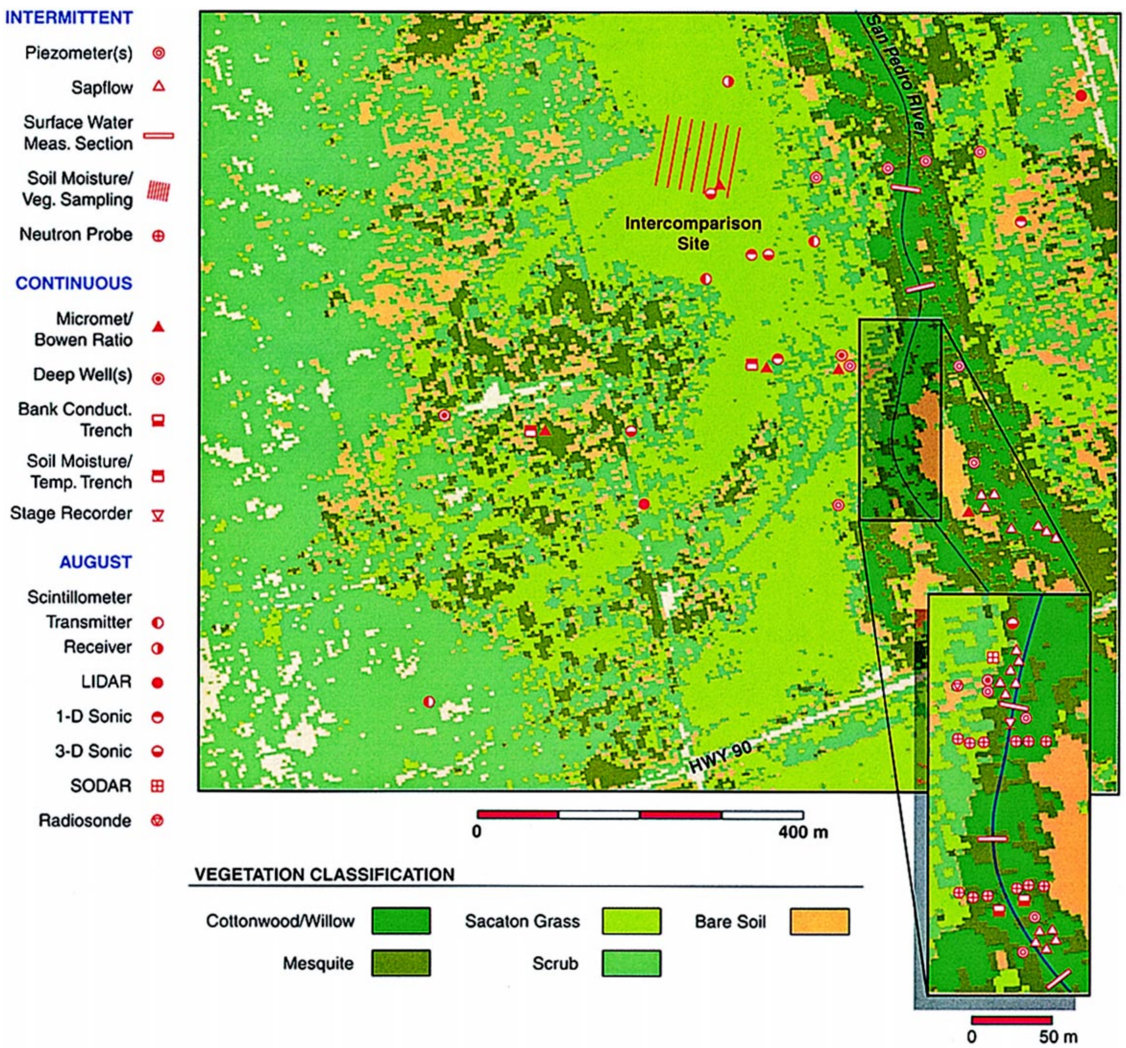


Fig. 3. A schematic of the network of instrumentation installed at Lewis Springs.

stages and environmental conditions (pre-greenup, initial leaf-out, summer drought, monsoon, and post-monsoon) of the entire growing season. This enabled characterization of the seasonal variations in evapotranspiration, and surface-water–groundwater interactions. Measurements taken during the synoptic runs included hourly stream stage and water levels from five river sections and the piezometer network as well as stream discharge measurements determined by current metering, dye-dilution, and an in-stream flume for the June campaign (Maddock et al., 1998; MacNish et al., 2000). Neutron probe measurements of soil moisture were made during synoptic runs and other periods of dynamic change. Tree sap flow, water potential, stomatal conductance, and water sources using stable oxygen and hydrogen isotope ratios were determined for mesquite, cottonwood, and willow. These measurements were made during each of the synoptic campaigns to capture variations in transpiration demand as a function of atmospheric demand and surface moisture availability (Schaeffer et al., 2000; Snyder and Williams, 2000). A subset of the vegetation and water source measurements were made in an intermittent, losing and ephemeral riparian stream

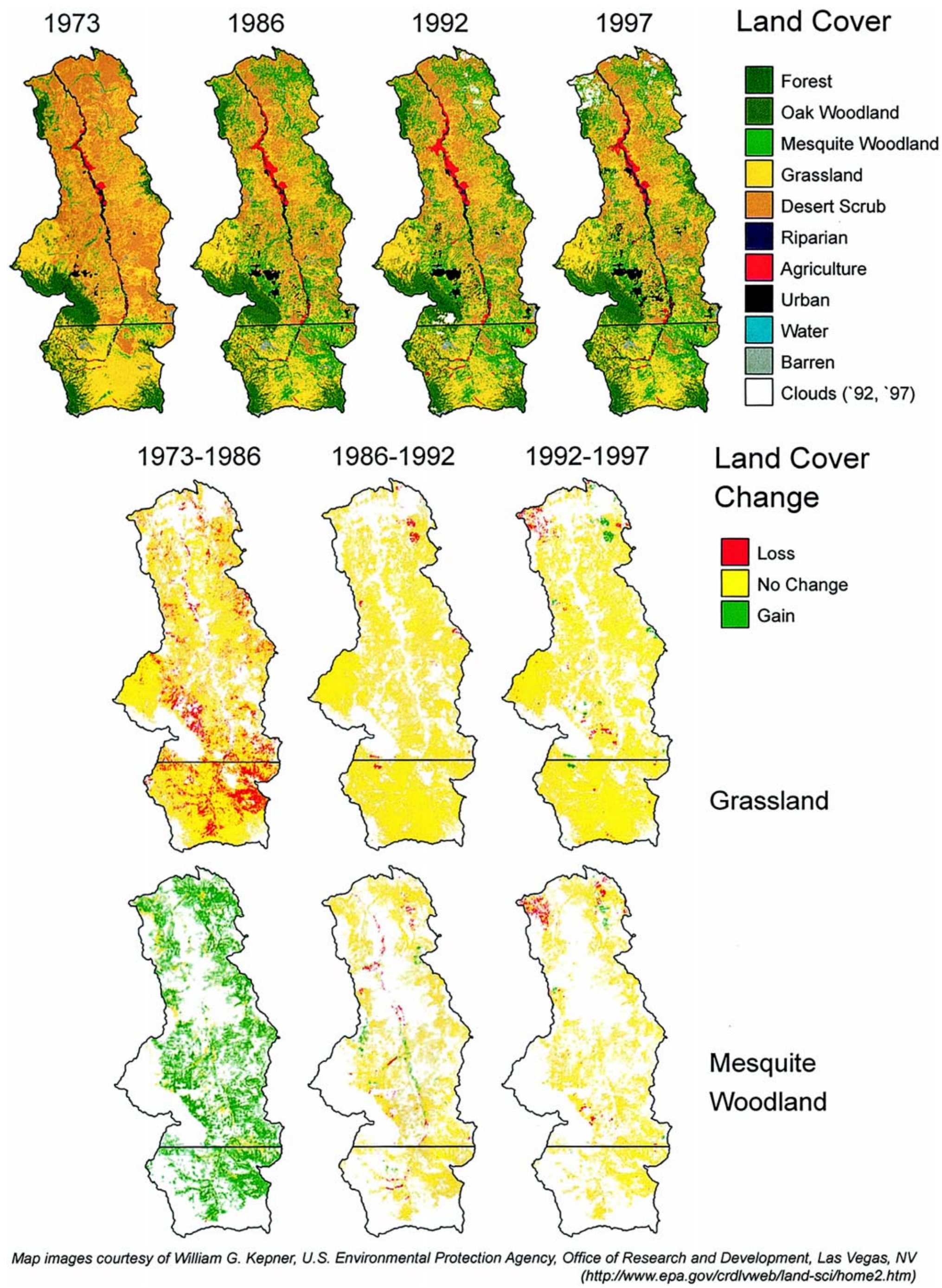


Fig. 4. Top row: San Pedro Basin land cover in 1973, 1986, 1992 and 1997. Middle row: change in grassland cover; 1973–1986, 1986–1992, 1992–1997. Bottom row: change in mesquite woodland cover; 1973–1986, 1986–1992, 1992–1997. Note, for the middle and bottom row red denotes a loss in cover type, yellow — no change, and green denotes a gain over the respective time period.

reach (at Boquillas and Escapule locations, respectively, see Fig. 1). This design enabled the proportion and magnitude of surface water use by the gallery trees as a function of groundwater availability to be evaluated.

Concurrent with these in situ measurements, ground-, aircraft-, and satellite-based remotely sensed measurements were taken. Reference tarps were also deployed to allow for atmospheric and systematic corrections of image data (Perry and Moran, 1994; Moran et al., 1994; Qi et al., 1998). These included monthly acquisition of image sets from the Landsat TM and ERS-2 SAR satellite sensors (Table 1). Furthermore, at each site measurements of surface reflectance and temperature were made with hand-held radiometers for small-scale studies and for validation of the satellite images. The five synoptic measurement periods were also selected to coincide with overpasses of the Landsat and ERS-2 satellites. In addition, arrangements were made for aircraft overpasses to provide fine-resolution (1, 5 and 15 m) images of the riparian site, the Mexican border area, and several upland sites of interest (see Table 1).

4.4. Objective four

The research related to this objective was motivated by the critical need for defining status, trends and changes in land use and land cover for contemporary land management. Kepner et al. (2000) addressed this objective through classifications of basin imagery from the 1970s, 1980s and 1990s. They noted that numerous studies (e.g. Houghton et al., 1983; Turner, 1990; McDonnell and Pickett, 1993) suggest that human land use management practices are the most important factor influencing ecosystem structure and functioning at local, regional, and global scales. The distribution of land use, including its type and extent, is a major factor affecting ecological and hydrological condition related to alteration of species composition, food-web structure, ecosystem carbon storage, and interactions between biota (Forman and Gordon, 1986). Kepner et al. (2000) employed a landscape framework, as it provides the context: (1) to investigate changes in composition, pattern distribution, and process function; (2) to compare conditions across mixed landscapes; and (3) to assess cumulative sources of environmental change (Jensen and Everett, 1994).

Kepner et al. (2000) acquired Landsat MSS and TM imagery over the USPB from 1973, 1986, 1992, and 1997. The images were resampled to $60\,\mathrm{m}\times 60\,\mathrm{m}$ pixel resolution, coregistered, and georeferenced using the UTM coordinate grid. Vegetation and land use within each image was processed into a 10-class system (see top portion of Fig. 4). Using this data, the change in land cover classes was computed between successive land cover maps. These maps allowed computation of a variety of discrete landscape metrics to assess dominance, fragmentation, and rates of conversion.

In order to document the impact of land degradation (grass–mesquite transition) on the partitioning of available energy into sensible and latent heat flux, and on the partitioning of precipitation into runoff and infiltration, a specific investigation was carried out in Mexico. This involved infiltration tests, isotopic sampling and analysis, and soil moisture monitoring. The results indicated that infiltration decreased, and therefore runoff and erosion increased with increasing mesquite invasion. They also indicated that the mesquite develops, along with its deeper roots, an extensive surface root system. This dual root system allows the mesquite to extract water from the shallow soil when this is available (during the monsoon season) and to switch to deeper sources during the dry season (also see Snyder and Williams, 2000).

5. Conclusions

Major progress has been made in addressing the Primary Objective through a series of intensive experimental campaigns, long-term monitoring, application of innovative remote sensing techniques, and subsequent analyses. The synthesis paper by Chehbouni et al. (2000c) at the end of this special issue summarizes the primary findings and conclusions related to objectives one through three. Several of the conclusions resulting from research related to objective four are presented here as they present an excellent overview of the character of the Upper San Pedro Basin. In addition, they demonstrate the dynamic nature of the basin as well as the great degree of change taking place in the USPB.

The middle and lower portions of Fig. 4 illustrate a substantial loss of grassland and a dramatic increase in mesquite woodland during the period between 1973 and 1986. Table 3 contains a list of the relative land cover changes over several time periods for each of the cover classes. It is readily apparent that the mesquite woodland has encroached upon the entire watershed with over a 400% increase in the 1973–1986 period. Its total extent increased fivefold between 1973 and 1986, from 20,812 to 107,334 ha. Where grassland was the dominant cover type, its total extent has steadily declined over each of the three sample periods. Over 50,000 ha of vegetative communities dominated by perennial and annual grasses were lost between 1973 and 1992, with the major decrease occurring between 1973 and 1986 (46,025 ha lost).

Additional spatial analyses indicated that extensive, highly connected grassland and desert scrub areas are the most vulnerable ecosystems to fragmentation and actual loss due to encroachment of xerophytic mesquite woodland. During the study period, grasslands and desert scrub became more fragmented as well as decreasing in extent. As stated by Kepner et al. (2000), greater fragmentation implies the number of grassland and desert scrub patches increased and their average patch sizes decreased. “In stark contrast, the mesquite woodland patches increased in size, number, and connectivity. These changes have important impact for the hydrology of the region, since the energy and water balance characteristics for these cover types are significantly different.” Mesquite woodlands can exploit water sources at greater depths and can therefore out-compete shallow rooted grasses. To reverse this process and replace mesquite with grasses is energy intensive and very difficult to accomplish on a large scale. These dramatic changes at the basin scale are an indication of the urgency needed to provide policy and decision makers of the basin with sound research and data to enhance their ability to manage basin resources for a sustainable future.

Table 3
Percent relative land cover change for the Upper San Pedro Watershed (1973–1986, 1986–1992, and 1973–1992) from Kepner et al. (2000)

Time period	1973–1986	1986–1992	1973–1992
Forest	0.12	−4.93	−4.82
Oak woodland	0.54	−4.23	−3.71
Mesquite	415.72	−1.02	410.47
Grassland	−14.70	−2.04	−16.44
Desert scrub	−17.69	−2.68	−19.90
Riparian	−28.01	3.41	−25.55
Agriculture	55.95	33.05	107.49
Urban	207.83	22.51	277.14
Water	−67.63	342.37	43.21
Barren	55.23	4.62	62.40

From a programmatic perspective SALSA has served as a model of interagency cooperation. Scientists from about 20 US, five European, and three Mexican agencies and institutions currently cooperate in conducting SALSA research. These scientists readily share resources and data with other SALSA researchers with whom they are co-investigators. In addition, SALSA cooperates with several federal, state, and local government agencies, and non-governmental organizations, that it considers to be SALSA information-users, or clients.

The SALSA Program has broken new ground in the approach to large scale interdisciplinary science where limited resources are available. Careful planning resulted in the identification of critical and exciting scientific challenges that not only required, but fostered, interdisciplinary collaboration. Careful attention to enhancing interdisciplinary communication built the foundation for trustful collaborations. This enabled unselfish sharing of numerous small grants and in-kind resources to accomplish a goal which is much greater than the sum of the individual parts. An additional driving force behind the SALSA Program’s success is the knowledge that the results of this research will directly aid land managers and decision-makers in the near term.

The order of papers within the special issue is roughly aligned with the first three objectives discussed above, with results from the forth discussed herein. Remote sensing results are presented first followed by SVAT-related research and the parameterization of water and energy fluxes in arid and semi-arid regions. Next a series of papers discuss the representation of heterogeneity in surface-controlling parameters. Several papers then follow addressing the function and dynamics of basin vegetation with special emphasis on the competition for water between grass and mesquite. Finally, a set of papers focused on the San Pedro riparian corridor and the interaction between riparian vegetation, ground water and surface water are presented.

Acknowledgements

Financial support from the USDA-ARS Global Change Research Program, NASA grant W-18,997, NASA Landsat Science Team, grant No. S-41396-F, USDA National Research Initiative Grant Program, Electrical Power Research Institute, Arizona Department of Water Resources, US Environmental Protection Agency, Office of Research and Development; IRD-France, the French Remote Sensing Program (PNTS); EU through VEGETATION Projects and the ERS2/ATSR2 Projects; CONACYT (Project 4298P-T), and US Bureau of Land Management is gratefully acknowledged. Assistance was also provided in part by the NASA/EOS grant NAGW2425, EPA STAR Graduate Student Fellowship Program, National Science Foundation, US Geological Survey, US Department of Energy contract W-7405-ENG-36, California Institute of Technology-Jet Propulsion Laboratory (NASA, EOS/ASTER), WAU (Wageningen Agricultural University, Netherlands), Cochise County Highway and Flood Control Department, and Fort Huachuca; this support is also gratefully acknowledged. Support from the NSF-STC SAHRA (Sustainability of semi-Arid Hydrology and Riparian Areas) under Agreement No. EAR-9876800 is also gratefully acknowledged. Special thanks are extended to the ARS staff located in Tombstone, AZ for their diligent efforts and to USDA-ARS Weslaco for pilot and aircraft support. We also wish to extend our sincere thanks to the many ARS and University of Arizona staff and students, and local volunteers who generously donated their time and expertise to make this project a success.

Appendix A. List of acronyms

ADEOS	Advanced Earth Observing Satellite
ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
ATSR2	Along Track Scanning Radiometer
AUW	Wageningen Agricultural University (Netherlands)
BLM	Bureau of Land Management
CEC	Center for Environmental Cooperation
CEFE	Centre d'Ecologie Fonctionnelle et Evolutive
CESBIO	Centre d'Etudes Spatiales de la Biosphére
CIRAD	Centre de Coopération Internationale en Recherche Agronomique pour le Développment
CNRS	Centre National de la Recherche Scientifique
EFEDA	European Field Experiment in a Desertification-Threatened Area
ERS-2	European Remote Sensing Satellite
FAO	Food and Agriculture Organization of the United Nations
HAPEX	Hydrology–Atmosphere Pilot Experiment
IMADES	Instituto del Medio Ambiente y el Desarrollo Sustentable del Estado de Sonora
INRA	Institut National de la Recherche Agronomique
IRD	Institut de Recherche pour le Développment
Landsat-MSS	Land Satellite Multispectral Scanner
Landsat-TM	Land Satellite Thematic Mapper
MODIS	Moderate Resolution Imaging Spectroradiometer
NASA-EOS	National Aeronautics and Space Administration Earth Observing System
NOAA-AVHRR	National Oceanic and Atmospheric Administration Advanced Very High Resolution Radiometers
SPOT4	Satellite Probatoire d'Observation de la Terre
SPRNCA	San Pedro Riparian National Conservation Area
SVAT	Soil–Vegetation–Atmosphere Transfer Model
UNEP	United Nations Environment Program
USDA-ARS	United States Department of Agriculture-Agricultural Research Service
US-EPA	United States-Environmental Protection Agency

USGS-WRD	United States Geological Survey-Water Resources Division
USPB	Upper San Pedro Basin

References

Agricultural Research Service, 1998. Global Change. National Resources and Sustainable Agricultural Systems. Draft National Program Statement 204, February 1998. US Department of Agriculture, Agricultural Research Service, Washington, DC. Internet Document, URL: http://www.ars.usda.gov/nps/programs/204b.htm.

Bahre, C.J., 1991. A Legacy of Change: Historic Human Impact on Vegetation in the Arizona Borderlands. The University of Arizona Press, Tucson, AZ.

Bolle, H.-J., 1995. Identification and obsenation of desertification processes with the aid of measurements from space. Results from the European Field Experiment in Deserification-threatened Areas (AFEDA). In: Mouat, D.A., Hutchinson, F. (Eds.), Desertification in developed countries. Kluwer Academic Publishers, Dordrecht, 1995, pp. 93–101.

Boulet, G., Chehbouni, A., Braud, I., Vauclin, M., Haverkamp, R., Zammit, C., 2000. A simple water and energy balance model designed for regionalization and remote-sensing data utilization. Agric. For. Meteorol. 105, 117–132.

Bureau of Land Management, 1989. San Pedro River riparian management plan and environmental impact statement. Final. US Department of the Interior, Bureau of Land Management, Safford, AZ.

Cayrol, P., Chehbouni, A., Kergoat, L., Dedieu, G., Mordelet, P., Nouvellon, Y., 2000. Grassland modeling and monitoring with SPOT-4 VEGETATION instrument during the 1997–1999 SALSA experiment. Agric. For. Meteorol. 105, 91–115.

CEC (Commission for Environmental Cooperation), 1999. Ribbon of life, an agenda for preserving transboundary migratory bird habitat on the Upper San Pedro River. CEC, Montreal, Canada, 31 pp. http://www.cec.org.

Chehbouni, A., Kerr, Y.H., Hartogensis, O., Goodrich, D., Scott, R., Schieldge, J., Lee, K., Shuttleworth, W.J., Dedieu, G., De Bruin, H.A.R., 1999. Estimation of area-average sensible heat flux using a large aperture scintillometer. Water Resour. Res. 35, 2505–2512.

Chehbouni, A., Watts, C., Lagouarde, J.-P., Kerr, Y.H., Rodriguez, J.-C., Bonnefond, J.-M., Santiago, F., Dedieu, G., Goodrich, D.C., Unkrich, C., 2000a. Estimation of heat and momentum fluxes over complex terrain using a large aperture scintillometer. Agric. For. Meteorol. 105, 215–226.

Chehbouni, A., Watts, C., Kerr, Y.H., Dedieu, G., Rodriguez, J.-C., Santiago, F., Cayrol, P., Boulet, G., Goodrich, D., 2000b. Methods to aggregate turbulent fluxes over heterogeneous surfaces: application to SALSA data set in Mexico. Agric. For. Meteorol. 105, 133–144.

Chehbouni, A., Goodrich, D.C., Moran, M.S., Watts, C.J., Kerr, Y.H., Dedieu, G., Kepner, W.G., Shuttleworth, W.J., Sorooshian, S., 2000c. A preliminary synthesis of major scientific results during the SALSA Program. J. Agric. For. Meteorol. 105, 311–323.

Cooper, D.I., Eichinger, W.E., Kao, J., Hipps, L., Reisner, J., Smith, S., Schaeffer, S.M., Williams, D.G., 2000. Spatial and temporal properties of water vapor and latent energy flux over a riparian canopy. Agric. For. Meteorol. 105, 161–183.

DeBano, L.F., Ffolliott, P.F., Ortega-Rubio, A., Gottfried, G.J., Hamre, R.H., Edminster, C.B. (technical coordinators), 1995. Biodiversity and management of the madrean archipelago: the sky islands of southwestern United States and northwestern Mexico, September 19–23, 1994, Tucson, AZ. General Technical Report RM-GTR-264. US Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station, Fort Collins, CO, 669 pp.

Eichinger, W., Cooper, D., Kao, J., Chen, L.C., Hipps, L., 2000. Estimating of spatially distributed latent energy flux over complex terrain from a raman lidar. Agric. For. Meteorol. 105, 145–159.

FAO, 1993. Sustainable development of drylands and combating desertification. FAO Position Paper. Food and Agriculture Organization of the United Nations, Rome, 1993.

Forman, R.T.T., Gordon, M., 1986. Landscape Ecology. Wiley, New York.

Goodrich, D.C., 1994. SALSA-MEX: a large scale Semi-Arid Land-Surface-Atmospheric mountain experiment. In: Proceedings of the 1994 International Geoscience and Remote Sensing Symposium (IGARSS'94), Vol. 1, Pasadena, CA, August 8–12, pp. 190–193.

Goodrich, D.C., Simanton, J.R., 1995. Water research and management in semi-arid environments. J. Soil Water Conserv. 50 (5), 416–419.

Goodrich, D.C., Scott, R., Qi, J., Goff, B., Unkrich, C.L., Moran, M.S., Williams, D., Schaeffer, S., Snyder, K., MacNish, R., Maddock, T., Pool, D., Chehbouni, A., Cooper, D.I., Eichinger, W.E., Shuttleworth, W.J., Kerr, Y., Marsett, R., Ni, W., 2000. Seasonal estimates of riparian evapotranspiration using remote and in situ measurements. Agric. For. Meteorol. 105, 281–309.

Goutorbe, J.-P., Lebel, T., Tinga, A., Bessemoulin, P., Bouwer, J., Dolman, A.J., Engman, E.T., Gash, J.H.C., Hoepffner, M., Kabat, P., Kerr, Y.H., Monteny, B., Prince, S.D., Saïd, F., Sellers, P.J., Wallace, J.S., 1994. Hapex-Sahel: a large scale study of land–surface interactions in the semi-arid tropics. Ann. Geophys. 12, 53–64.

Hipps, L.E., Cooper, D., Eichinger, W., Williams, D., Schaeffer, S., Snyder, K., Scott, R., Chehbouni, A., Watts, C., Hartogensis, O., Lhomme, J.-P., Monteny, B., Brunel, J.-P., Boulet, G., Schieldge, J., De Bruin, H., Shuttleworth, J., Kerr, Y., 1998. A summary of processes which are connected to evaporation of riparian and heterogeneous upland vegetation in arid regions. In: Proceedings of the Special Symposium of American Society of Meteorologists on Hydrology, Phoenix, AZ, January 11–16, pp. 13–17.

Houghton, R.A., Hobbie, J.E., Melillo, J.M., Moore, B., Peterson, G.J., Shaver, G.R., Woodwell, G.M., 1983. Changes in the carbon content of terrestrial biota and soil between 1860 and 1980: a net release of CO_2 to the atmosphere. Ecol. Monogr. 53, 235–262.

Jackson, W., Martinez, T., Cuplin, P., Minkley, W.L., Shelby, B., Summers, P., McGlothlin, D., Van Haveren, B., 1987. Assessment of water conditions and management opportunities in support of riparian values: BLM San Pedro River properties, Arizona, Project Completion Report. Report No. BLM/YA/PT-88/004+7200. US Department of the Interior, Bureau of Land Management Service Center, Denver, CO.

Janetos, A.C., 1997. Do we still need nature? The importance of biological diversity. Consequences. The Nature and Implications of Environmental Change, Vol. 3, No. 1, 1997. Saginaw Valley State University, Michigan. Internet document: http://www.gcrio.org/consequences/vol3no1/biodiversity.html.

Jensen, M.E., Everett, R., 1994. An overview of ecosystem management principles. In: Jensen, M.E., Bourgeron, P.S. (Eds.), Eastside Forest Ecosystem Health Assessment, Vol. II: Ecosystem Management: Principles and Applications. PNW-GTR-318, USDA Forest Service, Missoula, MT, pp. 7–16.

Kao, C.-Y.J., Hang, Y.-H., Cooper, D.I., Eichinger, W.E., Smith, W.S., Reisner, J.M., 2000. High-resolution modeling of LIDAR data: mechanisms governing surface water vapor variability during SALSA. Agric. For. Meteorol. 105, 185–194.

Kepner, W.G., Watts, C.J., Edmonds, C.M., Maingi, J.K., Marsh, S.E., Luna, G., 2000. A landscape approach for detecting and evaluating change in a semi-arid environment. J. Environ. Monitoring Assessment, 64 (1), 179–195.

Kustas, W.P., Goodrich, D.C., 1994. Preface to special section on MONSOON'90. Water Resour. Res. 30, 1211–1225.

Lagouarde, J.-P., Chehbouni, A., Bonnefond, J.-M., Rodriguez, J.-C., Kerr, Y.H., Watts, C., Irvine, M., 2000. Analysis of the limits of the $C_T{}^2$-profile method for sensible heat flux measurements in unstable conditions. Agric. For. Meteorol. 105, 195–214.

MacNish, R.D., Unkrich, C.L., Smythe, E., Goodrich, D.C., Maddock III, T., 2000. Comparison of riparian evapotranspiration estimates based on a water balance approach and sap flow measurements. Agric. For. Meteorol. 105, 271–279.

Maddock III, T., MacNish, R., Goodrich, D.C., Williams, D., Shuttleworth, W.J., Goff, B., Scott, S., Moran, M.S., Cooper, D., Hipps, L., Chehbouni, A., 1998. An overview of atmospheric and surface water coupling to regional groundwater models in semi-arid basins. In: Proceedings of the Special Symposium of American Society of Meteorologists on Hydrology, January 11–16, Phoenix, AZ, pp. 38–42.

McDonnell, M.J., Pickett, S.T.A. (Eds.), 1993. Humans as Components of Ecosystems. Springer, New York.

Moran, M.S., Weltz, M.A., Vidal, A., Goodrich, D.C., 1993. Characterization of hydrologic properties of a semi-arid rangeland ecosystem for combined optical–microwave remote sensing. In: IEEE Symposium on Combined Optical–Microwave Earth and Atmosphere Sensing, Albuquerque, NM, March 22–25, pp. 82–85.

Moran, M.S., Clarke, T.R., Kustas, W.P., Weltz, M.A., Amer, S.A., Huete, A.R., 1994. Evaluation of hydrologic parameters in semi-arid rangeland using remotely sensed spectral data. Water Resour. Res. 30, 1287–1297.

Moran, M.S., Hymer, D.C., Qi, J., Sano, E.E., 2000. Soil moisture evaluation using multi-temporal synthetic aperture radar (SAR) in semi-arid rangeland. Agric. For. Meteorol. 105, 69–80.

Nouvellon, Y., Rambal, S., Lo Seen, D., Moran, M.S., Lhomme, J.-P., Bégué, A., Chehbouni, A., Kerr, Y.H., 2000a. Modelling of daily fluxes of water and carbon from shortgrass ecosystems. Agric. For. Meteorol. 100, 137–153.

Nouvellon, Y., Bégué, A., Moran, M.S., Lo Seen, D., Rambal, S., Luquet, D., Chehbouni, A., Inoue, Y., 2000b. PAR extinction in shortgrass-ecosystems: effects of clumping, sky conditions and soil albedo. Agric. For. Meteorol. 105, 21–41.

Perry, E.M., Moran, M.S., 1994. An evaluation of atmospheric corrections of radiometric surface temperatures for a semi-arid rangeland watershed. Water Resour. Res. 30, 1261–1269.

Pinker, R.T., Laszlo, I., Goodrich, D., Pandithurai, G., 2000. Satellite estimates of surface radiative fluxes for the extended San Pedro Basin: sensitivity to aerosols. Agric. For. Meteorol. 105, 43–54.

Pool, D.R., Coes, A.L., 1999. Hydrogeologic investigations of the Sierra Vista subbasin of the Upper San Pedro River basin, Cochise County, Southeast Arizona. US Geological Survey Water-resources Investigations Report 99-4197, 41 pp. and 3 sheets.

Qi, J., Moran, S., Williams, D., Goodrich, D., Scott, R., Chehbouni, A., Cooper, D., Hipps, L., Eichinger, W., Marsett, R., Ni, W., 1998. Estimation of evapotranspiration over the San Pedro riparian area with remote and in situ measurements. In: Proceedings of the Special Symposium of American Society of Meteorologists on Hydrology, January 11–16, Phoenix, AZ, pp. 55–60.

Qi, J., Marsett, R.C., Moran, M.S., Goodrich, D.C., Heilman, P., Kerr, Y.H., Dedieu, G., Chehbouni, A., 2000. Spatial and temporal dynamics of vegetation in the San Pedro river basin area. Agric. For. Meteorol. 105, 55–68.

Renard, K.G., Lane, L.J., Simanton, J.R., Emmerich, W.E., Stone, J.J., Weltz, M.A., Goodrich, D.C., Yakowitz, D.S., 1993. Agricultural impacts in an arid environment: Walnut Gulch case study. Hydrol. Sci. Technol. 9 (1–4), 145–190.

Schaeffer, S.M., Williams, D.G., Goodrich, D.C., 2000. Transpiration of cottonwood/willow forest estimated from sap flux. Agric. For. Meteorol. 105, 257–270.

Scott, R.L., Shuttleworth, J.S., Goodrich, D.C., Maddock III, T., 2000. Water use of two dominant riparian vegetation communities in southeastern Arizona. Agric. For. Meteorol. 105, 241–256.

Shao, X.M., Carlos, R.C., Kirkland, M.W., 1998. Observations of precipitable water vapor in the planetary boundary layer via microwave interferometry. In: Proceedings of the Special Symposium of American Society of Meteorologists on Hydrology, January 11–16, Phoenix, AZ, pp. 33–37.

Snyder, K.A., Williams, D.G., 2000. Water sources used by riparian trees varies among stream types on the San Pedro River, Arizona. Agric. For. Meteorol. 105, 227–240.

Turner, B.L. (Ed.), 1990. The Earth as Transformed by Human Action. Cambridge University Press with Clark University, Cambridge, MA.

UNEP, 1997. Climate change information kit. United Nations Environment programme, Information Unit for Conventions, Châtelaine, Switzerland, January 1997.

Wallace, J., 1995. Multidisciplinary program studies land–atmosphere interactions in semi-arid regions. A Meeting Report on the SALSA Workshop Held in Tucson, AZ, August 1995. EOS, Trans. Am. Geophys. Union 76 (46) 465, 469.

Watson, R.T., Zinyowera, M.C., Moss, R.H., Dokken, D.J. (Eds.), 1998. The Regional Impacts of Climate Change. An assessment of Vulnerability. A Special Report of IPCC Working Group II. Published for the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, 517 pp.

Watts, C.J, Chehbouni, A., Rodriguez, J.-C., Kerr, Y.H., Hartogensis, O., De Bruin, H.A.R., 2000. Comparison of sensible heat flux estimates using AVHRR with scintillometer measurements over semi-arid grassland in northwest Mexico. Agric. For. Meteorol. 105, 81–89.

Whitaker, M.P.L., Maddock, T., MacNish, B., Goodrich, D., Goff, B., 1998. Monitoring bank storage in the San Pedro riparian national conservation area, Arizona. In: Proceedings of the Special Symposium of American Society of Meteorologists on Hydrology, January 11–16, Phoenix, AZ, pp. 195–198.

Woolhiser, D.A., Keefer, T.O., Redmond, K.T., 1993. Southern oscillation effects on daily precipitation in the southwestern United States. Water Resour. Res. 29 (4), 1287–1295.

World Rivers Review, 1997. Biodiversity, North America. World Rivers Review, News Briefs, Vol. 12, No. 1, February 1997. International Rivers Network. Internet document: http://www.irn.org/pubs/wrr/9701/briefs.html.