SEMI-ARID LAND-SURFACE-ATMOSPHERE PROGRAM (SALSA)

WORKING SCIENCE PLAN

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1.0 INTRODUCTION

The Semi-Arid Land-Surface-Atmosphere Program ("SALSA") is a multi-agency, multi-national global-change 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 will accomplish this 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.

1.1 Purpose and Scope of Science Plan

The purpose of this Science Plan is to guide the long-term (5-10 year), programmatic development of SALSA and to serve as the basic terms-of-reference for ongoing and proposed SALSA research activities. Accordingly, the Science Plan defines the SALSA mission and mode of operation; describes the key societal needs and scientific challenges to be addressed; and outlines the general research approach, components, and expected outcomes of the program. As a "living document," the Science Plan will be modified occasionally to incorporate major changes in research needs or direction. The Science Plan focuses on program-level science issues and strategy whereas detailed information on program structure and function, schedules and budgets will be presented in specific implementation plans and related funding proposals.

1.2 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" and "WALNUT GULCH '92," conducted in southeastern Arizona, USA, in 1990 and 1992 (Kustas and Goodrich 1994; Moran et al. 1993); and "HAPEX-Sahel," conducted in Niger, western Africa between 1991 and 1993 (Goutorbe et al. 1994). Scientists from a variety of disciplines, agencies, and nations participated in these intensive, ground-, air-, and satellite-based measurement campaigns; and many of these scientists continue to be involved in SALSA. Several other research programs, emphasizing groundwater modeling, satellite-sensor testing, landscape change, and human dimensions, have since contributed to the development of SALSA and will be cited in subsequent sections of this plan.

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 which would focus initially on the Upper San Pedro Basin (USPB), a high-desert basin located in southeastern Arizona, USA, and northeastern Sonora, Mexico. This basin was chosen as an initial SALSA study area because it exhibits significant topographic and ecological diversity, is the subject of immediate social concern, and has a substantial scientific infrastructure already in place. The challenge posed by this proposal was to evaluate the energy balance for a heterogeneous landscape and then link this information to a regional water balance model.

In July 1995, sixty-five scientists from nine federal agencies, eight universities, six foreign agencies, and several NASA/EOS science teams met in Tucson, Arizona to discuss plans for the SALSA effort (Wallace 1995). They represented a broad spectrum of science disciplines including, ecology, soils, meteorology, remote sensing, atmospheric science, and hydrology, among others. During the workshop, participants formed several cross-disciplinary groups that proposed goals and objectives for specific research projects to be conducted under the umbrella of SALSA. These initial objectives and associations, along with the general agreement to cooperate toward a common research goal, evolved into an operational research program with the commencement of the 1996-1997 field campaign ("Riparian Campaign") and mesoscale meteorological modeling activities.

1.3 Primary Science Question

A principal outcome of the 1995 Workshop was the formulation of the Primary Science Question to be addressed by SALSA researchers:

> *What are 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?*

This fundamental question both defines the scope of the research problem and serves as the basis for deriving all secondary science questions and science challenges. It purposefully focuses on two separate but highly interrelated ecosystem components: water balance and ecological complexity. The terrestrial water balance determines water availability, which is 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 as well. This is especially true of basins in mountainous regions where the range-and-valley topography strongly influences habitat and landuse patterns. 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.

Ultimately, the scientific understanding of hydrological and ecological processes acquired by SALSA will be used to assess the "consequences" of global environmental change on human systems within semi-arid basins. Quantification of the "human dimensions" of global change will require cooperation among a broad range of earth and social scientists. This will be accomplished within SALSA as well as through interaction and cooperation with other research efforts that specifically address the social impacts of global change. The human dimension component of global change will serve both to guide SALSA research and as the end-point for the research effort.

1.4 Mission Statement

The Mission of the SALSA is to address the Primary Science Question; that is:

> *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?*

To accomplish this mission, SALSA must develop and sustain the following:

- a keen awareness of societal concerns and research needs regarding global change in semi-arid regions, and the ability to identify and overcome the scientific challenges to addressing these concerns and needs;
- a flexible and adaptive research approach that encourages innovation, collaboration, and a global perspective among scientists from a wide range of disciplines; and
- a strong core program responsible for coordinating and integrating research activities and developing a publicly accessible "knowledge-base" containing the products of the research effort.

These essential components of the SALSA mission are discussed in detail below.

1.5 Mode of Operation

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 Question. 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 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.

A simple analogy for the way SALSA operates is the "family jig-saw puzzle," where the puzzle-picture represents the answer to the Primary Science Question and the table represents the SALSA research platform. "Family members" are free to spend as much time at the table as they wish assembling those portions of the puzzle of interest to them. Each family member benefits from the previous and concurrent work of others, and in turn, helps others by completing some small portion of the picture. The completion of each portion of the puzzle requires new assessments to be made and provides new opportunities for fitting the remaining pieces. Over time, patterns and relationships become apparent and the remaining pieces are easily put in place to complete the picture.

This puzzle-solving process can be accelerated by collaboration and coordination among participants, and by directing extra effort at parts of the puzzle that are not being solved. The role of the SALSA core program is to help coordinate and facilitate the puzzle-solving process, that is, answering the Primary Science Question. The role of the SALSA researcher is to collaborate with fellow SALSA researchers to gain maximum benefit from the resources used to answer the Question. How SALSA collaborators will do this is described in the sections on Research Approach and Program Components below.

2.0 SOCIETAL CONCERNS AND RESEARCH NEEDS

Until relatively recently, large changes in earth systems have occurred as the result of natural forces beyond human influence or control (USGCRP 1997). Now, humans themselves have become powerful agents of environmental change, not only on local and regional scales but on a global scale as well. Although the eventual magnitude and direction of the change is still a matter of conjecture, all indications are that global change will have a profound and lasting impact on human and natural systems worldwide. The high-level of concern on this issue is reflected by the numerous national and international initiatives that have been established to investigate global change (USGCRP 1997, WMO 1998, IGBP 1998, IPCC 1998).

“Global change” is the collective term for changes in the global environment that may alter the capacity of the Earth to sustain life (U.S. Global Change Research Program Act of 1990). It encompasses the full range of natural and human-induced changes, including alterations in climate, land productivity, water resources, and ecological systems. These changes may lead to significant global warming, alter world climate patterns and adversely affect world agricultural production, biological diversity, human health, and global economic and social well-being.

Although the ultimate goal of SALSA is to evaluate the consequences of global change on semi-arid regions in general, the near-term research focus will be on a single river basin in a semi-arid region of the United States and Mexico. This location provides SALSA with the opportunity to investigate three interrelated areas of concern: semi-arid regions, Arizona-Sonora borderlands, and the Upper San Pedro Basin.

2.1 Semi-Arid Regions

Over 20 countries worldwide, most of them in arid and semi-arid (dryland) regions, are considered to be either water-scarce or water-stressed because their growing populations require more water then 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; about 30 percent 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 global climate 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 germplasm─drylands are the ancestral home of major crop species such as wheat, barley, sorghum, etc─increases the vulnerability to agricultural systems worldwide. Predicted rapid changes in global climate will only 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 have already manifested themselves in many 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. 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 (Upper San Pedro Basin) as its primary experimental and observational area but will incorporate information from related studies 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 Arizona-Sonora Borderlands

The borderlands between the US state of Arizona and the Mexican state of Sonora are characterized by arid to semi-arid conditions, mountainous terrain, and limited water availability—factors that historically limited human populations in the area (Sheridan 1995). Even though the history of land use has differed significantly between the two countries, after 150 years the integrity of many of the region's transborder ecosystems remains largely intact, if somewhat modified (DeBano et al. 1994). In recent decades, however, new technologies, trade liberalization, and demographic shifts have accelerated settlement on both sides border, greatly increasing human-induced changes to the environment and increasing the region's vulnerability to the adverse effects of natural climate fluctuations as well as prospective global climate change (Thompson 1997).

Both the regional water balance and the distribution of biotic communities are closely linked to long-term temperature and precipitation patterns. Liverman and Bales (1997) examined the effects of global warming on the climate Arizona-Sonora border region using the simulation output of a general circulation model. According to the model, a doubling of greenhouse gas concentrations in the atmosphere by 2050 would increase annual temperatures (but decrease the daily temperature range), increase the number of extreme hot while decreasing the number of cold days, and lead to more winter and less summer precipitation. Such changes, if they occurred, could have significant adverse impact on natural ecosystems as well as on the agriculture and ranching sectors in the region. (Udall Center 1997, McClaran 1997). The authors point out, however, that there are many uncertainties and unknowns in these predictions.

For example, the model cannot accurately simulate the effects of the complex regional topography on the summer monsoon, nor can it predict with certainty the degree to which the frequency and intensity of extreme storms will change. Even if the model had these predictive capabilities, our current understanding about the hydrology of river basins in the border region is insufficient to fully assess the effects of climate change (Liverman et al. 1997). More information is needed about the role of mountain snowpack in recharging regional aquifers, the rate of evapotranspiration from riparian areas, and the contribution of surface and groundwater flows from one country to the other, among other factors, to make reliable assessments.

Thompson (1997) emphasized that, whether or not global climate change does occur, human-induced environmental change has already affected the ecological complexity of the Arizona-Sonora border land. Livestock grazing, fire reduction, habitat loss, and invasion by exotic species have all reduced, to some measure, regional biodiversity. This process is not new, but a continuation of the changes brought on by European settlement of the area in past centuries (Bahre 1991). Even so, the rapid conversion of grassland to shrubland (a form of desertification), the fragmentation and reduction of habitat patches, and the disruption of wildlife corridors by suburban development—as revealed by repeat satellite observation over the past 20 years (Kepner, Riitters, and Wiickham 1995)—indicates an overall decline in ecological complexity within the border environment.

The Arizona-Sonora borderlands experience environmental and societal stresses shared by many semi-arid regions worldwide: rapid population growth, historical and current human-impacts on the landscape, over-exploitation of water resources, and threatened loss of biodiversity. Added to this is the complication of an international border which cuts across watersheds and biotic communities, and separates two countries having different economic, social, and political resources and concerns. Even on the US side of the border, where a considerable amount of information is available on water and biotic resources, not enough is yet known to make reliable assessments about the effect of climate change on human and natural ecosystems. More information is needed on basic hydrological processes, such as aquifer recharge and evapotranspiration from riparian areas, and on ecological processes such as the historic and current role of fire, exotic plant species, livestock grazing, and habitat loss on the ecological complexity of the region.

2.3 Upper San Pedro River Basin

The Upper San Pedro Basin, located in the semi-arid borderland of southeastern Arizona and northeastern Sonora, is a broad, high-desert valley bordered by mountain ranges and bisected by a narrow riparian corridor sustained by an intermittent stream. 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 1998). Although commonly viewed as undisturbed wildland, the upland and riparian environments of the San Pedro valley have been radically altered over the past hundred years by human activities (Bahre, 1991). Despite this past disturbance, the extant cottonwood-willow riparian forest supports a great diversity of species—some endangered with extinction—and is widely recognized as a regionally and globally important ecosystem (World Rivers Review, 1997). In addition, the grassland and montane ecosystems at the higher elevations are considered to have great biological significance (DeBano et al. 1995)

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 (BLM, 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). By far, the biggest concern is excessive groundwater pumping by Fort Huachuca and the City of Sierra Vista which has resulted in a large "cone-of-depression" between the groundwater recharge area of the

Huachuca Mountains to the west and the river to the east (ADWR, 1991). Several hydrogeologic studies indicate that the cone-of-depression is intercepting groundwater that would otherwise contribute to river baseflow (USAG, 1997).

If pumping is diminishing groundwater flow to the floodplain aquifer, the resultant drop in the water table could kill riparian phreatophytes (Stromberg, 1993) and destroy protected habitat within the SPRNCA. This possibility has alarmed environmentalists, provoking calls for government to correct or mitigate the situation (Davis, 1995). In response, Fort Huachuca, the City of Sierra Vista, and Cochise County have undertaken programs to conserve water, recharge municipal effluent, and enhance natural recharge (City of Sierra Vista, 1997). However, some critics view these measures as insufficient. Pro-environmental groups have sued the US Army in an attempt to limit water use in the basin (Silver, 1994). They have also prompted the tri-national Commission on Environmental Cooperation (CEC) to study the potential transborder impact of habitat loss on migratory birds (Earthlaw, 1997). Pro-development groups counter that growth and habitat protection are compatible using the proposed technological solutions. The overall effect has been to polarize segments of the community, confuse others, and increase distrust in government efforts to resolve the problem.

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. Research needs to be conducted on the key hydrological components of 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 landuse features within a well-defined drainage system about 40 km across and 150 km long. These characteristics will be useful in developing and testing land-surface-atmosphere process models, and calibrating and validating satellite-based Earth observation systems (Wallace, 1995). 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., 1995). The study area also includes the USDA-ARS Walnut Gulch Experimental Watershed, a densely instrumented facility that has served as a center for research in the hydroclimatology of semi-arid lands for over 40 years (Goodrich and Simanton, 1995).

3.0 SCIENCE QUESTIONS AND CHALLENGES

If all were known about the state and operation of the water balance and ecological complexity of semi-arid basins in general, and the Upper San Pedro Basin in particular, answering the Primary Science Question would be a relatively straightforward exercise. In reality, there are substantial gaps in our knowledge about these systems that prevent us from doing this. To address the Primary Science Question, it is first necessary to ask and answer a series of secondary questions so as to provide information needed to fill in the knowledge gaps. In most cases, secondary questions themselves cannot be answered without further breaking them down into even simpler questions that can be investigated at the level of a "research project" having well defined objectives and testable hypotheses.

This is the primary challenge to SALSA: to devise and implement a research program that systematically fills in the gaps in our knowledge about the water balance and ecological complexity in semi-arid basins. This Science Plan outlines the way in which SALSA will meet the challenge of the Primary Science Question. In turn, each secondary and subsequent question will have its own scientific challenges associated with it. These secondary challenges will be identified and overcome by individual SALSA collaborators on a project-level.

Below is a list of science questions currently being addressed by SALSA researchers. This does not represent a comprehensive list of all science questions which must be addressed to answer the Primary Science Question, but rather reflects the opportunistic approach of SALSA research. They are project-level questions that can be addressed with available or potential resources. The questions have been arranged in the two categories specifically identified in the Primary Science Question and two that are implied: water as an ecosystem component and technology development. Most of the questions cross multiple categories so the division is somewhat arbitrary.

3.1 Water Balance

A considerable amount of knowledge is currently available regarding water balance dynamics in semi-arid regions in general, and the Upper San Pedro Basin in particular. For example, in the USPB, the long-term water budget and the workings of the regional aquifer system are generally well known. However, our current understanding of the system is not of sufficient detail to make accurate predictions about the effect of groundwater pumping or phreatophyte transpiration on streamflows. Nor is enough known about energy and water fluxes on the basin uplands and riparian areas to predict the rate and extent of evapotranspiration from these surfaces over time. The questions below try to address some of these issues.

<u>Basin Water Balance</u>

- Can estimates of basin recharge be made as a function of seasonal and interannual climate variation and can the uncertainty in these estimates be reduced?
- Can basin recharge quantities be separated into distinct sources (mountain front, upland, ephemeral channel)?
- Can accurate estimates of basin-wide precipitation be derived from ground-based radar for both summer (air-mass thunderstorms) and winter (frontal) precipitation regimes?
- In this dry environment, is snow sublimation a significant portion of the basin water balance? If so, how can it be better quantified?

Groundwater-Surface Water Processes

- What is the groundwater-surface water interaction at the stream-aquifer interface under conditions of regional pumping and seasonally and interannually varying streamflow?
- How does bank storage respond to diurnal, seasonal, and storm-induced riverbank groundwater-level fluctuations?
- What is the quantity of transmission loss that arrives in deep aquifers?
- What are the streamflow characteristics in ephemeral stream channels?

Surface Energy and Water Fluxes

- What are the effects of surface heterogeneities and terrain on the spatial and temporal distribution of sensible and latent heat fluxes in the semi-arid San Pedro Basin?
- What are the possible effects of land use changes (particularly from grasslands to mesquite lands) on various components of water and carbon dioxide fluxes in semi-arid ecosystems?
- What are the water and energy fluxes over the two dominant vegetation biomes in the riparian corridor of the upper San Pedro River?
- What are the C3 and C4 plant photosynthetic and evapotranspiration fluxes on seasonal and interannual scales from key ecosystems in the San Pedro Basin?
- What are the environmental control on leaf stomatal conductance and transpiration on diurnal and seasonal time frames?
- What is the energy balance, especially evaporation rates, from a tamarisk and cottonwood forest at the Bosque del Apache in southern New Mexico?

3.2 Ecological Complexity

Much of our understanding about ecological complexity in semi-arid regions is based on single-species or habitat management studies. Relatively little is known about how species and habitat interact with other landscape features. Research is needed in all areas of ecology that link structural and functional determinants of ecological complexity at species-, habitat-, and landscape-levels. The following questions are posed by SALSA collaborators representing the disciplines as diverse as botany, ecophysiology, wildlife ecology, and physical science.

Species-Level Processes

- What is the role of soil moisture, soil texture, and planting depth on establishment of sacaton seedlings?

- How do the vigor and abundance of mature sacaton vary with site factors including depth to groundwater and channel incision?
- Will inoculation with mycorrhizal fungi increase the survivorship and spread of sacaton on abandoned fields?
- What are the life history characteristics that determine the type and magnitude of a species' sensitivity to fragmentation and, more specifically, habitat edges and landscape boundaries?
- What are the water sources and patterns of water utilization and seasonal stress in riparian tree species?
- Are species with access to a stable water source, in this case groundwater or perennial streamwater, more or less likely to grow lateral surface roots to acquire soil moisture from precipitation?

Habitat and Community Level Processes

- Are there relationships between soil factors and plant community composition (including relative abundance of native vs. exotic plant species) within abandoned agricultural fields?
- How do microclimatic factors change when a large block of suitable habitat is fragmented into several smaller blocks?
- How do these factors vary along a chronosequence of time-since-abandonment, and can these relationships form the basis for proscribing management actions (such as soil amendments) that would hasten the development of native riparian communities?
- Are there sensitive and easy-to-measure stress indicators that can be used by managers to detect loss of biotic integrity in Fremont cottonwood forests?
- Are present river management practices along cottonwood-dominated rivers in the Southwest adequate to maintain natural successional processes, and if not, how the practices should be modified?

Landscape Level Processes

- Are landscape composition and pattern indicators sensitive measures of large-scale environmental change and can they provide an effective method for evaluating watershed and ecological condition related to disturbance from human and natural stresses?
- Can the impacts of change in landscape composition and pattern on watershed hydrologic response be quantified?
- Is wildlife habitat affected at multiple scales by landscape patterns and processes?

- What economic, social, political, and ecological processes interact to generate land use patterns in the Tijuana and San Pedro watersheds, and how do these patterns and processes influence environmental conditions in the two basins?

3.3 Water As An Ecosystem Component

Many questions are directly related to neither basin water balance nor ecological complexity but involve issues of "biohydrology" in which water is a key ecosystem component. However, the answers to these questions provide information needed to answer questions about the water balance and ecological complexity.

- Does passive transfer of soil water from wet to dry layers through root systems have an impact on hydrologic balance of streamside ecosystems?
- Does significant "deep" (greater than 30 cm) vadose zone recharge occur in semi-arid areas and does this recharge provide an ecological niche for deep- rooted plants?
- What is the seasonal to annual water use of different riparian vegetation communities and where does this water come from? (groundwater, deep soil moisture, flood flows, or recent precipitation?)
- How is biotic integrity affected by hydrologic alterations in the form of groundwater decline, loss of surface flow, and modification of flood patterns?

3.4 Technology Development

The answers to many of the questions posed above will provide important information about the river basin or basins being studied by SALSA (primarily the USPB). However, just as important, is the development of detection, analysis, and predictive technologies that can be used to assess environmental conditions and response in other basins. Thus, several SALSA researchers are asking questions that will test the applicability of satellite, airborne, and ground-based remote sensors, atmospheric and plant growth models, and decision support system, for use in semi-arid environments.

- How can ASTER be used to accurately represent surface energy fluxes from local to regional scales for use in limited area climatological and hydrological models?
- What is the sensitivity of ERS-2 C-band SAR (synthetic aperture radar) backscatter measurements to surface soil moisture content in a semi-arid rangeland with sparse vegetation cover?
- How can Landsat TM (thematic mapper) and radar (ERS-2 SAR) measurements be combined to improve regional estimates of surface soil moisture content?
- Can high resolution TIR (thermal infra-red) aircraft measurements from aircraft overflights be used to statistically analyze the relation between radiometric surface temperature and in situ surface measurements of temperature and convective heat flux densities?

- Can high-spatial-resolution optical digital images be used to monitor variability in plant vigor (e.g., transpiration rate and growth rate) of riparian cottonwood and willow trees and associated grasslands and mesquite thickets?
- How do different convective heat flux density methods compare in performance, accuracy, and robustness?
- Can water vapor flux from riparian vegetation be estimated using LIDAR measurements of humidity fields?
- Can the biologically significant aspects of habitat type and landscape composition be determined from remotely sensed data products?
- Are wildlife habitat composition and pattern indicators derived from remotely sensed imagery, e.g. Landsat MSS or TM, diagnostic of ecological condition and change and can they be utilized as an effective method for characterizing landscape vulnerability to disturbance associated with human-induced and natural stress?
- What adjustments are needed to improve the assimilation process for the effects of sub-grid heterogeneity?
- How can satellite-sensed surface thermal data be assimilated into the atmospheric model so as to improve the model's partitioning of surface energy fluxes?
- How can remotely sensed measurements be coupled with a soil-vegetation-atmosphere transfer (SVAT)-Vegetation Function model?
- How can hydrologic models, a riparian ecosystem integrity index and economic analyses be integrated into a user-friendly decision support system (DSS)?

4.0 RESEARCH APPROACH

In order to address the Primary Research Question and associated secondary questions, SALSA has adopted a research approach based on the principle of voluntary collaboration and opportunistic investigation. SALSA maintains an open research framework: new researchers and projects can be added or subtracted to the program to suit their particular needs. Each project contributes something to answering the Primary Science Question, while benefiting from the collaborative interaction. Knowledge is accumulated incrementally in the SALSA "knowledge-base" which will be the ultimate program product.

4.1 Interdisciplinary Research

To accomplish its multifaceted mission, SALSA must draw on the expertise and research skills of researchers from a variety of natural and social science disciplines. Hydrologists, biologists, ecologists, and other earth scientists will work to quantify key hydrologic and ecological processes and interactions within semi-arid basins. Physical scientists will collaborate with earth scientists to develop and apply the remote sensing technologies needed to measure and monitor surface processes over a broad range of spatial and temporal scales. Modelers will use the knowledge generated by SALSA experiments and observations to create better predictive tools, and together social and earth scientists will use these predictive capabilities to assess the impact of global change on human and natural systems.

Different types of research will require different levels of interaction among the disciplines: most process studies and monitoring activities will be uni-disciplinary, while field campaigns, sensor development, modeling, and assessment activities will require a high degree of inter-disciplinary and cross-disciplinary collaboration and cooperation. SALSA provides a common platform for scientists from various disciplines to come together and share resources and data to their mutual advantage. Any researcher that seeks to answer some component of the Primary Science Question, is welcomed to join the SALSA effort.

4.2 Phased Implementation

The components of the SALSA research program will not all be active at once but will be phased in and out according to need and available resources of the program. In the early stages, most effort will go into conducting process studies and field campaigns, and the establishment of observation systems and monitoring networks, within the Upper San Pedro Valley. Once sufficient data is available for analysis, more emphasis will be placed on process and systems modeling and prediction. These accumulated data will also support the development of new remote sensing technologies. The model outputs will contribute to assessments of global change impacts on the water balance and ecological complexity of the Basin. Ultimately, relationships, methods, and technologies developed for the USPB study can be extended and applied to other semi-arid environments within the region or globally.

4.3 Innovative Technologies

A vital part of SALSA research is the use of innovative technologies to measure and evaluate land-surface-atmosphere processes and interactions. For example, SALSA will use a combination of airborne and satellite-based remote sensors to help determine the distribution of energy and water flux over a basin. In return, ground-based data collected by SALSA will help calibrate and validate processing algorithms used by these systems. Because of SALSA, it is anticipated that the value of the Upper San Pedro Basin as a semi-arid test site for a number of remote sensing programs including EOS Pathfinder, Landsat, ASTER, ERS-2, SPOT4, ADEOS, ATLAS, and MODIS systems.

Two other ground-based remote sensing systems are also being further refined as part of the SALSA program: the Raman Lidar and the Large Aperture Scintillometer. The Lidar, laser ranging device, can be used to map humidity fields over transpiring vegetation. Research is being conducted to use Lidar data, in conjunction with other micrometeorological measurements, to measure actual evapotranspiration fluxes. The Scintillometer has been used extensively by SALSA researchers in Mexico and the United States to measure average sensible heat flux over large, heterogeneous surfaces. These measurements can than be used to help calibrate satellite remote sensing systems that integrate fluxes over several hectares.

SALSA data is also being used in the development of models ranging in scale from vegetation patches to regional climate. SALSA data have been used to develop a soil-vegetation-atmosphere transfer (SVAT) model of the grassland on the Mexico side of the USPB. Remotely sensed and ground-based energy flux data collected by SALSA have been used to make real-time adjustments to a mesoscale climate model. Several SALSA researchers are using remote sensing technology and geographic information systems to detect and analyze landscape change and to model the effect of landscape change on watershed response. Still others are expanding and improving a groundwater model of the USPB in order to better predict the effects of human and natural water use on water levels in the aquifer and river.

4.4 Interagency Cooperation

SALSA serves as a model of interagency cooperation. Scientists from about 20 US, 5 European (4 French), and 3 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. This includes such agencies as the US Bureau of Land Management, Arizona Department of Water Resources, Cochise County, and the National Audubon Society. Some of these agencies have provided funds or services-in-kind for SALSA-related activities and SALSA, in turn, has provided these groups with information to help in policy-making and resource management within the USPB. SALSA also maintains contact and shares some data with other research programs involved in global change research or planning within the USPB, such as the UA-NOAA Southwest Climate Assessment Program and the Army-Harvard Alternative Futures Program. It is likely that SALSA will cooperate more closely with this groups as the "human dimensions" aspect of the program becomes better developed.

4.5 Links to Other Programs

SALSA is linked to several other global change research programs, primarily through its collaborating scientists whose agencies and institutions typically have their own global change research emphasis. Thus SALSA is closely tied to the ARS's national global change program, which like most US agencies is guided by the US Global Change Program, and similarly, to the global change research activities of the French agency IRD. SALSA is also associated with various remote sensing technology development efforts including NASA-EOS, ASTER, ERS-2, SPOT4, ADEOS, and MODIS programs.

It is anticipated that, in the future, SALSA will play a role in some of the continental and global-scale climate studies currently underway or being developed. These include the GEWEX Continental-Scale International Project (GCIP), CLIVAR (Climate Variability and Predictability, and SuomiNet. Climate research in the Upper San Pedro Basin, and

Arizona-Sonora in general, can help these larger programs understand the relationship of the American monsoon to global climate patters. SALSA is well situated to help in this regard.

5.0 PROGRAM COMPONENTS

The SALSA research program can be divided into several linked components which operate to fulfil the SALSA Mission. The core program component, provides for the coordination of the other components. Environmental data are collected through the process studies and field campaigns, and monitoring and observation, components. These data are managed by the data assimilation component, and used in the modeling and prediction component to determine system response to various stressors. Information from the field and modeling studies contribute to the environmental assessment component which address the "consequences" part of the Primary Science Question. The technology development and transfer component of the program assures that new knowledge and understanding gained through SALSA contributes to the body of science about global change.

5.1 Core Program

Maintenance of a strong core program component is critical to the success of the SALSA mission. The purpose of the core program is to provide long-term institutional support to SALSA, particularly in terms of administration, strategic planning, and information management. The agencies responsible for this component will take the lead in promoting SALSA mission objectives, coordinating funding proposals, and serving as liaison between the researchers and the stakeholder community. Most importantly, these agencies will ensure the successful close-out of the program at the end of its tenure, including the incorporation of SALSA findings into the greater body of global change knowledge.

The USDA Agricultural Research Service (ARS) in Tucson, Arizona is the institutional home of SALSA and supports the program as part of the agency’s global change research effort (ARS 1998). 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. In addition to its administrative role, the ARS is a major contributor to the SALSA effort in terms of science infrastructure (Walnut Gulch Experimental Watershed), field and office support (Tucson and Tombstone offices), and research design and implementation. The ARS works closely with its cooperators at the University of Arizona in performing core program tasks.

IRD is a principal SALSA collaborator and shares program leadership and research management responsibilities with the ARS. IRD and its sister agencies CESBIO, CNES 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—direct and implement SALSA activities in Mexico. IRD and the ARS also share responsibility for the development and long-term maintenance of the SALSA knowledge-base.

5.2 Process Studies and Field Campaigns

Process studies will be a primary mechanism by which SALSA acquires new knowledge about hydrological and ecological processes operating within semi-arid river basins. A process study is typically a uni-disciplinary investigation or experiment involving the measurement of one or more closely related environmental variables. Individual process studies serve to address secondary or tertiary science questions derived from the Primary Science Question; that is, to discover relationships among variables or to test hypotheses. Data and other information products generated by process studies will be incorporated into the central SALSA knowledge-base in order to support modeling and assessment activities, as well as subsequent process studies.

A field campaign represents a highly coordinated, multi-variate process-study centered around a specific theme. Field campaigns require a high-degree of cross-disciplinary collaboration, interagency cooperation, and resource sharing. They are typically conducted over one or more intensive measurement periods during which the variables of interest are sampled at comparable time intervals over a wide range of spatial scales, using both *in situ* and remote sensing techniques. SALSA field campaigns are designed to answer one or more secondary science questions and to generate an integrated "packet" of knowledge that can be disseminated in a unified format, such as a special-issue publication of a scientific journal. Such efforts are anticipated to provide major systematic increases to the knowledge-base.

Basin water balance will be examined primarily in terms of the hydrologic cycle, requiring process studies in the sub- and allied disciplines of hydrology (e.g., hydrogeology, watershed hydrology, climatology, atmospheric science), as well as those sub-disciplines of biology that control water fluxes (e.g., plant physiology). Typical collaborative groupings for water balance studies include: groundwater-surface water interactions, surface energy and water flux dynamics, watershed response, and ephemeral stream recharge. Ecological complexity of a basin will be evaluated primarily through process studies in biology, ecology, and geography-related disciplines. Typical collaborative groupings for ecological studies include: riparian ecology, grassland and shrub-steppe dynamics, habitat fragmentation, and landscape analysis.

Although there will always be some degree of cross-disciplinary collaboration in individual process studies, the thematic field-campaigns will provide the major opportunity for interdisciplinary research. Remotely sensed measurements of surface conditions and fluxes will be used to provide synoptic and integrative views of the processes affecting water balance and ecological complexity within the basin. In turn, ground-based measurements of these processes will be used to calibrate and validate existing remote sensing systems and to develop new remote sensing technologies and applications.

5.3 Monitoring and Observation

SALSA will utilize monitoring networks and observation systems to collect data needed to support its process studies, modeling, and assessment activities. This will involve the periodic or occasional measurement of key environmental variables (geoindicators) over short and long time spans (event to decadal). In this discussion, monitoring networks refer to point- or area-integrated- measurement stations (*in situ* sensors) that record non-spatial data (time series), whereas observation systems refer to remote-sensing platforms (e.g., satellites, aircraft, radar) that provide spatial data (imagery). For the most part, SALSA will rely on data collected and made available through existing monitoring and observation systems, but when needed may initiate its own basin-scale systems. Geoindicator data generated by SALSA or acquired elsewhere will be incorporated into the common SALSA knowledge-base and will be used in support of subsequent process studies, modeling, and assessment activities.

The existing science infrastructure in the Upper San Pedro Basin features numerous monitoring networks having sufficiently long periods-of-record to be used in water balance analysis. Meteorological and precipitation networks are operated by several government entities on both sides of the international border, including the National Weather Service, the US Army-Fort Huachuca, and the USDA-ARS Walnut Gulch Experimental Watershed. Groundwater (well-level) networks are maintained in the basin by the US Geological Survey, the Arizona Department of Water Resources, the Bureau of Land Management, and the US Army-Fort Huachuca. The USGS also maintains several stream gaging stations on the mainstem and tributaries to the San Pedro River, while the ARS uses a nested-set of flumes and stock-ponds to measure surface runoff from the Walnut Gulch Experimental Watershed (WGEW).

Ecological monitoring networks in the Upper San Pedro basin are less formalized than those for water resources, but they do exist. The US Bureau of Land Management, US Forest Service, and the US Army-Fort Huachuca periodically assess land condition and trends on the property they manage. The USDA Natural Resources Conservation Service, the US Fish and Wildlife Service, the Arizona Game and Fish Department, and the ARS (on the WGEW) in the US, and agencies like IMADES and the Secretaría de Medio Ambiente, Recursos Naturales y Pesca Comisión Nacional del Agua in Mexico (SEMARNAP), also monitor the condition of certain ecological resources on public and private property within the Basin. Additionally, some non-governmental organizations, such as the Audubon Research Ranch and The Nature Conservancy, sustain their own monitoring programs, typically in conjunction with university (e.g., University of Arizona, Arizona State University, and Colorado State University) and agency researchers.

The development and application of remote sensing technologies for observing basin-wide hydrological conditions and processes is a major goal of SALSA. Satellite and airborne remote sensing imagery will be used to measure watershed conditions (topography, drainage pattern, vegetation and soil moisture distribution, etc.) as well as energy and water and fluxes (albedo, evapotranspiration, etc.). Repeat satellite and airborne imagery will be used to examine trends in surface conditions over a range of time scales from seasonal to decadal.

5.4 Data Assimilation

Assimilation of new data into a coherent body of scientific knowledge is fundamental to the SALSA mission. This body of knowledge, or “knowledge-base,” will be a principal product of the SALSA effort, serving not only SALSA collaborators but other global change scientists and interested stakeholders as well. For purposes of this Science Plan, the knowledge-base need only be described in general conceptual terms: its eventual scope, structure, and operational characteristics will be determined over time as the program evolves. However, it is important that the central concept of a knowledge-base be understood and endorsed by SALSA collaborators, and included as a key component of their research and data organization efforts.

The SALSA knowledge-base is envisioned as a “system” that will allow SALSA-related data sets, meta-data, information products, and research tools to be stored, organized, accessed, and retrieved in an efficient and effective manner. It is not meant to be a single, all-encompassing “data-base” containing file after file of experimental-data, but rather it would be a distributed network of data and information sources that could be accessed through a central interface. A crucial component of the knowledge-base will be the meta-data (descriptive files) stored within a central computer server, housed at one of the SALSA core institutions. The meta-data will direct the user to the physical location of the information source, either via an internet link (the ideal) or by other means.

This knowledge-base will be an important mechanism for exchanging data and information during the life of the program. Data sets created by process studies, field campaigns, and observation and monitoring efforts will be used to develop hydrology and ecosystem models, test remote observation systems, and provide base-line data for new process studies and resource assessments. Information products derived from these activities will feed-back into the knowledge-base where they will contribute to subsequent research activities. In this way, the SALSA will maximize the benefit obtained from each unit of effort.

SALSA data sharing policy will follow that established by the U.S. Global Change Research Program, which encourages timely and full disclosure of research results. SALSA collaborators will be expected to abide by these principles. Whenever possible and practical, data sets and information products that are commonly needed by SALSA collaborators and end-users will be stored on the central SALSA server or that of another major institution where the files can be accessed through the internet. Meta-data standards will be made compatible with existing formats (e.g., NASA DIF files) so that SALSA data sets can be available to the greater global change community.

5.5 Modeling and Prediction

Data derived from process studies and field campaigns, as well as observation and monitoring activities, will serve as input to various water balance and ecological models of the basin. The nature and extent of these models will be determined by the needs of individual SALSA investigators or collaborative groups: there is no plan to develop an all-encompassing, integrated model of the basin. However, SALSA derived models will serve two principal purposes: 1) to provide a framework for analyzing basin systems and identifying gaps in understanding (conceptual modeling) and 2) to predict the effect of various conditions and stresses on system outputs (process modeling). The results of the modeling effort will be used to support SALSA environmental assessment activities; improve experimental, monitoring, and observation methods; and develop modeling tools and procedures that can be applied to other semi-arid regions of the world.

5.6 Environmental Assessment

The results from SALSA field research, monitoring, observation, and modeling activities, will provide much of the information needed to assess the “consequences” of natural and human-induced changes on the water balance and ecological complexity of semi-arid river basins. Additional information will be obtained through cooperation and collaboration with related research efforts, such as those conducting research on the socio-economic or human dimensions aspects of global environmental change. The theme, scope, and format of the environmental assessments will be determined by the needs of the user community.

6.0 EXPECTED OUTCOMES

6.1 Near-Term Outcomes

Because SALSA research is driven by societal concerns and focuses on applied science applications, the transfer of research data and information products to SALSA information-users will be relatively rapid. Preliminary findings will be released to SALSA cooperators and information-users shortly after completion of the field study and initial data analysis, primarily through the SALSA website at:
http://www.tucson.ars.ag.gov/salsa/salsahome.html. After additional analysis and peer review, these findings will be published in scientific journals either as individual papers or as a SALSA special issue.

In the near-term, SALSA will develop a "distributed database" in which most of the data will be held by the originating researcher, but a centralized "meta-data" base will be used to track the type and extent of the data held by individual researchers. Important common data sets, such as some remote sensing images, GIS layers, and standard meteorological conditions will be incorporated into a centralized SALSA database accessible to all SALSA researchers.

6.2 Mid-Term Outcomes

As SALSA continues to assimilate data from process studies, field campaigns, and observation and monitoring activities, these data will contribute to the development of processed-based models of water balance and ecological complexity; and to the calibration and validation of remote sensing technologies. These models can be used to identify knowledge gaps in our understanding and to indicate further areas of research. The models will also be used to make initial assessments of the potential effects of global change on the hydrologic and ecological systems within the USPB.

It is anticipated that SALSA will acquire funding that can be directed at specific knowledge gaps, thereby accelerating progress towards answering the Primary Science Question. As SALSA collaborators complete research projects within the USPB, they will likely extend SALSA to other semi-arid regions of interest. This will create the need for a more sophisticated level of research coordination and database management.

As SALSA collaborators complete their analysis of initial field data, relevant data sets will be transferred to the central database for archiving and use by other interested researchers. Also, SALSA will begin development of a "knowledge-base" that will ultimately incorporate the database, as well as analysis tools, models, and other information products. The knowledge-base will be designed to facilitate technology transfer between SALSA and public information-users.

6.3 Long-Term Outcomes

If adequately funded for the next 5 to 10 years, SALSA will have completed the number and kind of process studies and experimental campaigns needed to accomplish its mission of answering the Primary Science Question. Information generated from the field studies and modeling activities will allow SALSA researchers to make reliable assessments of how the water balance and ecological diversity of the USPB will be effected by different natural or human-induced stressors. The knowledge and technology acquired from this program can then be applied to address similar problems in other semi-arid regions, and perhaps to other climate zones.

The SALSA knowledge-base will be the ultimate product of this effort, and will be maintained by a collaborating institution into the future. Much of the information contained within the knowledge-base will contribute to larger databases managed by major global change research programs. By this time SALSA will likely evolve into another research program of either greater scope or different focus.

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