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Osman C. Wallace

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INTEGRATION OF REMOTE SENSING, GIS, AND CENSUS DATA FOR IDENTIFICATION OF LAND USE AND LAND COVER DRIVERS IN A SEMI-ARID ECOSYSTEM

A TEMPORAL AND SPATIAL ASSESSMENT OF CHANGES IN A SOUTHEASTERN ARIZONA COMMUNITY

By

Osman C. Wallace

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ABSTRACT

INTEGRATION OF REMOTE SENSING, GIS, AND CENSUS DATA FOR IDENTIFICATION OF LAND USE AND LAND COVER DRIVERS IN A SEMI-ARID ECOSYSTEM: A TEMPORAL AND SPATIAL ASSESSMENT OF CHANGES IN A SOUTHEASTERN ARIZONA COMMUNITY

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Understanding the drivers of landscape change is vital for assessing the total Earth system and the impacts of ecological and anthropogenic changes at global scale. Since rangelands cover nearly a half of the global land surface, and because a large part of rangelands are located in semi-arid ecosystems, they serve as critical land cover types for determining biogeochemical cycles and energy and gas fluxes. Satellite reflectance data is often used to inventory biophysical materials and man-made features on Earth's surface. However, few studies have examined the utility of remote sensing for analyzing human influence on grasslands and other range cover types in brittle, semi-arid ecosystems. By integrating remote sensing, geographic information systems, and census data, this thesis assesses the impact of anthropogenic stress in a semi-arid ecosystem and identifies several key drivers of land use and land cover change in a dynamically growing southeastern Arizona community. In addition, a framework for a rangeland decision support system is discussed as a value-added tool for helping ranchers, land managers, and land use planners to determine rangeland health and forage levels, and for developing improved and accessible grazing plans for protection of lands from overuse.

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CHAPTER 1 – INTRODUCTION

1.1 IMPORTANCE OF RANGELAND LAND USE AND LAND COVER CHANGE

Land cover change may be the most significant agent of global change; it has an important influence on hydrology, climate, and global biogeochemical cycles (Skole et al. 1997). Characterizing the forcing factors that drive changes in landscapes, and the resultant impacts on biogeochemical and hydrological cycles and energy and gas fluxes, is essential to understand the total Earth system and the effects of natural and human-induced changes on the global environment. In addition, assessing the responses to drivers of changes in land cover and land use, particularly in those parts of the world that are currently undergoing the most stress, is an important function for understanding the consequences of land cover and land use changes as they impact ecological processes as well as evaluating what human activities contribute to changes occurring on the landscape. Arguably, land cover change will have greater impact on human habitation, especially in arid and semi-arid environments, than climate change over the next 20 to 50 years. It is an issue with far-reaching policy implications, internationally, nationally, and locally. Indeed, global cover change is as inextricably linked to policy and sustainable development as it is to basic research needs.

The collective area of rangeland is large. If forested ranges and natural vegetation in tropical savanna and tundra areas are included, the total land area of rangelands may be as high as 47 percent of the global land surface (Food and Agriculture Organization 1995). In the United States, rangeland cover type expands to even higher spatial coverage; it encompasses one half of the conterminous land area. Although rangelands of the world have been used by livestock pastoralists for thousands of years, information about the land's response to anthropogenic processes and grazing is limited (Mouat and Hutchinson 1995). The use of this important and often brittle ecosystem is based on conflicting requirements. On one hand, the valuable rangeland resource is exploited to the advantage of livestock producers. On the other, maintenance and improvement of the range condition is essential not only for the obvious environmental benefits, including controlling erosion and sediment delivery as well as providing aesthetics and recreation, but also for determining sustainable optimal grazing capacity and maximum profitability of range sites while preventing their overuse at any time of the year.

A large part of rangelands resides in the semi-arid zones of the world. These zones consist of fragile ecosystems that are substantially modified by the activities of people. For example, increasing human populations in the western United States during the 1990s has resulted in greater demands on the ecosystems of this mostly semi-arid zone. Faced with the intricate problem of population demand for limited resources like land, water, and agricultural production, the challenge to policy makers, ranchers, land managers, and municipal officials of the region is to manage these zones so that growth is controlled, productivity is stabilized, and environmental deterioration is decreased.

1.2 REMOTE SENSING AND ITS ROLE IN SOCIOECONOMIC ANALYSIS

Satellite images offer a unique facility for observing and documenting changing land cover. Assessing and characterizing how land use and land cover changes are manifested at multiple space and time scales using multispectral remote sensing data are critical and vital steps in expanding scientific knowledge of the Earth system using the unique vantage point of space. Satellite data could be utilized to gain a better understanding of drivers of land use and land cover change, to relate observed landscape patterns to processes of change, and to provide the initiative for strategic planning after gaining a clear understanding of drivers of change.

The large area coverage and frequent acquisition cycle of satellite images in digital format make earth observation data useful for observing region-size areas and for integrating with other types of spatial information using Geographic Information Systems (Wagner and Ryznar 1999). Although remotely sensed data are inherently suited to provide information on urban land cover characteristics related to ecological, demographic, socioeconomic, and dynamic aspects of developed regions at various spatial and temporal scales (Ridd 1995), few studies have looked at how satellite data may be utilized to document and analyze human intrusion and influence on grasslands and other range cover types in brittle, semi-arid environments. Unlike their widespread comfort with municipal economic and demographic statistics, social scientists are relatively new to the opportunities provided by the growing archive of satellite-derived earth observational data. This fact was highlighted by a recent study of the U.S. National Research Council entitled *People and Pixels* (National Resource Council 1998). While traditionally satellite data were used to address questions concerning vegetation types and amounts, my study asks a different question. How can satellite data be used to understand underlying anthropogenic processes that shape the environment?

1.3 A NEED FOR DECISION SUPPORT SYSTEMS IN RANGELAND MANAGEMENT

Due to the extensive nature of rangelands and the recognized need to manage them at low cost, remote sensing and remote sensing-based products are considered to have significant promise for the future (Tueller 1989). As the increasing human pressure on semi-arid landscape mounts in the western United States, there is a greater need for an information delivery system to help livestock farmers, land managers, government officials, environmentalists, and other interested parties to quickly locate areas of interest based on their respective criteria. For example, livestock farmers and land managers, utilizing near-real time, satellite-derived maps of vegetation indices (NDVI, NDSVI) and other biophysical parameters (Fc, LAI, biomass estimates), might prefer to focus on areas suitable for seasonal grazing, deferred and/or rotational grazing, as well as those areas needing extensive protection from overuse in semi-arid regions (Qi et al. 2000). As a result, ranchers and managers would know where to graze the cattle and how much fodder pastures produce per unit area.

Current satellite-based sensors such as TM, ETM+, HRVIR, VISSR, and SAR have the disadvantages of fixed spectral bands that are inappropriate for within-field analysis, inadequate repeat coverage for intensive agricultural management, long time periods between image acquisition and delivery to user, and large pixel sizes that are unsuitable for precision crop management (PCM) (Moran et al. 1997). However, a decision support system (DSS) designed to collect and analyze data from recently launched ASTER and MODIS sensors mounted on the EOS-AM platform, in addition to other commercial sensors such as EarlyBird, QuickBird, SIS, OrbView, IKONOS, and Resource-21, with short off-nadir repeat cycle, fine pixel resolution, and short delivery time from acquisition to user should overcome such limitations. The only caveat to image acquisition from these sensors will be the cost. For example, SPOT Image Corp. charges an extra $2000 (nearly twice the normal cost) for requests of image acquisitions guaranteed on a certain date or in a narrow time interval due to conflict with other users (Moran et al. 1997). Future work should focus on determining which remote sensing-based DSS applications are most economically beneficial and technically feasible, and furthermore, funded multi-season projects with satellite-based sensors designed specifically to investigate the economic and scientific viability of remote sensing products for PCM applications should be given high priority (Hough 1993).

Decision support systems have evolved in response to the need to create 'mechanisms to develop and transfer technology that meets the needs of individual landholders and overarching values of society' (Stuth et al. 1993). The delivery system, therefore, should provide rangeland managers with a proactive tool to survey large areas to determine rangeland health and forage levels, and to develop improved and accessible grazing plans for protection of lands from overuse. Further, the product should offer additional potential benefits including better wildlife habitat monitoring (sparrow nesting sites in grass cover), and improved fire-fuel estimation and watershed management strategies. Finally, the product must be designed in accordance with input from the end user at every stage of development. Design and implementation strategies for a web-based decision support tool essential for monitoring the landscape for sustainable land use practices, successful regional planning, and effective policy implementations will be discussed in the final chapter of the thesis.

1.4 RESEARCH OBJECTIVES

The main objective of this study is to demonstrate how satellite data might contribute to an understanding of human-environment interactions and impacts of change in land cover in a fragile and semi-arid rangeland environment. By analyzing remotely sensed data with an appropriate processing model, an objective method may be developed for relating remotely sensed data from the urban or urbanizing environments to biophysical parameters relevant to hydrologic and socioeconomic attributes (Jensen et al. 1994; Phinn 1998; Phinn et al. 1998). To that end, coupled with demographic and statistical data and a GIS spatial model, an analysis of multitemporal satellite imagery will be conducted to assist in qualitatively determining the human drivers and proximate causes responsible for land use and land cover change over the Sierra Vista landscape. Specifically, the temporal change in economic base of the region and loss of productive range cover will be evaluated through integration of remote sensing, GIS, and census data.

To sum up the main objective, the study will illustrate that (1) utilizing satellite technology is an effective approach to document cover change and to determine anthropogenic causes of dryland degradation. In addition, using a qualitative approach, the thesis will infer the main drivers of land use and land cover change in a region that is undergoing dryland degradation. According to Dregne (1983), the definition of dryland degradation in North America is:

(a) Substitution of edible grasses by human-based development, as well as by forbs and shrubs that are not or less edible.

(b) Badly controlled drainage and leaching resulting in 50 percent reduction in grass and/or crop biomass.

The evidence of dryland degradation will be based on multitemporal, multispectral satellite imagery covering a time series from 1973 to 1999. The study will further reveal that (2) continuous urban intrusion and changing economic base of the region have led to increased fragmentation and degradation of rangelands. Further, (3) hydrologic and legal issues resulting from increasing residential, municipal, and industrial demand for water from depleting regional and floodplain aquifers influence rangeland sustenance. And finally, (4) range management practices and fire suppression policies function as externalities that transform species composition of native rangelands in southeastern Arizona. To a large degree, the framework for the identification of LULC drivers will rely on bid rent theory and concept of externalities, i.e., fire suppression policies and range management practices.

1.5 STUDY AREA

Landsat data of the Sierra Vista census division in southeastern Arizona (Figure 1) provides the basis for the exploration. Sierra Vista (Spanish for "Mountain View") is a thriving community of 40,000 people that serves as the regional center for southeastern Arizona. Located approximately 75 miles southeast of Tucson, the city is surrounded by Huachuca, Dragoon, and Mule Mountains, and is bordered on the east by the San Pedro River. Changes in land management techniques, coupled with tremendous urban growth, have altered the vegetation patterns and dynamics in the San Pedro River basin (Qi et al. 1999). In the last thirty years, the Sierra Vista census division has experienced a rather sizable increase in developed land. According to satellite data, in the period between 1992 and 1999 alone, the total area of developed land rose from 5,642 hectares to 7,101 hectares – a 26 percent increase. Between 1973 and 1999, the increase in the urban cover category was 192 percent. Most of the new growth took place over areas of native, perennial grasslands in the San Pedro River basin. For this study, therefore, there was a need to map the spatial and temporal distribution of land cover types in order to understand how human activities affect the ecosystem in this semi-arid region.

1.6 STRUCTURE OF THESIS

Chapter 1 has introduced the importance of rangeland land use and land cover change, the role of remote sensing as a socioeconomic analysis tool, some preliminary discussion on decision support tools for rangeland management, as well as a list of research objectives, and a description of the study area.

Chapter 2 discusses relevant issues related to rangeland ecosystems and rangeland management in the study area. The topics of discussion include:

- a review of LULCC dynamics and linkages,
- southeast Arizona land use history prior to 1973,
- the important role grasslands play in the environmental and economic sustenance of greater Sierra Vista,
- hydrologic resources and water demand on the Upper San Pedro watershed, and,
- rangeland management and grazing methodologies, and the role of fire in southeastern Arizona.

Chapter 3 introduces the data structure of the analysis. Sources and metadata of census information and satellite imagery, as well as methods utilized for atmospheric correction, geometric correction, co-registration, incorporation of ancillary data, and image classification will be discussed. In addition, temporal constraints of remote sensing and census data, spatial limitations of census-derived information, spectral limitations of visible satellite imagery, and classification limitations of remotely sensed data will be given attention. Due to the integrated nature of this research effort, incorporation of remote sensing, GIS and socio-economic data requires a discussion of GIS methods including coverage processing, data structure, and the GIS spatial data model. Additional methodologies covered include the development of analysis tools consisting of overlay and magnitude GIS algorithms designed for the convergence of demographic census division and tract coverages with remote sensing-based land cover classification images. The final section of the chapter focuses on inferring human-environment relationships from the data sources.

Chapter 4 examines the results of the study. The main body of the chapter will consist of identification and discussion of land use and land cover drivers for greater Sierra Vista. Furthermore, contributions of remote sensing and GIS to the identification of the drivers of change will be given attention.

Finally, Chapter 5 discusses design and implementation strategies of a prototype web-based DSS for rangeland management. The chapter concludes the study by summarizing the research initiative and its results, and examines future research needs and recommendations for rangeland land use and land cover analysis.

CHAPTER TWO—ISSUES

Land use and land cover change dynamics and linkages are discussed first. Definitions of terms as well as the function of land use and land cover change as a research endeavor for global, regional, and local applications will be highlighted.

This discussion of multitemporal environmental change analysis using remote sensing does not cover the time period before 1973, as no satellite data over the Sierra Vista census division were available prior to that date. Therefore, a clarification of the region's land use history prior to first date of data acquisition will reveal human impacts on greater Sierra Vista before the availability of remote sensing data needed for land use and land cover change analysis. An overview of pre-1973 human influence on the landscape is essential for understanding the continuum of human-environment interactions in the region.

The importance of grasslands in our national life and in southeastern Arizona has been difficult to assess. As a result, these lands have generally been accorded far less consideration than warranted by the important roles they fulfill. Judgments of knowledgeable specialists on prudent conservation and management of the exceedingly varied categories of these land areas are fragmented and dispersed (Sprague 1974). To comprehend the significance of grasslands, two dimensions of this resource should be examined, the importance of such lands to the local economy of Sierra Vista and their function and significance as a cover type in a fragile, semi-arid ecosystem.

No discussion of environmental analysis in southeastern Arizona can be adequate without an examination of hydrologic resources and water demand. Sustenance of the urban and military populations in the Sierra Vista-Fort Huachuca area and irrigation water for agriculture along the San Pedro River constitute the two major cultural water uses in the Upper San Pedro Basin. Hydrologic studies of the Upper San Pedro Basin have shown that continued pumping in the greater Sierra Vista region at its present rate or higher will most likely threaten surface flows of the San Pedro River (Lacher 1994). This threat, discussed in detail in later chapters, is posing serious concerns to both the environmental and economic vitality of the region.

The vast expanses of rangelands, the numerous benefits that may be derived from them, and the acceleration of changes imposed on them combine to create unique challenges for range managers responsible for range mapping and management. These challenges can often be effectively met by remote sensing techniques. Changes observed in remotely sensed data could complement ecological assessments of restorable rangelands (Tueller 1989). Restoration of degraded lands caused by poor grazing methods, as well as selection of environmentally and economically beneficial grazing methods for effective long-term management require location-specific information and monitoring of the spatial patterns of change. Regional maps of rangeland vegetation change should provide range managers with information for setting long-term grazing practices. Although many studies of production and protection have already been done on grazing practices in arid and semi-arid rangelands of the west and southwest (Kruse and Jemison 2000), future research should consider broadening the scope of livestock grazing systems to be responsive to native ecosystem parameters, the role of fire, and functions such as critical habitat requirements for biodiversity. Ongoing biological research should be developed with specific grazing practices in mind. In addition, grazing management has an economic component that is difficult to assess within an ecosystem management context. When new practices are implemented, sometimes involuntarily, the costs of these alternative methods should be understood. A broader understanding of the relationships of grazing management practices to overall ranch operations and policies imposed by land management agencies are needed to make informed decisions on alternative grazing systems. Selection of grazing methods for use on semi-arid rangelands requires a thorough understanding of the pros and cons of each practice and the cost to implement it. Items to consider include land use restrictions, shared uses, types of animals to be grazed, topography, climate, soils, accessibility to water, and vegetation (Holechek et al. 1998). Therefore, it is necessary to include a short discussion of typical grazing methodologies practiced in Arizona to understand their role in the implementation of environmentally and economically beneficial livestock management strategies as well as to comprehend their impact on land cover change in semi-arid grasslands.

2.1 LAND USE AND LAND COVER CHANGE DYNAMICS AND LINKAGES

Land use and land cover change research is an endeavor to understand the effects of natural and human-induced changes at local, regional, and global scales within the total Earth system. The distinction between land cover and land use is fundamental. Land cover is the observed physical cover, as seen from the ground or through remote sensing, including the vegetation (natural or planted) and human constructions (buildings, roads, etc.) which cover the Earth's surface (Food and Agriculture Organization 1997). Water, ice, bare rock or sand surfaces count as land cover. Land use is based upon function, the purpose for which the land is being used. Thus, a land use can be defined as a series of activities undertaken to produce one or more goods or services (Food and Agriculture Organization 1997). A given land use may take place on one, or more than one, piece of land and several land uses may occur on the same piece of land. Definition of land use in this way provides a basis for precise and quantitative economic and environmental impact analysis and permits precise distinctions between land uses. Land use and land cover change analysis is regarded as a tool for a more sound scientific understanding of the Earth system that provides a foundation for sustainable development—economic development that meets the needs of the present without compromising the ability of future generations to meet their own needs (Turner et al. 1995). It examines theoretical linkages between social and natural systems through land use, direct utilization, resource competition, and pollution (Long and Harwell 1993). Direct utilization comprises uses that do not lead to land-cover change from natural vegetation (e.g., recreational use). Resource competition occurs when humans exploit resources or components of the natural systems essential to natural-system function and process (e.g., water), while pollution is the transmission of harmful residuals of human activities, both consumptive and productive, into the natural area. These impacts are applicable to natural areas close to human settlement and use. Understanding the human and environmental drivers (i.e., causes of change) of land cover change and its impact at different ecological scales is the fundamental aspect of the research initiative (Long and Harwell 1993). Thus, LULCC attempts to answer the nature and extent of land cover and land use change and the consequences for sustained productivity.

2.2 LAND USE HISTORY

The semidesert and plains grasslands, which make up about 45 percent of the land cover of southeastern Arizona, (Brown and Lowe 1980) have been the lifeblood of southern Arizona's cattle industry. In fact, most of the recorded changes in the grasslands of southeastern Arizona occurred after the beginning of large-scale cattle ranching and fire exclusion in 1870 (Bahre 1977).

During the Spanish occupation of the region, livestock, especially cattle and horses, may have substantially degraded the rangelands adjacent to the presidios and villages, but there is no evidence that livestock numbers were very large. In 1804, for example, only 3,500 cattle, 2,600 sheep, and 1,200 horses were reported at Tucson, then the largest Spanish settlement in Arizona with a population of 1,015; at Tubac, the other major settlement, only 1,000 cattle and 5,000 sheep were counted (McCarty 1976).

The introduction of Old World technology, crops, and livestock by the Spaniards eventually led to major changes in the grasslands of southeastern Arizona. Because southeastern Arizona was on the margin of New Spain's northern frontier, however, Spanish settlement was sparse and concentrated in the upper

Santa Cruz valley. There is no doubt that livestock, especially cattle, horses, and sheep, were abundant near the presidios and missions, but their effect on regional grasslands was probably minimal.

After Mexico gained its independence in 1821, several large stock-raising grants were established between 1821 and 1827 near the present international boundary (Officer 1987). These grants now represent some of the largest private landholdings in southeastern Arizona (see Figure 2; McClaran 1995). In their heyday, thousands of horses, cattle, and sheep were supposedly run on these grants. According to Bartlett (1854), there were 140,000 cattle on the Babocomari and San Bernardino grants alone. The primary social driving force for this first significant land use and land cover change in the region was the stock-raising grants, coupled with the government initiative to settle what was then the frontier areas, followed by secondary driving forces of increasing demand for beef attributed to rising population and income of the central Mexican core.

Beginning in 1846, when war broke out between the United States and Mexico, and continuing through 1854, when Mexican jurisdiction over the region ended with the Gadsden Purchase, several military and scientific expeditions and thousands of immigrants heading for the California goldfields crossed southeastern Arizona. According to numerous travel accounts, it is estimated that there may have been as many as 100,000 wild cattle on the abandoned Mexican land grants during the 1840s and early 1850s (Christiansen 1988). However, considering the general lack of livestock water developments then (there were no windmills or stock tanks) and the intermittent nature of most of the streams, it is difficult to believe that large numbers of cattle could have been supported by the grass and browse in the rangelands adjacent to major sources of perennial water. Furthermore, large-scale cattle ranching during the 1820s would have been curtailed by Apache depredations. Nevertheless, probably the most significant human impact on the grasslands during this period was large-scale ranching.

After the Gadsden Purchase Treaty of 1853, major Anglo settlement of southeastern Arizona did not begin until the 1870s. The subjugation of the Apaches and the completion of the Southern Pacific Railroad from Tucson to El Paso in particular facilitated the expansion of the ranching industry and heavy grazing of the grasslands. By 1885, so much investment capital, both foreign and domestic, had poured into southeastern Arizona's ranching industry that cattle numbers exceeded all expectations. By 1891, cattle numbers in the region had reached nearly 400,000, before the severe drought of 1891-1893 caused a massive die-off (Bahre 1977). The drought and its impact on cattle parallel with Malthusian positive checks on population growth and can be interpreted as triggering events, however overstocking, not the rising human population of the region, was the culprit in this case. After the drought, major changes in the grasslands became apparent, many of which have persisted to the present. The ranching industry had stabilized by 1900, but overstocking and overgrazing continued (McClaran 1992).

The early twentieth century saw a major nationwide push to conserve range and forest resources, and in 1907, the United States Department of Agriculture Forest Service curtailed the free use of forage resources in the newly established national forests and advocated grazing control and fire suppression. The Taylor Grazing Act was enacted in 1934 to prevent overgrazing and consequent soil and water deterioration, as well as to stabilize the livestock industry dependent on public rangelands (Voigt 1976). Grazing districts were established and grazing permits were issued. The Forest Service, the Bureau of Land Management (BLM), and other federal agencies charged with range and watershed protection introduced changes in the grasslands largely intended to improve them for cattle. During this time period, population growth and demand for land were the drivers for improved agricultural techniques and development. These chain of events follow closely with Boserup's (1965) theory on conditions of agricultural growth that critiques the Malthusian and neo-Malthusian position which ignores preservation and improvement of the productivity of land under increasing population. In further support of Boserup's theory on land use, innovations such as surface water irrigation aided by the development of efficient, low-cost irrigation pumps in the 1940s cleared thousands of hectares of grassland for intensive irrigated agriculture. This agricultural advancement not only increased labor and land productivity, but also was driven by population pressure on resources.

The rapidly growing population of Arizona, especially since the 1940s, has led to expanded urban and rural development on privately owned lands and is threatening federal and state trust lands, which are continually being sold to the public for development. Since 1950 the number of rural subdivisions being built in southeastern Arizona has exploded, especially in Cochise County, which has both the largest area of grassland and the largest amount of private land in the state (41 percent)---almost all of it being used for agriculture, ranching, or subdivision development (Hecht and Reeves 1981). According to Census of Agriculture statistics, cattle numbers in the county have declined from 81333 in 1974 to 69950 in 1999 in part because of tract development in former rangelands, and also because much of private grazing and agricultural land has been purchased by people seeking rural retirement or investment opportunities. As a result, between 1974 and 1999, total farm acres decreased from 2.1 million to 1.2 million.

2.3 SIGNIFICANCE OF PASTURE AND GRASS

An adequate evaluation of the significance of the greater Sierra Vista grasslands should include the following aspects:

1) The support they provide to the local livestock industry.
2) Their use in soil and water conservation.
3) Their role in regional water resource development and protection in service to people of nearby areas.
4) Their importance in balanced programs of wildlife and game conservation and protection.
5) Their contribution to outdoor recreation and aesthetics.

The following sections discuss the above aspects in greater detail.

2.3.1 Contributions of grasslands to local economy

Grasslands in greater Sierra Vista, and rangelands in general, due to poor soil and dry climate regime, are not basically suited for crop production or other intensive agriculture but can be used by domestic livestock and wildlife that can convert the forage on this acreage into food products useful for human consumption. This fact is reflected in agricultural statistics of the region which reveal that in 1997 the cash sales of livestock represented 64 percent of the total agricultural income in Cochise County, and on average, three-fourths of the beef cattle in Cochise County receive the major part of their feed (76 percent) from pasture (USDA 1997). In addition, cattle and calves were the major source of cash receipts to farm income. Therefore, grass cover contributes greatly to livestock feeding and thus indirectly to the food supply. If not for the ruminant sector of the livestock industry, it would have little market value as an agricultural product.

What will be the effects on the rural economy of the region from reduction of rangeland grazing? It has been estimated that a 20 percent reduction in grazing would cause an 11 percent decrease in gross ranch income (Caton 1985). To simulate the effect of this reduction, all range ranches were studied in nearby Hidalgo county in New Mexico (Bromley 1988). The dependent ranches generated over $5 million worth of new money in the county from export sales and spent almost $2.8 million for goods and services, which included agricultural, automotive, construction, and transportation services. As a result of economic interdependence in this rural county a reduction in rangelands caused an 11 percent reduction in ranch income, and $2 million total reduction in county business receipts.

Since production of beef cattle and sheep involves approximately the same combination of inputs for services required from the business community (Bromley 1988), this study gives some insight into the importance of grazing lands. More of this kind of information on interindustry dependence would be useful for evaluating the true importance of rangeland resources to the local livestock industry and economy.

2.3.2 Uses of grass in soil and water conservation

Hibbert (1981) obtained remarkable evidence of the increase in water yield that results from converting subhumid watersheds in Arizona from chaparral to grass. He demonstrated that eliminating brush with aerial herbicide applications of 2,4,5-T and fostering growth of grass increased water yield 1 to 4 inches per year. Deep-rooted shrubs depleted the soil moisture reservoir more than did the grasses, resulting in greater retention of the winter rains that provide most of the streamflow. This study emphasizes the excellent attributes of good grass cover in beneficially modifying land surfaces for desirable water behavior on the land. Additional benefits include the protection of the soil surface and the reduced surface runoff under grass that are also associated with great reductions in soil loss and sediment delivery (Sprague 1974).

The protective action of grass is utilized by many range conservation planners (Sprague 1974). Planners use grass cover on waterways to provide the most economical means of conveying surface runoff from fields without incurring erosion of the channel. Grass maintains good infiltration, curbs runoff, and nearly eliminates sediment delivery. This has important implications in the transport of potential pollutants from the land to surface waters. In terms of total mass, sediment itself is the dominant water pollutant, and something in excess of 4 billion tons of sediment move from the land to water channels during the average year in western United States (Wadleigh 1971).

Studies at the Campbell Soup Company plant at Paris, TX provide clear evidence of the exceedingly remarkable effectiveness of grass in rectifying polluted water at low cost (Thornwaite 1979). The Paris canning plant discharges up to 3.6 million gallons of water a day. This water is contaminated from use in the preparation of food products and contains from 550 to 900 ppm biochemical oxygen demand (BOD). Thus the effluent from the Paris plant is about three times as polluted as raw city sewage. Paris is located in the Houston-Austin soils association. The soil is a silt and clay loam, similar to White House-Bernardino-Hathaway association found in greater Sierra Vista, which has been ravaged by severe sheet and gully erosion while under crop development. The soil is so erodible that it always should have had grass cover (Thornwaite 1979). This impervious soil has an infiltration rate of 0.1 inch per day or less when swelling has eliminated the major cracks that may occur upon drying. Obviously, runoff from rainfall or irrigation is exceedingly high. Some 400 acres of land were smoothed with a land plane and terraced at 200- to 300-foot intervals. The smoothed areas were planted to grass after a sprinkler irrigation system with underground mains was installed along the upper side of the smoothed area between the terraces. On establishment of the grass cover, the canning plant effluent was applied at the rate of about 0.1 inch per hour.

Since the soil had exceedingly low infiltration capacity, 80-90 percent of the applied polluted effluent became runoff at the lower terrace of each smoothed area.

Even though most of the polluted water did not enter the soil but was intercepted by the grass and trickled slowly downslope on the soil surface, 99 percent of the BOD was removed by the time the water reached the lower terrace. Up to 90 percent of the phosphorus and nitrogen in the polluted effluent was removed by the time tricklings reached the lower terrace.

This field application, conducted on a soil association similar to that found in greater Sierra Vista, is a demonstration of the tremendous capability of grass to rectify seriously polluted water. The cost for this rectification procedure is exceptionally modest. The capacity of good grass cover to disperse the entry of rainfall, to maintain maximal infiltration capacity of soil, to minimize runoff, to nearly eliminate sediment delivery, and to rectify polluted water so as to provide continual protection of soil and water resources makes grasses of fundamental importance in many undertakings for improved environmental protection.

2.3.3 Grasslands' service to people

Not all the sediment comes from farms and ranches. Much of it originates from housing and industrial developments, road construction, gullies, and streambanks. It is not unusual to lose 100 tons per hectare in one rain event from a construction site that is not adequately protected with grasses and mechanical measures (Sprague 1974). An established grass cover around municipal outskirts would greatly reduce the problem of runoff and sediment accumulation resulting from urban development.

In addition, researchers have stated that future reuse of sewage effluents will not be a question of economics but one of necessity in the arid West (Hibbert 1981). Many cities and industries are using forage plants to recycle municipal sludge and process wastes. For example, the Flushing Meadows Projects at Phoenix, Arizona is designed to handle effluent from an activated sludge plant serving the metropolitan area. The objective is to reclaim sewage water that can be used to recharge the groundwater. In order to meet this objective, six basins, 20 by 700 feet in size, were seeded to bermudagrass, while two were left with a gravel base. Inundations ranged from two days wet and three days dry to two weeks wet and ten days dry. The vegetated basins gave the best infiltration rate and the gravel basin the lowest. Water samples from sewage effluent and a 30-foot well on the site revealed sustained decrease to adequate levels in BOD, ammonium, nitrate, phosphorus, and bacteria after percolation of effluent through the soil profile (Sprague 1974).

Other research states that each year about one million acres in Arizona are currently subject to erosion as they are in transition from farming and forestry uses to urban, transportation, industrial, and related developmental uses (Rummell 1987). In addition to areas denuded by construction and development, highways need erosion control both during construction and maintenance. Obviously, the use of grass is prominent in such control.

2.3.4 Role of grasslands in wildlife and game preservation

Wildlife populations are regulated by the availability of food, water, and cover. The closer these basic components of wildlife habitat occur together, typically the greater diversity in wildlife species and total numbers. Grassland management practices and livestock grazing can promote habitat diversity or destroy habitat diversity, depending on their application. Diversity in both plant species and plant communities over short distances is the key to healthy wildlife populations. A good grass cover, along with carefully controlled livestock grazing, is beneficial to the habitat needs for wildlife (jackrabbits, rodents, and other small mammals) and birds (sparrows and raptors) (Cook 1966) that typically reside in greater Sierra Vista.

Many range management practices can be used to improve habitat for wildlife as well as increase forage for livestock. Livestock affect wildlife habitat directly by removal and trampling of vegetation that could otherwise be used for food and cover. When defoliation is carried to an extreme, the number of wildlife species will decline because of loss of diversity in food and cover. Size, pattern, and location of defoliated areas determine both how and to what extent wildlife is affected. Moderate grazing (30 to 50 percent use of current year's herbage production) in broken terrain generally results in heavy use of lowland areas close to water and light use of upland areas removed from water sources (Roath and Krueger 1982). Such grazing favors a mosaic of grazed and ungrazed vegetation, although the best wildlife habitat near and around the watering areas will receive heavy use (Cook 1966). Although uniform use of vegetation is desirable from the standpoint of maximizing livestock production, it can be undesirable to wildlife because of reduced habitat diversity, lack of heavy escape grass cover, and greater social interaction between domestic and wild species (Brown 1978; Mackie 1978). However, in many situations water development for livestock has been beneficial to wildlife in the western United States because it has permitted the use of areas from which wildlife were previously excluded due to lack of free water. Wood et al. (1970) reported that development of water for livestock increased mule deer numbers, as well as several game and nongame species, in southcentral New Mexico.

Virtually all the gallinaceous game birds depend heavily on annuals and/or early successional forbs for food (Greenfell et al. 1980). In addition, annuals are important foods of many species of rodents and lagomorphs (Wood 1969). Annual grasses and forbs are particularly important to these categories of wildlife during the winter because they have large seeds that are high in energy, unlike most scrub species.

Vegetation requirements for cover of many wildlife species are often much different than those for livestock feeding. These requirements may also vary drastically between seasons for some wildlife species. Therefore, diversity in grassland vegetation structure, vegetation composition, and terrain favors the highest diversity and density of wildlife. It is important to note that multiple species of grass, rather than scrub or mesquite mixture, is the definition of grassland diversity. If carefully controlled, livestock grazing can be a useful tool to obtain and maintain habitat diversity.

2.3.5 Recreational and aesthetic uses of grasslands

The urbanization of the greater Sierra Vista region does have some advantage to the ranching industry and nearby grasslands. Increased human population provides considerable opportunity for ranchers who are willing to diversify their enterprise. Multiple use involves the harmonious use of the range for more than one purpose (Society for Range Management 1989). The potential for fee hunting is a good example. Other forms of recreation, such as packing trips, horseback riding, sightseeing trips, bird watching, and dude ranching are proving to be highly lucrative in certain areas (Holechek et al. 1998). These enterprises in some cases bring in far more net income than sale of livestock. It appears that recreational enterprises will increasingly displace livestock as the main source of income from ranches in many parts of the western United States (Holechek et al. 1998).

Grass, if used properly, can go a long way toward preventing or abating the unattractiveness of streams and lakes laden with such pollutants as silt and other sediments, sewage, and agricultural waste. Grass has been used for years to heal eroding hillside gullies, to prevent scouring of waterways and drainage systems, and to tie down soil subject to sheet erosion (Sprague 1974). We are learning more about grass-covered soils as filter fields to effectively dispose of sewage sludge, livestock manures, and certain processing wastes—all of which are harmful pollutants to the environment.

Alternative uses of the various types of grasslands, i.e., the degree to which present occupation of land by grass cover and its associated use constitutes the most effective ecological adjustment of these land types for balanced and prudent management of the total environment, deserves more attention of researchers and land managers alike.

2.4 HYDROLOGIC RESOURCES AND WATER DEMAND

2.4.1 Surface water

The San Pedro River originates about 30 miles south of the International Border, north of Cananea, Sonora, Mexico. The river enters the United States near Palominas, Arizona and flows northward toward its confluence with the Gila River. Most of its tributaries are ephemeral, flowing only in response to rainfall or snowmelt events. The San Pedro River is perennial (flowing continuously all year) for approximately 36 of the 62 river miles in the United States portion of the Upper San Pedro River Basin. The floodplain aquifer recovers during the winter, with streamflow returning over most of the river reach in November of December, and remaining until March or April (ADWR 1990). Outside of the perennial reach, the San Pedro flows intermittently. Most of the perennial reach of the San Pedro River falls inside the San Pedro Riparian National Conservation Area (SPRNCA), a federal reserve managed by the United States Bureau of Land Management (BLM). The reserve constitutes a narrow band of 56,000 acres of riparian habitat along the San Pedro River (USDA 1988). The United States Congress established the SPRNCA in 1988 in an effort to protect the rare riparian habitat from damage due to increasing demand for water in the surrounding area (National Resource Council 1992).

Like most rivers, the San Pedro River has two major flow components: runoff and baseflow. Runoff occurs after precipitation events or as result of snowmelt, and lasts a few days until all flow is either lost to outflow from the basin or to bank storage along river. The highest annual flows in San Pedro River and its tributaries occur between July and September, and are typically of short duration. Baseflow results from the discharge of groundwater to the stream and sustains streamflow in dry seasons. Intermittent flows result from the timing of water uses (by crops and riparian vegetation) along the stream and from the climatic regime (Putman et al. 1988).

2.4.2 Groundwater and subsurface regime

Roeske and Werrell (1973) report that artesian conditions generally exist for wells penetrating to depths greater than 200 feet. The majority of recharge to the subsurface regional aquifer occurs along mountain fronts and a small portion via stream channel infiltration. Direct infiltration over the valley floor is considered negligible because of high evaporation and low precipitation rates, and, in general, no groundwater communication exists between adjacent basins (Freethey 1982).

A secondary aquifer exists in shallower floodplain aquifers, deposited above the valley fill sediments by the San Pedro River and its tributaries. The most important floodplain aquifer in the Upper San Pedro Basin bounds the San Pedro River. Recharge to the floodplain aquifer derives from streamflow, upward leakage and lateral flows from the regional aquifer, agricultural return flows, runoff water percolation, and underflow across the U.S.-Mexico border (ADWR 1990). In addition to serving as the main conduit for surface water/ground water interaction, the floodplain aquifer provides necessary water for phreatophytes (deep-rooted plants which obtain water from the underlying aquifer) within the riparian zone of the inner valley and is the major supplier for irrigation wells along San Pedro River and its principal tributaries (Putman et al. 1988). Groundwater communication between the regional aquifer and floodplain aquifer is generally from the regional aquifer to the central floodplain aquifer, but this may reverse in times of low river flow. Flow between the floodplain aquifer and the San Pedro River is toward the San Pedro River in perennial reaches (baseflows).

2.4.3 Natural and anthropogenic demand for water

The most important natural depletion of the San Pedro River and its tributaries is evaporation from bare soils in and along stream courses (Putman et al. 1988). Water that evaporates from alluvial soil depletes near-surface water storage and provides a sink for infiltrating water from streams, thereby decreasing subsequent surface flows and recharge rates to the regional aquifer. Evapotranspiration by phreatophytes, including several species of cottonwood, Gooding willow, Seep willow, mesquite, and salt cedar, comprises the single largest natural consumptive use of water in the Upper San Pedro Basin (Putman et al. 1988). The effect of phreatophyte consumption of groundwater is similar to that of bare soil evaporation. Water that is used by the plants is replaced by surface water infiltration. Hence, that volume of infiltrated water is no longer available in streamflow or for recharge to the aquifer system. Phreatophytes comprise most of the riparian vegetation and depend largely on the floodplain alluvium for their water supply. Their roots either extend to the water table or to the saturated capillary fringe just above the water table (Brown and Lowe 1980).

The Sierra Vista subwatershed contains approximately 6,490 acres of land irrigated almost exclusively from groundwater wells (Lacher 1994). About 4,610 of these acres (71 percent) are cultivated as pasture, and the remaining lands are either inactive croplands or crops that include grapes, pecan, and fruit tree orchards as well as vineyards (ADWR 1990). Domestic well use increased rapidly from 1950s onward, when high volume pumps became widely available. Most urban and industrial wells tap the regional aquifer. Most irrigation wells pump from the floodplain aquifer near the San Pedro River, although some do pump from the regional aquifer (Lacher 1994).

Water use in the Upper San Pedro Basin is concentrated in two zones and serves two primary purposes (ADWR 1990): 1) the Sierra Vista-Fort Huachuca area well field supplies groundwater for municipal, military, and industrial uses. These wells in the regional aquifer are up to 1500 feet deep; 2) the Palominos-Hereford area well field supplies water for agriculture. Some of these wells penetrate the regional aquifer, but most are shallow and only penetrate the floodplain aquifer. Small, isolated wells outside these two areas pump just enough water for domestic and livestock use (Vionnet and Maddock 1992).

2.5 GRAZING SYSTEMS IN SOUTHEASTERN ARIZONA

2.5.1 Yearlong grazing

Yearlong grazing is a system in which a pasture is grazed "constantly" for all 12 months of a year. That pasture may or may not be grazed in subsequent years and supplemental feeding may or may not be required for portions of the year that it is being grazed. This system is more efficient the more uniform the distribution of forage plants, the better the distribution of water, and the more diverse the plant communities (Kruse and Jemison 2000). In the past, because the range was essentially an "open range", this grazing method resulted in the inability to determine grazing capacity for introduced domestic livestock, the inability to respond to adverse weather conditions (severe drought), and the continuous and rapidly increasing animal numbers set the stage for severe damage in semi-arid rangelands.

2.5.2 Continuous grazing

Yearlong grazing of an area (pasture or range) for a 12-month period is not necessarily synonymous with continuous grazing (Society of Range Management 1998). Continuous grazing refers to grazing the same area throughout a year or that part of the year during which grazing is feasible. It may be yearlong or shorter depending on environmental or other restrictions to grazing by livestock. On annual ranges, Ratliff (1986) showed that cow and calf weights responded more productively on continuously grazed annual grassland range than with repeated seasonal or rotated seasonal grazing. Grazing the same area year after year provides the manager with a systematic advantage of using the pasture when it is optimal for grazing; it requires less handling and moving of livestock; and it may lessen the need for fencing and water development (Kruse and Jemison 2000). Often, however, trying to balance plant development with animals' selective grazing provides an uneven grazing distribution of palatable plants, resulting in an overall deterioration in the quality of the prime forage plant community. Ultimately this creates a less than desirable overall range condition.

2.5.3 Seasonal grazing

Seasonal grazing is restricted to one or more specific seasons of the year (Society of Range Management 1998) and is that portion of the year during which grazing is most feasible for livestock production. Ratliff (1986) describes the forage seasons as determined by environmental conditions that limit, or promote, plant growth. During the forage production season, plant growth can be so accelerated that livestock cannot use all the forage produced, assuming an adequate growing season. Protein and energy supplements are generally not necessary in these situations. On the other hand, during the dry season when plant growth is usually limited, there can an insufficient quality of green forage for livestock needs and protein supplements are often supplied. Seasonal grazing is more appropriate in high mountain meadows, transitional zones (spring/fall ranges), and areas where the livestock are trucked in to utilize the forage at peak production and condition, and range managers develop stocking plans based on annual environmental events such as seasonal weather patterns for forage plant growth and development (Kruse and Jemison 2000). Predicting whether an adequate amount of precipitation will provide an adequate amount of forage for the number of livestock of a specific class within a given year can be difficult.

2.5.4 Deferred grazing

The discontinuance of grazing or deferred grazing by livestock on an area in a specified period (e.g., during the growing season) promotes plant reproduction, establishment of new plants, or restoration of vigor to older plants (Kruse and Jemison 2000). The term often suggests cattle movement but it actually relates more specifically to plant growth and development. Grazing is deferred for some range management objective (e.g., until after seed maturity or the establishment of new plants) and more than not, is used in combination with rotation grazing. Because it is the forage plant community that is being focused upon, grazing can be deferred for values other than livestock production (e.g., wildlife habitat). For range management objectives, deferment is usually done to enhance the forage plants within that pasture, but could just as well be done to improve the habitat of a specific wildlife species. For example, research indicates that a deferred grazing system can be used to maintain and heighten riparian vegetation including willows and cottonwoods that provide food, cover, and nesting areas for various bird species (Clary and Webster 1989).

2.5.5 Deferred rotation grazing

This system discontinues grazing on various parts of a range, allowing each part to rest successively during the growing season to permit seed production, establishment of seedlings, or restoration of plant vigor. Rotation and deferred grazing combine to produce a pasture rotation situation, which also can be termed a "deferred grazing system" in that the livestock are rotated among a set of pastures, and grazing commences on one while grazing has just been deferred from another (Kruse and Jemisen 2000). The deferment may be necessary to strengthen the forage plant community, and there must be an available pasture. In this case, both the animals and the pasture benefit. Although similar, the deferred rotation grazing system is an improvement over the deferred grazing system in that another pasture or two are available. An ideal situation for a deferred rotation grazing system in a riparian area when wildlife habitat protection is desired would be to have two or three riparian pastures, one of which does not contain nesting habitat for the target species (Kruse and Jemison 2000). In this situation, livestock moving into it benefits the receiving pasture, while the deferred pasture is being rested.

2.5.6 Rotational deferment

In this system one or more parts of the range are rested during the growing season each year, and use on other segments of the range are rotated. This system differs from deferred rotation because the livestock are not being rotated systematically and, therefore, where they are being rotated is less important. It is the rotation deferment of grazing that is the key. Generally, three or four pastures are required. As with other deferred grazing systems the primary objectives are improvement of plant utilization, overall range improvement, and maintenance of livestock production. This system can be utilized more easily to accommodate wildlife and other values than other systems because it provides more management options (Clary and Webster 1989). The system functions better when livestock are not allowed to physically degrade site conditions to such a degree that they have to be removed. Livestock removal, for the expressed purpose of habitat regeneration, may involve a time factor that is not in the best interests of livestock production. However, with a set of pastures available for grazing, all without constraints on use, rotational grazing of the pastures would offer the most options.

2.5.7 Rest-rotation grazing

In this intensive system of management, grazing is deferred on various parts of the range during succeeding years, allowing the deferred part complete rest for one year. Two or more units are required and control by fencing is usually necessary on cattle range (Kruse and Jemison 2000). Rest can mean deferred grazing or ungrazed pasture, but in combination with the word rotation it is more appropriately assigned to a management decision rather than to the grazing animals. Therefore, it is the loss or lack of grazing that allows a pasture to be rested, and that rested condition rotates among other pastures or areas of the range during succeeding years. Resting a pasture for an entire year allows plants to complete a full year growth cycle without interruption (Ratliff 1986). Altering grazing systems can have long-term beneficial effects. Hughes (1998) showed that overgrazed BLM allotments that had previously been grazed season-long or with continuous grazing systems by sheep and cattle responded beneficially following 30 years of rest rotation grazing in the Mojave Desert of California. In this example, rest appeared to be the dominant factor while rotation provided grazing options and alternatives.

2.5.8 Rotation grazing system

An orderly sequence of use, when each subdivision is both grazed and deferred during the same grazing season, is called rotation grazing. This generally refers to animals being rotated among pastures or to the next pasture in sequence. These moves are systematic in that the animals are rotated to a new pasture because the forage in that new pasture is proper for grazing. The pasture from which the livestock are removed is deferred from grazing. Grazing could commence systematically, with rotation being initiated by growth and development patterns of the forage plants within each newly entered paddock (Kruse and Jemison 2000). An important management aspect of rotation grazing is utilizing a number of paddocks or subsets of a larger pasture unit, which enhances grazing distribution. The strength of a rotational grazing system is its flexibility. By utilizing unbalanced paddocks, grazing could more easily be deferred for reasons other than grazing or plant development, e.g., wildlife protection and recreation. Therefore, while even a few paddocks provide for greater flexibility and optional diversity, the greater the number of small paddocks, the more the diversity and flexibility.

2.5.9 Best pasture system

Based on research trials in New Mexico, Herbel and Nelson (1969) advocated a highly flexible system that provides for always moving to the best pasture in the system: thus, the "best pasture system". McCulley (1968) used a comparable system that he referred to as "repeated seasonal" grazing in trials that he conducted at the San Joaquin Experimental Range in California. Although these grazing schemes are not new, they provide the flexibility of rotating between several paddocks within grazing units, range types, subtypes, or condition classes when it is most advantageous to livestock, vegetation, or both (Holechek et al. 1998).

2.5.10 Holistic management, holistic resource management, or the Allan Savory grazing method

According to Savory and Parsons (1980), any of the aforementioned systems can be interwoven into this method. While Savory suggested that America's rangelands (southwestern ranges in particular) were understocked by livestock and at the same time overgrazed, he was introducing a rotation grazing system that many range scientists and managers had been looking at and studying for some time already. This system concluded:

- Continuous, yearlong grazing at moderate rates produces the best individual animal performance, but range condition declines below its potential.

- Range condition can be maintained at an acceptable level if livestock remove less than 40 percent of the current year's growth during the growing season.
- Three-herd, four-pasture deferred-rotation grazing at a moderate stocking rate allows slow range improvement with good individual animal performance.
- High-intensity, low-frequency grazing with six to eight pastures and one herd provides for faster range improvement, but animal performance suffers presumably because of the high stock density.
- High-intensity, low-frequency grazing systems might produce acceptable animal performance if grazing deferment periods are shortened.
- Increased stocking of 50 to 100 percent can be achieved only by using some form of range improvement, such as brush control, fertilizer, or water-spreading.

Savory's grazing management was holistic in philosophy. It included (a) using one herd, (b) shortening the grazing and rest periods, (c) managing plant growth through better harvest efficiency at proper grazing intervals, and (d) applying hoof and herd impact to alleviate soil surface crusting (Savory and Parsons 1980). Savory's animal grazing model gained popularity with many ranchers and some land managers. His management philosophy is the most popular and widely practiced among ranchers in southeast Arizona (Marsett 2000). After widespread acceptance among cattle ranchers, he has broadened his philosophical concepts of holistic management to encompass more challenging management objectives, such as biodiversity and species variability, on public lands. His model continues to be controversial among much of the academic community because of its lack of scientific hypothesis testing.

2.6 THE ROLE OF FIRE

Fire is a pervasive and powerful force in desert grasslands. Its importance in controlling ecosystem structure and function rivals that of precipitation (Kimmins 1987). As the frequency, season, and behavior of fires have shaped plant communities, communities have in turn shaped the frequency, season, and behavior of fires. The long-term fire regime is probably more a consequence than a cause of vegetation patterns; that is, vegetation probably affects fire regime to a greater extent than fire regime affects vegetation, at least at a coarse level of resolution (Clark 1990). Nonetheless, as an integral component of rangeland ecosystems, fire should not be viewed as external to these systems; rather, fire is part and parcel of community organization and development.

Perhaps nowhere is the role of fire more widely acknowledged than in grasslands. In fact, some North American researchers have proposed that treeless grasslands were a product of repeated fires set by Native Americans (Sauer 1944; Stewart 1951). Fire interacts with ecological factors including topography, soil, insects, rodents, lagomorphs, and herbaceous plants to restrict woody plant establishment in grasslands. There is general agreement that fire is necessary (though usually not sufficient) to control the abundance of woody plants and maintain most grasslands (Grover and Musick 1990; Wright and Bailey 1982).

2.7 CONCLUDING REMARKS

The discussion on greater Sierra Vista's land use history is intended to convey the important impact of human activities on the regional land cover, and how different perceptions and uses of the land have affected the grasslands, especially in the last 100 years. The resulting landscape fragmentation from human activities may influence the extent of natural processes like fire and water drainage patterns as well as the dispersal of grassland plants and animals.

The beneficial role grasslands play in both the economical and environmental sustenance of rangelands is vital to understanding the issues affecting human and environment interactions in the region. Grasslands play a vital role in maintaining ecosystem health, balance, and maintenance. Their beneficial characteristics such as increasing infiltration, decreasing surface runoff and sediment delivery, rectifying polluted streams, and serving as cover for wildlife, are a few examples of the importance of grasslands for environmental protection. And, in addition to providing the main source of income to the region, the value of grassland is not only the forage and livestock but also the water, timber, minerals, recreation, and wildlife.

Hydrological resources and water demand are vital and critical variables in land use and land cover issues in arid and semi-arid ecosystems. Often, large areas of farmland revert back to rangeland because of increased irrigation costs, loss of water to urbanization, and lowering of the water table. However, as water depletion continues, there is a grave danger that rangelands, in turn, could revert to desertlike conditions, largely through human actions, in fragile areas that do not have desert climates, e.g., the semi-arid region of Sierra Vista.

Livestock grazing is an important human-controlled activity that has considerable potential to either improve or degrade vulnerable ecosystems. Techniques developed to utilize grass cover for livestock production are critical in maintaining biodiversity, promoting healthy range cover, and sustaining profitable livestock production.

CHAPTER 3—METHODS

All images in this thesis are presented in color. A graphical representation of methods and procedures used in GIS and remote sensing integration is displayed in Figure 3. The first section of the chapter outlines sources, metadata, characteristics, processing procedures, use of ancillary data, along with co-registration and classification procedures of remotely sensed data. The second section discusses GIS coverage processing, as well as the data structure and spatial data model for the integration of a well registry database with a GIS as a tool for observing patterns of water usage. The third section examines the sources and characteristics of census data. Temporal, spatial, spectral, and classification limitations are discussed in the fourth section. Integration of GIS and remote sensing, overlay analysis, and the magnitude procedure code are examined in the fifth section. Finally, the section on the use of data sources to infer human-environment relationships concludes the chapter.

3.1 IMAGE COLLECTION AND PROCESSING

Remote sensing derived information is critical to the successful modeling and monitoring of numerous natural and cultural processes (Jensen 2000). For this analysis, as typically is the case with most long-term, multi-temporal land use and land cover studies, images from different sensors at various scales and resolutions were required for assessing land use and land cover change.

Although additional images would have been desirable for a more comprehensive time series analysis, due to cost limitations and image quality, a total of four images were selected for the years 1973, 1985, 1992, and 1999. The source of the images was the Arizona Regional Image Archive located at the University of Arizona, Tucson. All the images were scanned during the growing season and were relatively close to the maximum green-up time in the region (usually late August through early October). The dates of acquisition were September 5 1973, September 27 1985, September 30 1992, and October 12 1999. Figures 4 through 7 display the image data in sequential order. To aid in summarizing system and optical characteristics of these images, Table 1 lists the sensor systems and their major characteristics, and Table 2 lists the spectral wavelengths associated with each sensor.

3.1.1 Atmospheric correction

The atmosphere influences the amount of electromagnetic energy that is sensed by the detectors of an imaging system, and these effects are wavelength dependent (Slater et al. 1983). This is particularly true for imaging systems such as the Landsat Multispectral Scanner (MSS), Thematic Mapper (TM), and Enhanced Thematic Mapper Plus (ETM +) that record data in the visible and near-infrared portions of the electromagnetic spectrum. The atmosphere affects images by scattering, absorbing, and refracting light. Various methods to remove the effects of scattering from remotely sensed data have been developed. However, a problem with most of these techniques is that the haze values for each spectral band are selected independently. This can create problems because atmospheric scattering is highly wavelength-dependent in the visible part of the spectrum and the scattering values are correlated with each other (Chavez 1988). Chavez's improved dark object subtraction (DOS) technique was utilized for atmospheric correction of the 1973 MSS image since this technique allows the user to select a relative atmospheric scattering model to predict the haze values for all the spectral bands from a selected starting band haze value, thus the method normalizes the predicted haze values for the different gain and offset parameters used by the imaging system. According to the metadata, the 1973 image quality was high and the image was acquired on a very clear day with no cloud cover. As such, I used a relative scattering model for a very clear atmosphere. By utilizing band 1(green) as the starting band, the improved DOS atmospheric correction procedure generated the predicted and final DN values for haze correction as listed in Table 3. The final DN values derived from Chavez's improved DOS procedure were subtracted from the DN values from each corresponding band of the original image to correct for atmospheric scattering.

For the TM images of 1985, 1992, and the ETM+ image of 1999, a location-specific correction method developed to utilize within-image targets was used. This method, called the refined empirical line (REL) approach, requires only one within-scene calibration target, minimal field measurements of that target, and a reasonable estimate of at-satellite radiance (or DN) for a surface reflectance factor (the ratio of directional reflected and incident radiation at the surface within a spectral band) of zero (Moran et al. 2000). The estimate of DN for surface reflectance factor of zero is based on an empirical relationship between DN and the surface reflectance factor. It is derived by the use of the Herman and Browning atmospheric radiative transfer model (RTM). The implementation of the REL approach was based on data derived from the Walnut Gulch Experimental Watershed located inside the Sierra Vista census division study area. The Landsat TM and ETM+ DNs for surface reflectance factor of zero at Walnut Gulch, estimated from a RTM with inputs based on on-site measurements of atmospheric conditions taken during the growing season from June to September, were used for atmospheric correction in TM2, TM3, TM4, and TM5 bands. This procedure was performed independently on each image.

3.1.2 Geometric correction

The 1973 MSS image was located on path 37, and row 38 of the World Referencing System One (WRS-1) used by Landsat satellites. The 1985, 1992, and 1999 TM and ETM+ images were located on path 35, and row 38 of the World Referencing System Two (WRS-2). For Landsat and other satellite images the systematic distortions, i.e., geometric distortions whose effects are constant and can be predicted in advance such as scan skew, variations in scanner mirror velocity, and cross-track distortions, are corrected before the data are distributed. In addition, random or nonsystematic distortions, i.e., distortions caused by variations in the spacecraft attitude, velocity, and altitude, were corrected, according to metadata from Arizona Regional Image Archive, by the cubic convolution method of resampling before distribution. However, all images contain inherent geometric distortions because they record the curved surface of the earth on a flat display. Areas, distances, and angular relationships are distorted to varying degrees. To correct the inherent distortion, all images, except the 1999 image that was projected before distribution, were projected to the Universal Transverse Mercator (UTM) projection, zone 12. For all images, the NAD83 datum, which was designed to fit the surface well in the North American region, was specified.

3.1.3 Image co-registration

Image-to-image registration is the translation and rotation alignment process by which two or more images of like geometry and of the same geographic area are positioned coincident with respect to one another so that corresponding elements of the same ground area appear in the same place on the registered images (Chen and Lee 1992). This type of correction is necessary for multitemporal remote sensing analysis as it promotes the comparison of two or more images obtained on different dates to see if any change has taken place in them.

Since the 1999 image was orthorectified before distribution, it was used as the rectified scene to register the 1973, 1985, and 1992 images. Before registration, the 1973 MSS image spatial resolution was adjusted from 80 to 30 meters (TM and ETM+ ground resolution) by resampling. For each rectification, roughly 30 ground control points were selected at easily identifiable locations such as road intersections, edges of fields, as well as the intersections of utility corridors. The precision and accuracy of co-registration were enhanced by utilizing ERDAS remote sensing software that uses a chip extraction algorithm that zooms in and performs subpixel sampling. The root mean square (RMS) error, a measure of distortion of each control point, for all the GCPs was acceptable at less than the threshold value of 0.05 pixel, and consequently, precision error was less than one pixel size of 30 meters.

After all the images were co-registered, a GIS coverage of the study area, i.e., the census division of Sierra Vista consisting of tracts 14 through 20, was used to clip the original images to create a multitemporal set of land cover data bounded by the census division extent.

3.1.4 Image classification

Remotely sensed data of the Sierra Vista census division was analyzed to extract useful thematic land cover information. The multispectral classification was performed using the supervised algorithm approach. Known a priori land cover types were identified by combination of previously published vegetation maps, previous fieldwork data, recent personal field observations (utilized only for the 1999 image classification), and personal interviews with U.S. Department of Agriculture personnel with over 30 years of classification experience in the region (Marsett 2000). The specific sites in the remotely sensed data represented homogeneous examples of these known land cover types. These sites were collected by on-screen selection of polygonal training data, and conversely, by seeding an x, y location specific to a cover type in the image space using the cursor. In addition, feature space plots depicting the distribution of all the pixels in the scene using red and NIR bands were especially helpful in separating mixed mesquite, oak woodland, and riparian classes. Automated in ERDAS software, spectral characteristics of the training sites were evaluated, multivariate statistical parameters were calculated in each training site, and every pixel both within and outside these training sites was evaluated and assigned to the class of which it had the maximum likelihood of being a member.

Before the supervised classification algorithm was run on the atmospherically and geometrically corrected raw images, image data were merged with topographic information. A 1990 digital elevation model (DEM) was registered to the images to aid in montane forest and oak woodland mapping in the Huachuca Mountains region of the scene. In this region, species that have very similar spectral characteristics (e.g., mesquite, aspen, and evergreens) occupy quite different elevation ranges. Mesquite is commonly found in lower elevations whereas aspen is typical of higher terrain. Use of ancillary DEM data as a discriminatory tool thus aided in defining and classifying the various associations between these land cover types present in the scenes and their habitats.

The classification scheme is based on the resource-oriented USGS Land Use/Land Cover Classification System Level I (Anderson et al. 1976) with slight modifications (addition of mixed mesquite and desertscrub, and subtraction of tundra and ice) to accommodate the native vegetation of the region. Following is a name and description list of land cover classes used in the classification:

Forest	Vegetative communities comprised principally of trees potentially over 10m in height and typically characterized by closed or multi-layered canopies. Species in this category are evergreen (with the exception of aspen), largely coniferous (e.g., ponderosa pine), and restricted to the upper elevations of mountains that arise off the desert floor.
Oak Woodland	Vegetative communities dominated (>30% total cover) by deciduous trees (Quercus spp.) with a mean height usually between 6 and 15m. Tree canopy is usually open or interrupted and singularly layered. This cover type often grades into forests at its upper boundary and into semi-arid grassland below.
Mixed	Vegetative communities composed of leguminous trees (Prosopis spp.) whose crowns cover 15% or more of the ground often resulting in dense thickets (30-75% total cover). Historically maintained maximum development on alluvium of old dissected flood plains; now present without proximity to major watercourses. Winter deciduous and generally found at elevations below 1,200m.
Grasslands	Vegetative communities dominated by perennial and annual grasses (>35% total cover) with occasional herbaceous species present. Trees and shrubs do not exceed 20% of the total cover. Generally grass height is under 1m and occur at elevations between 1,100 and 1,700m, sometimes as high as 1,900m. This is a landscape largely dominated by perennial bunch grasses separated by intervening bare ground (45-50% total cover) or low-growing sod grasses and annual grass with a less-interrupted canopy. Semi-arid grasslands are generally positioned in elevation between evergreen woodland above and desertscrub below.

Desertscrub	Vegetative communities comprised of short shrubs with sparse foliage (>35% total cover) and small cacti that occur between 700 and 1,500m in elevation. Within the San Pedro river basin this community is often dominated by one of at least three species, i.e. creosotebush, tarbush, and whitethorn acacia. Individual plants are often separated by significant areas of barren ground (40-45% total cover) devoid of perennial vegetation. Many desertscrub species are drought-deciduous.
Riparian	Vegetative communities adjacent to perennial and intermittent stream reaches. Trees can potentially exceed an overstory height of 10m and are frequently characterized by closed or multi-layered canopies depending on regeneration. Species within the San Pedro basin are largely dominated by two species, i.e. cottonwood and Goodding willow. Riparian species are largely winter deciduous.
Agriculture	Crops actively cultivated (and irrigated). In the San Pedro River basin these are primarily found along the upper terraces of the riparian corridor and are dominated by hay and alfalfa. They are minimally represented in overall extent (less than 3% total cover) within the basin and are irrigated by ground and pivot-sprinkler systems.
Urban	This is a land-use dominated by small ejidos (farming villages or communes), retirement homes, residential neighborhoods, commercial buildings, industrial sites, as well as airstrips and buildings inside Fort Huachuca.
Water	Sparse free-standing water is available in the watershed. This category would be mostly represented by perennial reaches of the San Pedro and Babocomari rivers with some attached pools or repressos (earthen reservoirs), ponds near recreational sites such as parks and golf courses, and sewage treatment ponds east of the city.
Barren	A cover class represented by large rock outcropping, abandoned mines (including tailings), and other surfaces that are largely absent of above-ground vegetation.
Clouds/Shadows	1985, and 1992 images.

The classified images represent categorized pixels in an image representing the 11 land cover classes discussed above. These images covering the years 1973, 1985, 1992, and 1999 are displayed in Figures 8, 9, 10, and 11, respectively.

3.2 GIS DATA

A political boundary coverage consisting of the seven census tracts comprising the Sierra Vista census division was utilized for analyzing the human influence on the local semi-arid ecosystem. The coverage was obtained from the USGS National Biological Information Infrastructure (NBII), a national biological information partnership.

3.2.1 Coverage processing

The coverage, geocoded before distribution, was imported into Arc/Info, topologically cleaned to remove gaps at nodes and breaks in arcs defining the tract polygons, and projected to UTM zone 12 using NAD83 datum (Figure 12).

3.2.2 Attribute data structure

The well attribute data dictionary, obtained from the Arizona Department of Water Resources, was entered into a GIS by (1) creating a new INFO data file to hold the attributes, (2) adding the attribute values to the newly created INFO data file, and (3) relating the attributes in the INFO data file to the polygon attribute table of the census coverage.

3.2.3 Spatial data model

The census division coverage served as a logical construct for the storage and retrieval of water usage data relating to land use and land cover change. This simple model consisted of seven census tracts with a data dictionary of attributes from numerous wells located in the census division.

3.2.4 GIS queries

Some of the important variables of water usage in the greater Sierra Vista are the number of wells, well depth, water level, and primary well usage. The ADWR (1990) reported 5,298 registered wells on file with the ADWR in the Sierra Vista census division. This number increased by 1031 to 6,329 by the year 2000. The year 2000 data included geo-referenced UTM coordinates for each registered well in the division. The locations and the total number of registered wells for each census tract are included in Figure 13.

The 2000 data dictionary for the wells point coverage provided input for simple GIS queries that calculated average well depths, average water levels, and usage percentages of registered wells for each census tract.

3.3 SOCIOECONOMIC DATA

Every effort was made to collect demographic data as close as possible to the years of image acquisition. The sources of census data used in this study are listed in Table 4.

Table 5 lists the population and housing data for the 1970, 1980, and 1990 census for Cochise County and the Sierra Vista census division. Tract data for the Sierra Vista census division were only available for 1990 and 1997, and are listed in Table 6. New tracts for the census division were designated by the Census bureau for the 1990 census due to the influx of population during the 1980s.

County business patterns were collected to augment population and housing data for detection of urbanization patterns. The number of businesses and taxable payrolls per economic sector were collected from the same years of image acquisition, and are listed in Table 7.

Table 8 is data collected from the agricultural sector of Cochise County. Specifically, farm-level information includes number of farms, total area, average size, average market value, and percent of land area in the county used for farming activities. In addition, county totals of different farming systems, i.e., cropland, cropland pasture, woodland pasture, pastureland farms, in addition to number of cattle farms and cattle totals are listed to monitor land use change. Irrigated farms and irrigation totals in acre-feet are included for detection of water usage patterns.

3.4 DATA LIMITATIONS

Several data limitations were discovered during data collection and processing. Temporal constraints of remote sensing and demographic data, spatial limitations of designated census areas, spectral limitations and choice availability of remote sensing data, and classification limitations were the major topics of concern.

3.4.1 Temporal limitations

Due to budget constraints, lack of low-cost availability of remote sensing data was a limitation to a more broad time series analysis. Because image acquisition during the peak green-up time was essential to differentiate cover types (e.g. mesquite vs. riparian, grass vs. scrub, etc.), only images taken from late August through early October were sought. Available low-cost images acquired during these times of year were limited to 1973, 1985, 1992, and 1999.

Census of population and housing were only applicable to years 1970, 1980, and 1990. Obviously, data for the evaluation of spatial variations and shifting patterns in distribution of population and housing in 10-year periods between census tabulations were not available for analyzing human influence on the ecosystem. Similarly, except for 1992, agricultural statistics did not coincide with the years of image acquisition. County business patterns were available for every year; therefore this data source did not pose any temporal constraints to the analysis.

3.4.2 Spatial limitations

As mentioned, the census tracts 14 through 20 for the Sierra Vista census division were implemented starting with the 1990 census. Pre-1990 demographic data were available only for the census division without any delineation of tract-level spatial coverage. Therefore, the analysis was limited to examining population and housing units at only the larger-area census division for 1973 and 1985. For 1992 and 1999, population and housing units were available at tract level. In addition, agricultural statistics and economic business patterns were available only at the county level. However, because Sierra Vista is the major economical and agricultural hub of the southeastern Arizona region, the majority of exchange of goods and services, as well as sales of agricultural products take place within the census division (ADWR 1990).

3.4.3 Spectral limitations

Two important temporal resolutions should be held constant when performing change detection using multiple dates of remotely sensed data. First, the data should be obtained from a sensor system that acquires data at approximately the same time of day. Landsat MSS, TM, and ETM+ data were acquired around 10:30 A.M. for the study area. This eliminated diurnal sun angle effects that can cause anomalous differences in the reflectance properties of the remotely sensed data. Second, whenever possible it is desirable to use remotely sensed data acquired on anniversary dates (same dates of the year for each image). Using anniversary date imagery removes seasonal sun angle and plant phenological differences that can destroy a change detection analysis (Jensen et al. 1994). Although anniversary dates of images in the study were not identical, sun angle and phenological differences are minimal since the maximum date difference between the images was a matter of weeks.

Ideally, remotely sensed data are acquired by the same sensor system that collects data with the same instantaneous field of view (IFOV) on each date. However, the MSS sensor has a different IFOV (resulting in 80-meter spatial resolution) than TM and ETM+ sensors' IFOV (30-meter spatial resolution). Therefore, it was necessary to resample the MSS image to the uniform 30-meter pixel size. This does not present a significant problem as long as it is recognized that the information content of the resampled data can never be greater than the ground resolution of original sensor system.

Different sensor systems do not record energy in exactly the same portions of the electromagnetic spectrums (i.e., bandwidths). For example, the Landsat MSS sensor records energy in four relatively broad multispectral bands, and the TM sensor in six relatively narrow optical bands and one broad thermal band. Therefore, only bands that approximated each other across the three sensors were selected for change detection. These included bands green, red, and NIR of the MSS sensor, and green, red, NIR, and SWIR bands of TM and ETM+ sensors (see Table 2). In order to improve the accuracy of the training sites, however, a hyperspectral sensor consisting of numerous narrow bandwidths capable of precisely differentiating plant phenological cycles and numerous urban and non-urban cover types would have been preferred for better classification outputs.

An analog-to-digital conversion of the satellite remote sensor data usually results in 8-bit brightness values ranging from 0 to 255. Ideally, the sensor systems collect the data at the same radiometric precision on different dates. Unfortunately, the radiometric resolution of the early MSS sensor was only 6-bit (as compared to 8-bit TM and ETM+ radiometric resolution), and therefore had to be decompressed to 8 bits for change detection purposes. However, the precision of decompressed brightness values can never be better than the original, uncompressed data.

Finally, the 1985 and 1992 images exhibited slight cloud cover and resultant shadow effects, although the cloud cover was much less than the prescribed upper limit of 20 percent of the scene (Jensen et al. 1994). Consequently, cloud cover and shadows had to be masked out before supervised classification was performed.

3.4.4 Classification limitations

Classification accuracy assessment of remote sensing-derived land use/land cover maps and associated area totals per census tract would ideally require comparison of two sources of information: (1) the remote sensing-derived classification and (2) reference test information. For this study, it would have been desirable to utilize Digital Orthophoto Quadrangles (DOQs) in assessing the classification accuracy of land cover maps derived from Landsat MSS and TM data. The cost of such an endeavor was prohibitive, however, because, based on previous land use studies of the region (Kepner et al. 2000), in addition to obtaining the orthophotos, it is recommended that the suitability of DOQs in distinguishing between different land cover classes must be assessed using high-resolution airborne color video data at further cost. Although it is desirable to collect the reference information as close to the date of data acquisition as possible, DOQs for the 1973, 1985, and 1999 images were not available, and the DOQs for 1992 were available in either early April or late October. These time periods are undesirable for interpretation because they are too distant from the maximum green-up time when discrimination of vegetation cover of the region would be most confidently assessed. Because reference information is required but was not available for accuracy assessment of supervised classification, several important classification evaluation statistics including the KHAT statistic, which is the measure of the difference between actual agreement of reference data and automated classifier and the chance agreement between reference data and a random classifier, as well as producer's accuracy, and user's accuracy could not be calculated. However, because known a priori land cover types were identified by a combination of previously published land cover maps, personal observations, previous fieldwork data, and interviews with USDA classification experts of the region, I am confident that the overall accuracy of the classifications is no less than 80 percent. In addition, deriving human drivers of land use and land cover change typically depends on detecting changing trends of land cover and land use, rather than a precise quantitative assessments of land cover maps derived for more systematic vegetation analyses (Jensen 2000). Further, because accounts and trends of land use and land cover change in the region were similar in detail to the results of classification maps produced, such as decreasing grass cover and increasing urban and mixed mesquite cover (Bahre and Shelton 1993), the classified maps were deemed appropriate for land use and land cover change analysis.

3.5 INTEGRATION OF REMOTE SENSING AND GIS

The following subsection discusses conversion of image data to GIS vector coverage, overlay analysis, and magnitude procedures built for generating land cover area totals per census tract for all years of image acquisition.

3.5.1 Image to coverage procedures

In order to discriminate census tract area totals of land cover change from one classified image to the next, a GIS procedure using Arc/Info's programming language Arc Macro Language (AML) was developed to sum land cover totals per census tract.

The first step in the procedure consisted of converting the classified images to vector data models. Using this format, feature boundaries are converted to straight-sided polygons that approximate the original regions. Vector data formats have the advantages of relatively lower data volumes, better spatial resolution, the preservation of topological data relationships, and better overlay searching capabilities. In addition, because the census tract coverage was also in a vector format, a consistent data model was necessary to spatially interrelate multiple layers of vector coverages.

3.5.2 Overlay analysis

After all the classified images were converted to vector coverages, the census tract coverage and classified land cover coverage were interrelated by an overlay analysis. In a map overlay, a new map was created that shared the space division of both source maps. Every new polygon created on the map has a new attribute record in an expanded attribute database associated with the map overlay. This means that the overlay map is searchable by either of the sets of regions used to create it. This capability was deemed necessary for summing land cover totals on a tract-by-tract basis.

3.5.3 Magnitude procedure

Spatial magnitude of land cover classes per census tract was calculated by writing a GIS procedure using Arc/Info's AML. The code for the procedure is listed in the Appendix A. The first step in the procedure consists of a frequency function that calculates land cover type area totals per census tract polygon. These totals are then related to an INFO file that consists of only census tract polygon information (tract ID's and tract area totals). Classified cover totals are then sorted and summed up per cover type and checked against census tract area totals. Finally, a data file is written that lists land cover totals per census tract. The procedure was performed for each year of image acquisition. Land cover area totals per census tract are listed in Figures 8 to 11.

3.6 INFERRING HUMAN-ENVIRONMENT RELATIONSHIPS

The integration of remote sensing, GIS, socio-economic, and agricultural data created a data model necessary to construe anthropogenic influences on the Sierra Vista ecosystem. The supervised classification maps derived from remotely sensed data provided a visual and statistical interpretation tool for temporal and spatial monitoring of natural land cover as well as human land use patterns over the study area. As evidenced from both remotely sensed and agricultural census data, land cover categories that experienced positive and negative areal changes provided important clues to the identification of drivers of land use change. The census division and tract data provided means to analyze the role of human settlement patterns, land-based economic activities and their impact on land cover change. The well registry database was given geographic properties and as a result could be mapped for visual processing and served as a vital instrument for determining patterns of water usage and the impact of water demand on land use and land cover change. Urban land area totals derived from classified land cover maps, coupled with population, housing, and agricultural statistics, served as important indicators for water demand as well. Finally, the temporal and spatial characteristics of vegetation cover types derived from remotely sensed data, with extra attention given to areas distant from the influence of urban intrusion, provided important links between grazing techniques and rangeland management strategies and their impact on the fragile semi-arid ecosystem.

CHAPTER FOUR—RESULTS

Land use and land cover change and global environmental change form a complex and interactive system linking human action to use/cover change, use/cover change to environmental feedbacks, and environmental feedbacks to their impacts and human responses (Turner et al. 1995). Further complicating this system is the fact that the linkages occur at different spatial and temporal scales. Decreasing native grass cover in greater Sierra Vista, for example, has immediate impacts on land productivity, vegetation changes (increase in distribution and frequency of mesquite and scrub species) and soil erosion, mid-term impacts on landscape fragmentation, and possible long-term impacts on regional environmental change.

Varied human driving forces (e.g., population, development), mediated by the socio-economic setting (e.g., market economy, resource institutions) and influenced by the existing environmental conditions or context (e.g., semi-arid climate regime), lead to an intended land use (e.g., livestock rangeland) of an existing land cover (e.g., semi-arid grassland) through the manipulation of the biophysical conditions of the land. These manipulations (e.g., grazing) are the proximate causes of change to distinguish them from the underlying human forces of change and are the most immediate activities or actions that create change. These actions may convert the existing cover, in this case by grazing practices and lack of effective fire policy, or modify it through introducing exotic grass species into existing rangelands and failing to effectively manage invasive species. Either cover change (conversion or modification) is further affected by biophysical forces that change it unless human inputs are used to maintain the converted or modified cover (physical maintenance: e.g., removal of scrubs, weeds, and invasive species). Changes in the landscape may themselves affect the driving forces and the social setting in which they operate, and these effects may alter the intended land use.

The causes and consequences of land use and land cover change are research paths that aim toward understanding the social, economic, and policy factors that manipulate land use, occasionally addressing environmental components of the problem, but are rarely directly relevant to regional and global change studies. A major exception is work drawing on integration of remotely sensed imagery, census data, and GIS, used as tools to link land cover to land uses, proximate sources of change, and the underlying human causes to improve knowledge of carbon flows and biodiversity change. The regional analysis of the Sierra Vista census division revealed three important social drivers of land use and land cover change. These are urban growth and land fragmentation, water demand and legal issues, and grazing management and fire suppression. The information and interpretations generated by these drivers could offer lessons with which to frame land use and land cover dynamics in rangelands, particularly for transitory stages of change, and provide a factual basis on which to develop and test models of land use and land cover change by improving our understanding of current and future use/cover activities. In addition, the drivers serve as the primary causality factors of land cover change and are important indicators of anthropogenic processes that directly link to patterns observed on the landscape. Understanding these processes as they pertain to semi-arid ecosystems is critical for sensible management of economic development and natural resources in drylands. After the discussion of drivers of change and their relation to patterns observed on the landscape, the chapter concludes with a short discussion on integrating spatial information and technical considerations involved in the development of a decision support system for promoting informed range management practices.

4.1 URBAN GROWTH AND LAND FRAGMENTATION

Results of the area totals derived from remotely sensed imagery classifications reveal a sustained increase in urban cover type (Tables 9 and 10, Figures 8 to 11, 14). Overall, the census division urban cover increased from 2433.9 hectares in 1973 to 7100.7 hectares in 1999, a 192 percent expansion. A tract-level inspection reveals more specific trends. Examining Tables 9 and 10 discloses that tract 15 experienced the least amount of urban expansion, probably because this tract is located in the inner core of the city of Sierra Vista. Tract 14 is comprised mostly of Fort Huachuca, a U.S. Army base. The temporal and spatial expansion of built cover in this tract is more stable and constant, and is characteristic of military installations that typically have regulated planning, design, site feasibility, and construction requirements (Balbach 2000). Tracts 16, 17, 18 and 19 show a large surge of growth in built cover between 1973 and 1985, and level off to a lower and more stable increase between 1985 through 1999. Tract 20 was virtually undeveloped until 1999 when it experienced a 95 percent increase in built land. Tables 5 and 6 show similar trends in totals of population and housing units for the county division and census tracts. The most densely populated tracts coincide with the urban core census tracts of 15, 16, and 18.

But what does urban growth have to do with changes in grass cover besides moderate increments of land transition? The transformation matrix (Table 11) shows that grassland to urban net gain was only 5 percent from 1973 to 1985, and 2 percent from 1985 to 1992 as well as from 1992 to 1999. As discussed next, the main urban impact on the grasslands of greater Sierra Vista is largely an economic phenomenon.

The major force governing land use in the region is economic or location rent. The term rent in this context has a specific meaning that differs from that implied by the everyday use of the term. Economic or location rent is the surplus income that can be obtained from one unit of land above what can be obtained from an inferior unit of land (Chisholm 1962); for the most part, it is measured against land at the margin or limit of major agricultural cultivation, i.e., grass rangeland. For our purposes, we can define economic rent as a measure of the level of return that the market at large (all the potential bidders for land) would expect a particular piece of land to produce. It is basically a measure of the advantage, as the bidders see it, of one piece of land over another. This implies that pieces of land differ in some respect and that such differentiation is reflected in higher or lower returns per unit of land. In this simplified model, the causes of differentiation are the friction of distance and spatial variation in the quality of the natural resources. However, the major variable is no longer simply the transport cost of agricultural commodities to transshipment points (as is the case in many traditional von Thunen-based location theory models), but rather demand for accessibility to urban markets and amenities that has occurred on a large scale in the Sierra Vista census division.

Urban land invariably commands a higher value than rural land, and where the two type of use are in direct competition, urban uses generally win. But land that is *expected* to become urbanized has a higher value—an *anticipated* value—and this has a considerable effect on the type of land use practiced in rural areas of the census division. In the typical von Thunen model, lands adjacent to the urban market tend to be farmed at the highest intensity. In reality, however, such land is most likely to become urbanized and thus has the highest anticipated value. Under these circumstances, a rancher is unlikely to invest large amounts of capital and labor in livestock production when, by waiting a little while, very large financial gain might be achieved by selling the land to property developers. The speculative value of land for agricultural purposes, therefore, is *lower* very close to an expanding urban center and increases with distance as the likelihood of urban encroachment declines. As evidence, the value of agricultural land per farm in Cochise County has decreased on average from $ 795,292 in 1987 to $ 545,528 in 1997 (Table 8). In addition, Table 8 also reveals that the region has experienced a steady decline in total agricultural and pastureland area. In 1981, Santa Cruz and Cochise counties were first and second, respectively, in the sale of remote subdivision lots in Arizona. Tighter temporarily imposed restrictions on developers in the early 1970s forced many major rural subdivisions into bankruptcy (Hecht and Reeves 1981), leaving behind thousands of cleared hectares with eroding, unused bulldozed roads.

The encroachment of urban land use on the hinterlands is a testament to models developed by Douglas (1994) and Sinclair (1967) that emphasize the role and impact of urban settlements and settlement-related activities in promoting land cover change and conversion of land from rural and natural uses to urban usage. The typical scenario of land exchange involves the sale of agricultural land to speculators who wait until encroaching development is imminent before selling the land at a larger profit to subdivision developers. This relationship is illustrated in the classified imagery as well as in the GIS wells coverage of tract 20 (Figures 11 and 13). Tract 20 is adjacent to the urbanized tracts and is a transitional zone in the sense that urban land rent is greater than nonurban land rent, though not by enough to lead to massive development (notice unpaved road and utility corridors in Figure 7, and the large spatial coverage of wells in Figures 13). Land speculation in this zone is likely in its later stages. The transition zone is likely to be partitioned into subcategories such as that zone where urban land rent is greater than the cost of the sum of the compensation to agriculture and speculators' earnings (Thrall 1987). It is important to note that between the city core and the transition zone, people are willing and able to pay the cost of converting nonurban land to urban land use; hence, the land here is urban. This is equivalent to requiring that infrastructure is in place prior to development and that the new residents at the urban margins pay the cost of the infrastructure.

Land development in tract 20 started recently with low-density housing developments often with unpaved roads, water wells, and underground septic systems. This zone of transition is now leading to urban development to the extent that the infrastructure of highways and other public goods are being installed as the zone is being developed. This particular transition zone is mostly reserved for high to median-income housing for retirees and white-collar workers (Marsett 2000).

Tract 20, evidenced by land cover totals in Figure 8, was dominated by grass cover in 1973. The majority of the grass, however, is being converted to urban land use and land cover through the mechanism of economic rent and land speculation, which in turn is being fueled by a steady influx of new residents to this particular tract. The increasing trend in population is attributed to the census division's locational advantage for a booming tourism industry as well as its locational advantage as a sun-belt community for retirement. Although the economic rent variable is identified as a contributor to urban growth, another question remains in the explanatory power of urban growth and land fragmentation as a driver of land use and land cover change. What role do biophysical factors, including global climate change, play in augmenting urban expansion and outbidding of agricultural lands?

McCarthy and Lindberg (1966) developed a physical optima and limits model on the spatial pattern of agriculture. Two key variables are employed: temperature and moisture. Over a particular area, there is an optimal combination of both inputs for a particular crop (i.e., grass rangeland). Outward from this, however, the restrictions imposed by the physical and environmental limits of the two variables make conditions less and less favorable for agricultural resources. Although in need of further research, the most serious problem associated with the greenhouse effect, brought by the ability of the atmosphere to be selective in its response to different types of radiation (mainly short-wave solar radiation) which are augmented largely by carbon dioxide and methane gases that absorb solar energy, is the increasing dryness often accompanied by rising air temperatures in many areas (Kemp 1990). Reduced precipitation following changes in circulation patterns, plus the increased rates of evapotranspiration caused by higher temperatures would create severe moisture stress for grasslands in already fragile ecosystems. Ultimately, under extreme but likely conditions, physical limits will be reached that make livestock production undesirable. Of course, it is always possible, even within the context of environmental limits, to provide production. Costs, however, rise to infinity near extreme limits, meaning that a real technological barrier exists. In fact, the optima provide the rancher free of charge with the maximum benefits that nature can provide in terms of temperature and moisture. To move away from the optimum imposes costs and recourse to scarcer resources. If global warming-induced low precipitation and high temperature patterns become the norm in southeastern Arizona (as suggested by the recent lack of snow cover, and consequent lack of recharge in regional aquifers), it is ventured that the price of agricultural land will fall at an even faster rate, creating a climatologically intensified, greenhouse-based expansion of the transition zone between urban and agricultural land open for speculation and development. As non-urban land prices fall, speculators will likely opt to purchase more and more rangeland property for future urban uses. Therefore, global environmental factors in addition to land rent will contribute to urban expansion. Given the characteristics of spatial economic production and consequent labor inputs discussed below, this chain of events will only lead to a cycle of depletion of additional grass and other natural cover coupled with a rampant pattern of urbanization.

Sierra Vista serves as a commercial center for southeastern Arizona and northern Mexico, and is rapidly attracting capital, banking, and additional commercial interests (Clark 2000). The large influx of new firms into the region is likely to create external economies of scale, defined by Dicken and Lloyd (1990) as "savings that a plant or firm gains from its connection with other plants or firms." One source of such external economies is explicitly spatial. By clustering in close spatial proximity to other activities, it is believed, firms will benefit from a particular kind of external economy of scale called economies of agglomeration. In this context, scale economies achieved during the early phases of growth are passed on as external economies expand. The cumulative process of development has a multiplier effect by which direct effects (production and sales) are followed by indirect effects (increase in labor pool, local consumption of goods, rise in real income, and increase in the number of services) in a chainlike sequence as expansion induced in one sector has repercussions on other sectors, though the effect becomes less and less pronounced as distance from the original stimulus increases (Dicken and Lloyd 1990). This phenomenon is readily observed in Table 7. Contract construction, retail trade, transportation and public utilities all experienced tremendous sequential increases in the number of employees and payrolls in selected years. The service sector, a crucial sector of external economies of scale, experienced an even more impressive boom (payrolls for the first quarter rose from almost $2 million in 1973 to over $44 million in 1999).

But agglomeration may also generate diseconomies. There may be a point at which an expanding urban agglomeration becomes incapable of maintaining its efficiency although sustainable steady growth continues. Problems such as congestion and clogged transportation arteries, soaring land prices, pollution, and administrative overload begin to transform urbanization economies into diseconomies. However, the most crucial affect of agglomeration in Sierra Vista from a local and regional viewpoint, fueled by both economic and environmental stimuli, may be its strong detrimental effect on the ecosystem resulting from cumulative encroachment into open spaces of grass cover. The landscape fragmentation that has resulted from extensive abandoned rangeland combined with increasing urban and rural settlements isolate areas of desert grassland and hinder the dispersal of species and the spread of fires. There is a need for more research in determining optimal sizes for agglomerations just as for individual plants, sizes at which public utilities and services are provided at optimum levels of efficiency, and the environment is protected from mass-scale encroachment of built land.

4.2 WATER DEMAND AND LEGAL ISSUES

Although groundwater is renewable through natural recharge, overpumping can temporarily deplete the resource. If groundwater-pumping withdrawals exceed aquifer recharge, then groundwater is being "mined" or overdrafted from the basin (Lacher 1994). Further, groundwater overdraft conditions may be evident in groundwater declines that form a large "cone of depression" in the aquifer around a pumped well or in the area of an active well field. If pumping continues to exceed aquifer recharge over time, the cone of depression will continue to expand outward from the wells. The rate of water level decline and growth of the cone of depression depend on the aquifer's hydraulic characteristics, the surrounding geohydrology, the rate and volume of water pumped, and the rate of recharge to the aquifer (Lacher 1994). The cone of depression will continue to grow until equilibrium is achieved and aquifer recharge equals aquifer discharge.

Currently, although groundwater is renewable through natural recharge, groundwater pumping withdrawals exceed aquifer recharge in greater Sierra Vista region due in large part to increased municipal and industrial demand for water (ADWR 1999). The same ADWR report also reveals that total volume of recoverable groundwater held in storage in the upper San Pedro basin has decreased by 13 percent in the regional aquifer since 1990. Due to technological innovations, improved well system design for groundwater extraction (such as turbine and centrifugal pumps with electric engines) has allowed for deeper well depths. The average depth for all wells in the Sierra Vista census division is 275 feet, a depth that penetrates well into the regional aquifer located under the region's substrata. These deep artesian wells have taken a toll on the groundwater supply. ADWR (1990) reports the existence of a cone of depression approximately 4 miles long and 2.5 miles wide (10 square mile size) in the Sierra Vista-Fort Huachuca area, with long axis parallel to Huachuca Mountains (NW-SE direction). The cone's extent in the area north and east of Sierra Vista is ill defined because it falls within the firing range on Fort Huachuca where few wells are accessible. It has been reported that artesian pressures throughout the region have been declining due to prolonged pumping (Vionnet and Maddock 1992). The water levels in two wells located at the 1990 center of the cone of depression showed a net decline of 50.2 and 48.2 feet, respectively, during the period 1980 to 1988 (ADWR 1990). Net decline rates over an area of 25 square miles centered at Sierra Vista ranged from 0.4 to 3.9 ft/yr (averaging 1.4 ft/yr) for the same period. Schwartzman (1990) reported the existence of a second smaller (3-mile long) cone of depression near Huachuca City along the Babocomari River (northwest of Sierra Vista). Further, evidence indicates that perennial reaches of the Babocomari became intermittent after cultural development (Brown et al. 1981).

Shallow wells typically found on the San Pedro River floodplain aquifer have a potential impact on the regional aquifer as well. Decreasing water levels around a well form a roughly circular cone of depression, deepest at the well and lessening with distance from the well (Lacher 1994). As pumping time and frequency increases, the volume and radius of the cone increase and its edge may reach the streambed if the well is shallow. If streamflow is present, the well will draw water directly from the stream. If no surface water is present in the vicinity of the cone of depression, the cone continues to increase in size in the floodplain aquifer. If the cone reaches the interface between the floodplain aquifer and the regional aquifer, the well will begin drawing water from the regional aquifer. In Sierra Vista, groundwater pumping alone accounts for the wide spread water table decline (Putman et al 1988).

In addition, I would add the recent dry climatological pattern over the region to the contributors of declining regional aquifer. Typically, precipitation in southeastern Arizona is bimodally distributed with about 50 to 60 percent of the annual total falling in the summer monsoon season, and 21 to 35 percent occurring in the winter months (Lacher 1994). Spring and fall are usually dry. Winter storms originate mainly from mid-latitude Pacific (cyclonic) fronts, producing several days of rain, moderate winds, and mountain snow. Over the last 10 years, the precipitation pattern over the Sierra Vista census division has become event-driven with scattered and sporadic shower and thunderstorm activity rather than the normal frontal activity associated with cooler temperatures (Mauget and Upchurch 1999). Isolated precipitation events along with diminishing winter snow cover on the Huachuca Mountains cause a decrease in the amount of recharge level necessary to equal aquifer discharge since direct infiltration over the valley floor is considered negligible because of high evaporation and low precipitation rates. In effect, the drying climatological regime causes further imbalance on the supply-side of the regional aquifer equilibrium.

Hydrologic model studies provide further warnings of additional groundwater depletion in the near future. Putman et al. (1988) projected that pumpage in the Sierra Vista-Fort Huachuca area will triple from 1986 to 2006, with a maximum annual rate of groundwater level decline projected at 6 ft/yr by the year 2006. Pumping estimates for the future were based on population projections and consumptive use figures based on the 1980 census (228 gal/day/person). The projected pumpage in the Sierra Vista subbasin accounted for the BLM land exchange (establishment of the SPRNCA in 1988), which includes several land grants along the San Pedro River and additional farmland near the International Border. To make matters worse, however, the conceptual model did not take into account the dry climatological regime and characterized the aquifer system as being unconfined and regularly recharged by the Huachuca Mountains front recharge.

An aquifer's capacity to transmit water, or hydraulic conductivity, and the volume of water an aquifer can release or take into storage, described by the storativity value, are the primary scientific descriptors of an aquifer (Putman et al. 1988). These two values are used to estimate regional groundwater flow rates, groundwater storage volume, and the effect of a pumping well on the aquifer and other nearby wells. If regional aquifer overpumping continues, the ability of the aquifer to transmit and release water to the surface will diminish due to negative impact of overpumping on artesian pressures (Putman et al. 1988). The total volume of recoverable groundwater in an aquifer is determined by the geology and chemistry of the aquifer material, which in turn determine the number and size of open pore spaces that exist. Under Sierra Vista, water held in storage in the regional aquifer resides in these pores, and is released to the surface by an upward-declining pressure gradient through the upper basin fill which is composed mostly of permeable and porous material including gravel, sand, silt, and poorly cemented clay (Lacher 1994).

Increasing rates of well drilling and water demand due to residential and commercial development in the region, evidenced by increasing population, urban area, and housing units (Tables 5, 6, 9, and 10, Figure 13), are drivers of land use and land cover change in the Sierra Vista region because decreasing amounts of regional ground and surface water has a direct, frontal impact on agricultural use of land. Over the last 50 years, depletion of groundwater reserves has led to an initial increase in rangeland at the expense of farmland (Cox et al. 1983), and the same cycle is presently leading to potential depletion of grass cover on rangelands. The very nucleus of the range ecosystem is composed of the interrelations among grasses, soils, climatic variables (precipitation and temperature), and surface and groundwater. Annual and perennial grasses both have fibrous root systems, with the densest concentration in the top 15 to 20 centimeters of soil (Hyder 1973). On the other hand, competitors such as burroweed have few feeder roots in the top foot of the soil, but have a taproot that extends much deeper than the grass roots. Because of root system differences, depleting near-surface soil moisture caused by urban water demand, and potentially global warming, shrub and weed species have the competitive edge during the summer growing season. Furthermore, annual species such as tobosa grass, frequently encountered on heavier soils subject to flooding (Anderson et al. 1963), are disappearing due to lack of baseflow (discharge of groundwater to the stream which sustains surface flow in dry seasons) and competition with cholla, burroweed, mesquite, and phreatophytes.

As the water demand in greater Sierra Vista increases, the validation and quantification of surface water and groundwater rights are coming under the scrutiny of local, state, and federal institutions. On June 12, 1980, the Arizona legislature enacted a comprehensive groundwater management code governing the allocation and use of groundwater. This legislation was a direct product of Arizona's continued overdraft of groundwater (Lacher 1994). The 1980 code created four Active Management Areas (AMA's) with specific regulations on groundwater pumping and well construction, and two Irrigation Non-expansion

Areas (INA's) in which expansion of irrigated agriculture was prohibited. Because greater Sierra Vista falls outside of AMA's and INA's, however, the beneficial use rule applies to groundwater rights. That is, anyone may pump water from below his property as needed for a "beneficial" use on that parcel of land. The only restrictions that apply to drilling wells or pumping groundwater are the requirements of well registration and conformity to well construction standards. As seen in Table 12 and Figure 13, the freedom of "beneficial" use has been taken to an extreme by residential developers who drill wells at a significant depth below the upper reaches of the regional aquifer (presently around 200 feet for artesian conditions). Further, proliferations of wells in tract 20 exemplify the unregulated nature of water management in the region.

Due to urban water demand and its negative environmental effects, there is an urgent need to provide research and information for a decision on whether the ADWR should designate Upper San Pedro Basin as an AMA under the 1980 Groundwater Management Act. The 1980 Act allows the director of the ADWR to form an AMA if any of the following conditions exists: 1) active management practices are necessary to preserve the existing supply of groundwater for future needs, 2) land subsidence or fissuring is endangering property or potential groundwater storage capacity, or 3) use of groundwater is resulting in actual or threatened water quality degradation (Lacher 1994). It is humbly recommended that ADWR should designate this particular basin as an AMA given the recent unregulated urban demands on water resources and the propensity of most developers to overlook harmful environmental effects of unrestricted well construction.

In 1988, Congress passed the San Pedro National Conservation Area Act. This motion established the Conservation Area out of public domain lands managed by the BLM "in order to protect the riparian area and the aquatic, wildlife, archeological, paleontological, scientific, cultural, educational, and recreational resources of the public lands surrounding the San Pedro River in Cochise County, Arizona." The initial reservation comprised 56,000 acres and provided for the subsequent acquisition of additional parcels of land. The Act required the Secretary of the Interior to develop a long-term management plan and it expressly reserved water rights. Additional land purchases of subsequent threatened areas, especially those that are currently in danger of being developed adjacent to the river on tract 20 (Figure 11), should provide adequate protection from urban encroachment. Leasing of such lands for recreational purposes, wildlife and game management, as well as public domain grazing could provide revenue for additional restorative efforts and help promote sound range management practices on regulated federal lands.

4.3 GRAZING MANAGEMENT

4.3.1 Mesquite invasion

One of the most dramatic changes in the grasslands in greater Sierra Vista in the last 30 years has been the rapid increase of scrubby trees and shrubs (Bahre and Shelton 1993). These woody invaders, whose spread has been influenced, if not caused, by overgrazing and fire suppression, deserve inclusion into the discussion of grazing impacts and rangeland management.

The recent increase (1980s onward) in dense phreatophyte cover in the San Pedro riparian corridor is probably attributable to an increase in the percentage of vegetation made up by mesquite and tamarisk (Putman et al. 1988). As early as 1965, Hastings and Turner reported a dramatic increase in mesquite populations along the floodplains and an invasion of tamarisk. At present, mesquite invasion is widespread in the Sierra Vista census division. Examining the transformation matrix in Table 11, we see that nearly 20 percent of grass cover in 1973 became mixed mesquite by 1985. The net gain, however, was negative since 25 percent of mesquite was transformed to grass. A 13 percent net gain by mesquite occurred between 1985 and 1992. This percentage rose to 22 percent between 1992 and 1999. Figure 14 also demonstrates the invasive nature of mesquite. Total area of mixed mesquite in the census division increased from 11,843 hectares in 1973 to 18,548 hectares in 1999, a 57 percent increase. Most of the dramatic increases took place in tracts 14, 17, and 20 (Figures 8 to 11). The majority of lands on these tracts are located outside the 5-kilometer urban buffer comprised of tracts 15, 16, and 18. Because a vast majority of large-scale and hobby ranches are located in these rural areas, the proliferation of mesquite could have a direct relationship with grazing strategies and land management practices utilized by range managers and hobby farmers.

In the southwestern United States, range productivity on most sites can be greatly increased by control of mesquite, and tarbush, and seeding with Lehmann lovegrass and fourwing saltbush (Holechek 1998). Mesquite competes seriously with warm-season perennial grasses. The inverse relationship between density of mesquite and perennial grass production has been widely recognized (Reynolds and Martin 1968). The roots of mesquite and acacia plants are generally more extensive than those of herbaceous grass species, and allow the plants to tap soil water sources at greater depths. Other species, such as creosote bush, have a spreading root system that enables the plants to exploit water sources for extensive areas in the soil surface around the plant. Anderson et al. (1963) concluded that mesquite and acacia stands exceeding 15 to 25 trees per acre should be removed or thinned before reseeding with grass, and that recovery of perennial grasses under improved grazing management was faster on mesquite-free range than where mesquite was not killed.

The causes identified for the mesquite increase include (1) a reduction in the frequency and intensity of wildfires due largely to overgrazing following settlement and fire suppression; (2) a decline in natural perennial grasses, which, when healthy and dense, can reduce mesquite seedling establishment; (3) increased dissemination by livestock and/or Merriam kangaroo rats of scarified mesquite seed; (4) hoof damage to ground cover and soil compaction by livestock resulting in reduced moisture in the upper layers of soil, which hinders grass establishment and growth; and 5) land clearing and cultivation (Bahre and Shelton 1993). These management-related causation factors have contributed greatly to the demise of grass cover in the Sierra Vista census division.

The rural census tracts, namely tracts 14, 17, and 20, have the most noticeable loss of grass cover in the classified imagery (Figures 8 to 11). Tracts 14, 17, and 20 lost 78, 42, and 36 percent of grass cover, respectively, between 1973 and 1999. Although other causes previously discussed, such as urbanization and water demand, contributed to the decrease, it is safe to venture that a large portion of grass cover loss in these tracts was due to lack of effective livestock management practices.

4.3.2 Impact of grazing on rangelands

Livestock affect watershed properties by consumption of plant parts and through the physical action of their hooves. Accelerated erosion occurs when lack of proper range management leads to destruction of the vegetation cover that retards soil loss from the forces of water and wind. In addition, accelerated erosion is the most severe consequence of overgrazing due to the fact that, especially in arid and semi-arid regions, replenishment of lost soil is a very slow process. Severe erosion also leads to additional environmental problems such as decrease in water quality and infiltration, and increase in surface runoff (Holechek 1998). The condition of the soil and the vegetation complex on which precipitation falls has a major influence on the quality and quantity of water available to the semi-arid ecosystem. Therefore it is necessary to examine the relationship between range management and grazing impacts on the ecosystem and related land use and land cover change, with particular emphasis on infiltration, runoff, erosion, and water quality. As a management and decision support tool, remote sensing and remote sensing-based products could provide valuable information on monitoring and assessment of ecological impacts attributable to grazing methods as well as providing value-added assistance for future protection of rangelands from overuse and neglect.

4.3.2.1 *Infiltration*

Grazing and browsing animals reduce water infiltration by removing protective plant materials and compacting the soil surface by hoof action. The negative impact of heavy grazing on water infiltration is well documented. After reviewing grazing impacts on infiltration, Gifford and Hawkins (1978) concluded:

1. Ungrazed plots have higher infiltration rates than those of grazed plots.
2. Moderate and light grazing intensities have similar infiltration rates.
3. Heavy grazing causes definite reductions in infiltration rates over moderate and light grazing intensities.

Although it has been speculated that under some conditions the hoof action of grazing animals will loosen the surface of compacted or crusted soils, actual research shows just the opposite effect (Warren et al. 1986). Several studies in Texas and New Mexico are consistent in showing the concentration of hoof action under short-duration grazing reduced infiltration compared to continuous grazing (McCalla et al. 1984; Thurow et al. 1986). Heavy stocking consistently reduced infiltration during the grazing season, but this appeared to be alleviated by winter freeze-thaw activities. Other studies are consistent in showing that grazing systems other than short-duration grazing have little influence on infiltration rate but that reductions occur when stocking rates are increased from moderate to heavy (Wood and Blackburn 1981; Pluhar et al. 1987).

A few studies have evaluated the influences of grazing on soil structure. In New Mexico, lightly grazed, heavily grazed, and severely grazed ranges had pore spaces of 68 percent, 51 percent, and 46 percent, respectively (Flory 1936). It was also found that heavy grazing degraded soil structure by reducing the percentage of water-stable aggregates compared to moderate grazing, and that heavy grazing increased soil compaction (bulk density) more than moderate grazing (Wood and Blackburn 1984). In the same study, different grazing systems (continuous, Merrill three-herd/four-pasture, and high intensity-low frequency) had a similar effect on water-stable aggregates and bulk density.

4.3.2.2 *Runoff*

Livestock grazing increases runoff by reducing infiltration. Increased surface runoff due to heavy grazing is usually associated with water quality degradation because of increases in sediment and other pollutants (animal wastes, agricultural chemicals, and decayed vegetation).

It is well documented that heavy grazing increases runoff compared to moderate grazing (Sharp et al. 1964; Hanson et al. 1970). On the other hand, protected areas generally have the least runoff. Branson and Owen (1970) showed that runoff increases as vegetative cover and mulch decreases and the amount of bare soil increases. The same study documented the inverse relationship between runoff and vegetation cover.

Limited data indicate that moderate or light grazing can increase groundwater and runoff compared to no grazing, without having a detrimental impact on the watershed or water quality (Hanson et al. 1970; Lusby 1970). Under moderate or light grazing intensities, adequate vegetation is maintained to protect the site, but excessive vegetation that causes water losses by transpiration and evaporation is removed. More research is needed on the potential of controlled grazing to increase water yields. Information regarding influences on groundwater would be particularly useful for the southwestern United States, where many underground aquifers are being rapidly depleted.

4.3.2.3 *Erosion*

Sediment yields in runoff and streamwaters are commonly used as a measure of erosion on rangelands. Heavy grazing accelerates erosion by reducing plant cover that protects the soil and retards overland flow. Several studies have documented higher erosion under heavy grazing intensities than under moderate intensities, and concluded that moderate grazing will not cause watershed damage on most rangelands (Thurow et al. 1986; Pluhar et al. 1987). In many cases watershed recovery can be accomplished by changes in grazing practices. In New Mexico, Aldon (1964) reported that sediment loads were reduced more than 75 percent due only to better livestock control (change from season-long to winter grazing) and reduced grazing intensities.

The influence of short-duration grazing on sediment production compared to other grazing methods has been a concern. Available research is consistent in showing that short-duration grazing increases sediment production compared to moderate continuous grazing (McCalla et al. 1984; Thurow et al. 1986). The reduced vegetation cover associated with short-duration grazing in the studies cited previously appeared to cause the higher sediment production.

The most detailed evaluation of hydrologic responses under short-duration grazing was reported by Warren et al. (1986). They studied infiltration and sediment production on a silty clay soil (similar to the association in greater Sierra Vista) using a short-duration grazing system with moderate, double-moderate, and triple-moderate stocking rates. Short-duration grazing at all intensities reduced infiltration and increased sediment production compared to no grazing. These deleterious effects were increased as stocking rate increased. The damage was augmented when the soil was moist at the time of trampling. Thirty days of rest was insufficient to allow hydrologic recovery. Another part of the study evaluated seasonal changes in infiltration and sediment production under short-duration grazing at a moderate stocking rate. The infiltration rate declined and sediment production increased following the short-term intense grazing period inherent to this system. These effects were most severe during drought and dormancy, due to reduced vegetation standing crop. It was also found that there was no definite hydrologic advantage of increased stocking density via manipulation of pasture size and numbers.

Although limited data are available, the amount of vegetation required to protect different types of rangeland needs more study. Complete protection of the soil requires about 550 kg per hectare of plant material (Osborn 1956). Ground cover levels of 30 to 40 percent appear adequate for flat, arid areas, and levels as low as 20 percent will protect most soils from wind erosion (Branson et al. 1981).

The key to maintaining healthy hydrological conditions on rangelands is through grazing practices that develop and maintain a good grass cover. Perennial grasses, because of their high basal area and excellent soil binding properties, play the critical role in watershed stability (Holechek 1998). Moderate stocking rates in conjunction with grazing practices such as rotational deferment and rest rotation grazing that promote even livestock distribution over the range appear to be the best approaches to maintaining a good perennial grass cover. The success of any grazing program geared toward watershed maintenance and enhancement is best measured by the residue of living and dead vegetation it maintains on the site throughout the year. A good residue of forage left ungrazed prior to initiation of new growth in the spring may appear to be wasteful from a forage standpoint. However, in the long run, the land manager will be rewarded by higher forage production and less variation in the forage crop between years due to increased soil moisture and mineral supplies available for plant growth.

4.3.2.4 *Water quality*

Fecal wastes from livestock grazing can be a sizable pollution problem in range watershed management. Fecal coliform bacteria counts in water have been used as an indicator of infectious bacterial contamination (Wadleigh 1971). However, the coliform bacteria themselves are not pathologically harmful. Livestock operations have caused increased coliform bacterial pollution in rangeland washes and streams (Gary et al. 1983).

The extent of the bacterial pollution depends largely on livestock numbers, timing of grazing, frequency of grazing, and access to the stream. Tiedemann et al.'s study (1987) showed that fecal coliform bacteria levels tended to increase as intensity of livestock use increased. This study presented evidence that livestock removal may not provide an immediate solution to elevated fecal coliform bacteria levels in streams. Grazing strategies that disperse rather than concentrate livestock, such as rotational deferment and rest rotation grazing, appear best when fecal contamination is a concern. Practices that improve livestock distribution and attract livestock away from streamside areas are also recommended in Tiedemann et al.'s study.

Treated sewage sludge as a soil amendment on rangelands does not appear to deleteriously affect the quality of runoff water (Aguilar and Loftin 1991), and in some situations, applications of municipal sewage sludge increases herbage yields and reduces detrimental runoff and sedimentation.

4.4 FIRE SUPPRESSION

Fire has historically been common in most desert grasslands. Before 1882, fires were extensive, sometimes covering hundreds of square miles, and several lines of indirect evidence suggest that fires occurred at least every 10 years (Bahre 1977). Shrubs were inconspicuous in desert grasslands before 1880, which suggests that fires occurred frequently enough to prevent widespread shrub development. Most desert grassland shrubs are susceptible to fire, at least as seedlings (J.H. Bock and

Bock 1992). For example, velvet mesquite plants usually did not resprout following fire unless stems were larger than 1 centimeter in diameter when they burned (Glendening and Paulsen 1955). Furthermore, many woody species do not produce seeds until they are at least 10 years old, and their seeds on the soil surface are easily killed by fire (Martin 1975). Thus, a fire frequency of once every 7 to 10 years appears to maintain relatively shrub-free grasslands.

Considerable evidence suggests that widespread livestock grazing reduced fine fuel, and therefore fire frequency, in southeastern Arizona after 1880 (Bahre 1977). Historical accounts and direct evidence of reduced fire frequency in nearby pine forests of Huachuca Mountains document reduced incidence of fires concomitant with the buildup of the livestock industry (Martin 1975). In fact, forest administrators encouraged overgrazing to reduce fire hazard and promote tree growth (Bahre 1993).

Many grass species common in southeastern Arizona including blue and hairy grama, plains lovegrass, as well as the introduced lehmann lovegrass, recover much more quickly after a fire than large, decadent scrub and mesquite species because their rhizomatous roots are located below the soil surface, and thus usually escape lethal temperatures (Glendening and Paulsen 1955). However, large bunchgrasses, such as threeawns, and stoloniferous species like buffalo grass and black grama, are damaged more than smaller bunchgrasses because more fuel is present, fire duration is longer, and heat penetration is deeper into plant tissue (Holechek et al. 1998).

Burning may significantly affect nutrients in range soils. Burning sometimes increases the supply of nitrogen, phosphorus, and sulfur available for plant growth

(Holechek et al. 1998). Nitrogen is frequently limiting, especially on brush-supporting soils. Addition of even small amounts of available nitrogen may have a profound effect on revegetation (Hobbs et al. 1991). Although fire survivors have access to more resources (e.g., light and soil nutrients) than they had before the fire, it must be noted that a plant species need not survive a fire to reap its benefits. Species that produce abundant and widely dispersed seeds capable of establishing in the high-light, fluctuating-temperature environment characteristic of recent burned rangelands may also benefit from fire. Examples include annual grasses such as needle grama, threeawn, and Lehmann lovegrass (Hobbs et al. 1991).

After a fire event, the resprouting vigor of woody shrubs decreases with decreased soil moisture content; resprouting is generally less common following fires that occur during the growing season compared to dormant-season fires (Wright and Bailey 1982). Blue paloverde, burroweed, ocotillo, oneseed juniper, and snakeweed rarely sprout following fire (Wright and Bailey 1982).

The long-term absence of fire may produce dramatic changes in community structure and function, particularly if soils do not limit shrub establishment (Holechek et al. 1998). In the absence of fire, desert grasslands may develop dense, woody overstories that significantly reduce herbaceous grass production. The resulting lack of fine fuel reduces fire intensity and frequency, and the community changes from grassland to shrubland (Brown and Lowe 1980). After this threshold between grassland and shrubland has been crossed, land management strategies should be reevaluated. Once woody plants dominate a site, fire alone cannot return it to the earlier composition since fine fuel is too scarce and discontinuous to produce fires of sufficient intensity to kill woody plants. Thus, woody plants become permanent occupants of the site. Without herbicides or mechanical shrub control the change is irreversible. The net result of the absence of periodic fires is a reduction in herbaceous grass production.

CHAPTER FIVE—CONCLUSIONS

5.1 FUTURE RESEARCH AND DECISION SUPPORT SYSTEMS

Reversing the problems of grazed ecosystems requires a better ability to make good management decisions. The world's biological resources are being overexploited because local ecosystems, especially agroecosystems, are exporting resources to distant markets (McNeely 1990). Cities and foreign markets gain the benefits while local communities experience the environmental costs. Whether local or global, decisions always have a political component and always contain an element of subjective balancing. Inconsistencies and disagreements will be greatest when the subjective component of decision-making is greatest. Such problems are minimized when different parties (ranchers, land managers, public policy officials) share information, have common methods of defining problems, and agree on the broad objectives of sustainable development (McNeely 1990). In this circumstance, disagreements can focus on and resolve the value judgments without having to argue about what ought to be the objective underlying facts.

Decision support systems (DSS) offer a mechanism for improving the objectivity of decision making, especially where complex interactions are involved. An open and distributed web-based DSS for rangeland monitoring should aim to be flexible, with an integrated design for accessing, retrieving, and generating images and reports, as well as being able to accommodate decision models for conducting further analyses including sensitivity analysis using remote sensing algorithms such as numerous green and recently developed senescent vegetation indices, fractional cover, and biomass estimates.

The concept of a DSS has evolved over the last 15 years. As other computer-based tools have developed, the potential for integrating a wide range of data sources has become obvious. These include databases and graphically oriented systems such as remote sensing and data visualization. Furthermore, the limitations of some of the information sources and computer-based presentation techniques have been recognized; hence, non-computer elements are now commonly accepted as part of an overall DSS (Stuth and Lyons 1993). These features become particularly important when dealing with users and uses where computers or Internet connections are not available (e.g., ranchers in remote locations). Therefore, the major goal of a DSS must be to improve decision-making through conversion of variety of data sources into value-added information and provide users at all levels of technical access and training with the means to assess alternative outcomes against each other more objectively and comprehensively than could be done previously.

The technological development of remote sensing and data visualization began years ago as separate endeavors, but the two now meet at a time when their unification is an important objective for the development of decision support systems for natural resource management. Coupled with a distribution network utilizing the World Wide Web, we are now able to develop distributed, open, web-based DSS with data acquisition, data management, and data utilization capabilities.

For base tier data establishment, the most reliable source is satellite imagery. Displayed in Table 13, ASTER and MODIS sensors mounted on the EOS-AM platform, in addition to other commercial sensors, provide fine pixel resolution, short off-nadir repeat cycles, and quick delivery from acquisition time; the SPOT 4 VEGETATION sensor offers 48-hour repeat cycles because of its wide 2,250 km swath width although the spatial resolution is rather coarse (1.36 square kilometers). As such, this sensor should be utilized for regional rangeland analysis, while ASTER and MODIS sensors are ideal for detailed vegetation analysis desirable for most small- to medium-scale ranching operations. Although ETM+ sensor mounted on Landsat-7 has ideal pixel resolution (30-meter), its repeat cycle is 16 days, and delivery time is generally 2 weeks to one month. Therefore, this sensor may not be suitable for most rangeland DSS applications that require expeditious decision-making capabilities for determining optimum stocking rates in suitable areas.

Ideally, all the data acquired should be organized, managed, and used in an integrated manner, although segmentation of information resources is quite common. Since data sets are typically application-specific, they are often designed and operated independently of each other. However, there is an emerging awareness of the need to use a general purpose OODBMS (Object-Oriented Database Management System) to unify information management. The goal of such systems, e.g., ORACLE[1], is to increase the efficiency of information processing by maintaining greater data integrity, less data redundancy, and more

[1] Use of ORACLE trademark does not imply endorsement.

efficient data sharing and output. Greater data integrity means that if a data element (e.g., pixel reflectance value in an image) is stored in more than one place, its value should always be the same. When updated in one place, the data element's other locations will be automatically updated. Duplication of storage of the same data element should be kept to a minimum to reduce redundancy. Faster output and data sharing refers to the access of the same data item by more than one application. Obviously these three principles are closely related to one another and serve to expedite more efficient information processing. Major attractions of OODBMS are their functionality since they are applicable to both tabular and spatial data, and the fact that systems are comprised of objects and each object has its own distinct behavior. Certain behaviors in objects may trigger behavior in other objects. Objects are abstractions of real world entities, such as grass cover, soil moisture, images, information requests, etc. All these objects have their own behavior and characteristics and can influence one another in any manner that may occur naturally or abstractly in our own minds. As OOP (Object-Oriented Programming) handles objects in the way we treat them in our own thought processes, we should be more comfortable in understanding and implementing systems when they are developed in an object oriented fashion.

In OOP, the behavior of an object is represented by its state changes (changes in object property values) and by its communication with other objects, which normally triggers new behavior in those objects. Communication is accomplished through message sending. For example, a management plan object may send an "area" message to a specific grass cover object. The grass cover object would invoke its "area" method, which would retrieve its area value from the object-oriented database, which in turn was calculated by invoking a GIS process. As can be seen, both the database and GIS processes are methods of an object. The object itself forms the link. Therefore, specialized processes in raster data visualization (calculation of vegetation indices, fractional cover and biomass algorithms), topological calculations (parcel by parcel land cover totals, route analysis), and databases (retrieval of image and tabular data from related entities) will themselves be comprised of objects with behavior and inter-object communication.

A system can be built from a collection of objects, perhaps several hundred, with each object doing a very specialized job. These objects must be classified within a system under "classes" that form the abstraction from which objects can be created. For web-based applications, this requires the functionality and capability of an internet-savvy, object-oriented 4^{th} generation programming language such as Java. Java is a platform-independent language and is incorporated into all of the major Web browsers (Internet Explorer, Netscape). Therefore, Java-based applications may run as stand-alone executable programs on any platform (PC, UNIX, and LINUX) or as applets on the Web. Its powerful networking capabilities allow developers to create three-tier architecture system designs with databases, servers, and clients. Third-party data visualization library and methods packages, such as JWAVE, provide Java with server-side capability to manipulate and process orthorectified multi-band images to calculate vegetation indices, fractional cover, and biomass estimates.

The following is a simplified design of a three-tiered, distributed DSS created in Java (Figure 15). The middleware (a Java-CGI application residing on a web server), on a daily basis, calls two objects, search and input, that establishes a connection to a distributor's FTP site searching for the most recently available, sequentially-ordered raw images. If the images are present, the web server retrieves them. The database is opened for input via the recently developed ActiveX data object control (a predefined set of objects for accessing database servers), and the raw images are sent to the database by invoking a "send" message. In the database, the image objects are sorted by sensor, area coverage, and date. After the database connection is closed, the raw data are now stored and wait to be invoked by a user-defined client message received by the web server. The users on the client browser may specify to view the whole image, a subset of an image, an animation sequence, algorithm-derived indicators in either image or tabular format, or request a FTP to their IP addresses. These specifications, depending on user choice, become data-streamed image, subset, algorithm, or delivery methods handled by objects and pointers programmed in the web server. Obviously, these entities must be programmed to handle native data structure of the images. Once the web server receives the requests from the client browser, it invokes server objects that retrieve and process the raw images stored in the database. Outputs are sent with data coordinates to the browser to allow for client-side GUI interaction and FTP requests are sent to the user's IP address. Figure 16 provides a simple diagram of the DSS from the perspective of user-GUI interaction.

Level One algorithms in Figure 16 (NDVI, NDSVI) detect vegetation by examining red, NIR, and SWIR regions of the electromagnetic spectrum. Level Two products are based on NDVI-related algorithms that identify the fractional cover and the leaf area index of vegetation per unit of land. Biomass maps are used to estimate total dry plant weight per unit area, and time series include animation maps produced to aid managers in detecting spatial and temporal change by quick visual assessment. Forage production estimates will be derived from both Level One and Level Two indicators. Other products that can be created from Levels One to Three include environmental indicators such as forage weight, canopy cover, wildlife habitat and fuel loading.

Because most decision support systems are user-specific decision tools, one of the major goals of a rangeland DSS is to meet and exceed range managers' requirements for geospatial information. A rangeland DSS should utilize high-quality vegetation data and be designed as an aide for effective assessment of vegetation conditions. As such, it must assess large areas with varying species composition and frequency, and provide timely and valuable indicators of vegetation for user-defined areas of interest. Furthermore, requests for archived data, comments and feedback regarding improvements in GUI functionality and design, and user satisfaction surveys should be given prompt attention to improve the quality of the end product. By listening to user input, comments, and recommendations, a powerful product could be developed to aid range managers to quickly and accurately assess vast areas to determine rangeland health, forage levels, and optimal grazing plans.

5.2 FINAL REMARKS

Between 1973 and 1999, the rate of conversion of grasslands in the Sierra Vista census division has increased (Figure 14). According to satellite data, grasslands were reduced by 27.5 percent between 1973 and 1985, 24 percent between 1985 and 1992, and 29 percent between 1992 and 1999. Overall, 61 percent of the grass cover in 1973 was eradicated by 1999. During the same time period, mixed mesquite and scrub area totals increased by 57 and 21 percent, respectively. Of local and regional significance is not just the area converted but also the area modified or changed in ecological condition. Grasslands in the region are being degraded through mismanagement, with such consequences as soil erosion, changed floristic composition, and diminished productivity. In addition, population growth and water demand driven by the census division's locational advantage as a tourism and retirement spot are not only leading to conversion of land cover from grass to urban, but are also additional contributors to land degradation and fragmentation.

Of the major physical processes of global change—climatic change, alteration of biogeochemical cycles, and land use—the most influential agent of future change in grasslands will be land use. The most probable outcome in southwestern United States semi-arid ecosystems is an extensive transformation of the grasslands, either by degradation through unsustainable use or by conversion to urban use and cover. These changes will be principally, but not exclusively, driven by the requirements of the human population. Further, these land use changes will have far more extensive and degrading impacts on the grasslands than the forecast consequences of climate change.

Over the last 20 years, the rate of conversion of grasslands to croplands has slowed in the developed world (Meyer and Turner 1994). In the developing world the rates are high and increasing, but quite variable from one country to another. The rates of conversion are highest in grassland-rich nations and are small or negative in tropical nations where forests are being converted to croplands and grasslands. Unsustainable pastoral use is already a major ecological problem in many areas of the developed and developing world. Because the brunt of the human population growth is yet to come for many of the developing nations, global demand for the products of the land is likely to continue accelerating for the foreseeable future. For developed countries, environmental protection coupled with economic sustainability is the key issue. The capacity of the land—and of the ecosystems more generally—to sustain that demand will remain an issue of fundamental importance. The level of concern that current trajectories of change have elicited reflects the possibility that much land transformation in some sense constitutes land degradation, whether that is defined as a decrease in the capacity of the land to meet demands placed upon it or is given some other meaning. Environmental change in the aggregate or in particular cases, such as in greater Sierra Vista, raises serious questions about ecocentric versus anthropocentric views of nature. Therefore, the analysis of land use and land cover change in the Sierra Vista region is an attempt for better scientific knowledge than we now possess of the physical and anthropogenic extent, character, and consequences of land transformation.

One of the many useful applications of remote sensing is to inventory biophysical materials and man-made features on the surface of Earth. Some of the data are static, that is, they do not change over time. Conversely, some biophysical materials and man-made features, such as vegetation cover and built area, are dynamic, changing rapidly. It is important that such changes be inventoried accurately so that the physical and human processes at work can be more fully understood. In this study, remotely sensed data were used to transform satellite-collected reflectance data into land cover information using image-processing techniques that included supervised classification. Drivers of land use and land cover change were inferred by examining the link between changing rates of land cover information and socio-economic urban growth models, indicators of water demand, and grazing management strategies. Integration of remote sensing, GIS, and socio-economic data was vital in detecting and quantifying changes in land use and land cover, monitoring urban growth and water usage, and analyzing the impact of grazing strategies on the land surface.

Quantitative capabilities of remote sensing for accurately capturing land cover change detection were limited due largely to lack of available reference test information (DOQs and other field data). Comparison of ground truth with remote sensing-derived classifications would have allowed a meaningful quantification of land cover classification accuracy. Furthermore, the temporal nature of population and housing data prevented the analysis from detecting urban growth variations between the 10-year census collection gaps. A higher time frequency of image acquisition, preferably on an annual basis, coupled with annual tract-level census and agricultural data, would have provided a more detailed assessment and identification of drivers of land use and land cover change.

To understand the total Earth system and the effects of natural and human-induced changes on the global environment, it is critical to see the Earth as an intricately coupled system involving the interactions of land, oceans, atmosphere, ice, biota, and most importantly, man. A sound scientific understanding of the Earth system provides a foundation for sustainable development—economic development that meets the needs of the present without compromising the ability of future generations to meet their own needs. The unique capability for remote sensing of the Earth from space, coupled with in situ observations of human settlement patterns, provide the data needed on global, regional, and sometimes local scales to fuel that understanding. Land use, i.e., how the land is being used by human beings, and land cover, i.e., the biophysical materials found on the land, provide valuable insight on the complexity, fragility, and constraints of a particular ecosystem and its interaction with humans. Understanding this relationship requires the identification of interlinked factors and drivers that have a direct environmental and social impact on a given ecosystem. The drivers of change must be identified before the level of environmental and economic awareness can increase high enough to implement sustainable land use planning and ecosystem protection.

Lack of land use planning that recognizes the integrity of the ecosystems should be given the highest ranking of environmental priorities. Because land use decision-making is often fragmented, with numerous local and regional units having planning authority, there is a need for both qualitative and quantitative approaches to provide integrated and shared solutions. Knowing where and why land use conflicts currently exist and how they have impacted our environment and quality of life is the first step toward resolving these problems and preventing similar impacts in the future. To assist local, regional, and global planning, inferential insights into the driving forces of land use and land cover change is necessary to provide a portfolio of evaluative and predictive tools. To this end, there is an unprecedented need to determine mechanisms to develop and transfer technology that meets the needs of land managers, ranchers, planners, and values of society. Dissemination of temporal and spatial land cover and vegetation indication information over an open, distributed decision support system will increase the capabilities of concerned parties to make informed environmental and economic decisions.

TABLES

Year	1973	1985	1992	1999
Platform	Landsat 1	Landsat 5	Landsat 5	Landsat 7
Sensor	MSS	TM	TM	ETM +
Altitude	900 km	705 km	705 km	705 km
Swath Width	185 km	185 km	185 km	185 km
Spatial Resolution	80 m	30m (120m thermal band)	30m (120m thermal band)	30m(15mpanchromatic 60m thermal)
Radiometric Resolution	6-bit	8-bit	8-bit	8-bit
Number of Spectral Bands	4	7	7	8

Table 1. Sensor characteristics of images.

Wavelengths (in micrometers)	Sensors: MSS	TM	ETM+
Blue		0.45-0.52	0.45-0.52
Green	0.5-0.6	0.52-0.6	0.52-0.6
Red	0.6-0.7	0.63-0.69	0.63-0.69
NIR	0.7-0.8;0.8-1.1	0.76-0.9	0.76-0.9
SWIR		1.55-1.75;2.08-2.35	1.55-1.75;2.08-2.35
Thermal		10.4-12.5	10.4-12.5
Panchromatic			0.5-0.9

Table 2. Sensor wavelengths.

MSS DN values generated for haze corrections using Band 1 input Atmospheric condition: very clear; Date of Acquisition: 09/05/1973		
	Predicted	Final
1	18.110	17.000
2	9.290	9.095
3	5.234	5.443
4	2.173	0.470

Table 3. Improved-DOS haze correction values for 1973 image.

Source	Collection Years
Census of Population and Housing (U.S. Dept. of Commerce)	1970, 1980, 1990, 1997
Census of Agriculture (U.S. Dept. of Ag.)	1974, 1987, 1992, 1997
County Business Patterns (U.S. Dept. of Commerce)	1972, 1985, 1992, 1999

Table 4. Source and years of socio-economic data.

		1970	1980	1990
Population				
	Census division	20422	33939	41325
	County	61910	85686	97624
Housing Units				
	Census division	7140	12203	16830
	County	14378	32564	40238

Table 5. Population and housing data totals for county and census division, 1970-1990.

Tract	Pop. 1990	Pop. 1997	Pop.1990 Sq. Mi.	Housing Units
0014	8689	9819	68.3	1987
0015	7949	10225	4043.8	3896
0016	7263	9341	2459.0	3265
0017	7631	9686	231.4	3384
0018	4471	5778	1021.2	1661
0019	2121	2524	297.0	789
0020	4250	4949	75.6	1848

Table 6. Population and housing data totals for census tracts, 1990 and 1997.

Years	1973	1985	1992	1999
Number of employees				
Total	10901	12914	17091	21019
Agric.,forestry,fish,mine	D	226	254	195
Contract construction	661	986	858	1154
Manufacturing	1391	1375	1243	1242
Transportation/public util.	671	1125	1105	1379
Wholesale trade	318	507	504	609
Retail trade	3364	4376	5729	7277
Finance,insur., real est.	701	699	748	903
Services	1928	3148	6642	8245
Taxable payrolls (Jan-Mar.) ($1000)				
Total	16951	40503	69442	97062
Agric.,forestry,fish,mine	D	1181	1360	931
Contract construction	954	3011	2885	4840
Manufacturing	2797	6552	5857	6769
Transportation/public util.	1357	6407	7951	12193
Wholesale trade	483	1574	1886	3411
Retail trade	3436	9361	14464	20297
Finance,insur., real est.	959	2365	2880	4269
Services	1920	9272	32149	44319

"D" denotes figures withheld to avoid disclosure of operations of individual reporting units.
Services sector includes hotels, business, computer, auto, recreation, health, education, social, and management services.

Table 7. Number of employees and taxable payrolls per economic sector in Cochise county, selected years.

	1974	1987	1992	1997
All farms	721	836	831	824
Acres	2112344	2077793	1891664	1260021
Average size	2930	2485	2276	1529
Average market value($)	328857	795292	731623	545528
Percent of land area	52.80%	51.94%	47.28%	31.50%
Cropland farms	466	478	501	446
Cropland acres	149556	139086	120472	116018
Cropland pasture farms	174	203	233	185
Cropland pasture acres	149556	139086	27060	26353
Woodland pasture farms	35	27	15	20
Woodland pasture acres	35023	4597	2022	1988
Pastureland farms	598	597	607	583
Pastureland acres	1927765	1962436	1780389	1148704
Land irrigated	110485	49012	52434	63252
Land in irrigated farms	670039	486679	510020	222816
Irrigation water (acre-ft)	329528	154700	174318	107114
Sprinkler irrigation acres	14823	24813	29819	27114
Cattle and calves farms	484	544	522	517
Cattle and calves	81333	77788	65289	69950

Table 8. Agricultural patterns in Cochise county, selected years.

Total Area of Urban Land Cover, hectares

	1973	1985	1992	1999
Tract 14	1,316.88	1,447.65	1,665.99	1,689.75
Tract 15	375.48	471.87	475.29	470.70
Tract 16	174.60	465.12	578.88	582.80
Tract 17	77.76	555.39	748.35	938.79
Tract 18	60.84	642.06	724.05	747.63
Tract 19	29.16	465.57	725.67	1,258.47
Tract 20	399.24	550.98	723.33	1,412.55

Table 9. Total area, in hectares, of urban land cover, selected years.

Percent Change in Urban Land Cover

	1973-1985	1985-1992	1992-1999
Tract 14	9.93%	15.08%	1.43%
Tract 15	25.67%	0.72%	-0.97%
Tract 16	166.39%	24.46%	0.68%
Tract 17	614.24%	34.74%	25.45%
Tract 18	955.33%	12.77%	3.26%
Tract 19	1496.60%	55.87%	73.42%
Tract 20	38.01%	31.28%	95.28%

Table 10. Percent change in urban land cover by census tract, selected years.

		1985									
		Grass		Scrub		Mixed Mesquite		Barren		Urban	
Years	**Cover Classes**	%	Hectares	%	Hectares	%	Hectares	%	Hectares	%	Hectares
	Grass	50.23	11505.70	20.16	4617.18	19.74	4521.51	1.41	322.92	6.83	1564.56
	Scrub	15.13	2021.49	48.59	6490.71	29.08	3884.94	2.27	302.58	2.46	328.77
1973	Mixed Mesquite	25.15	2971.44	18.83	2225.61	36.88	4357.71	8.81	1041.30	4.60	543.15
	Barren	5.01	156.15	16.72	521.01	2.03	63.18	73.00	2275.02	2.47	76.95
	Urban	2.25	54.72	4.78	116.37	4.79	116.64	0.75	18.36	85.59	2083.32
		1992									
		Grass		Scrub		Mixed Mesquite		Barren		Urban	
		%	Hectares	%	Hectares	%	Hectares	%	Hectares	%	Hectares
	Grass	59.11	9899.19	7.66	1283.04	23.03	3856.59	7.24	1211.76	2.86	479.52
	Scrub	6.47	923.85	55.60	7943.13	30.44	4349.61	4.14	592.02	2.91	415.53
1985	Mixed Mesquite	10.21	1484.01	20.39	2963.34	62.37	9065.97	0.73	106.11	3.15	458.19
	Barren	5.83	234.45	12.51	503.01	7.99	321.21	71.90	2892.06	1.62	65.16
	Urban	1.06	48.96	3.47	159.75	2.87	131.76	2.41	110.88	90.14	4145.31
		1999									
		Grass		Scrub		Mixed Mesquite		Barren		Urban	
		%	Hectares	%	Hectares	%	Hectares	%	Hectares	%	Hectares
	Grass	54.73	6929.46	7.88	997.83	29.30	3709.17	4.24	537.12	3.76	476.55
	Scrub	2.54	331.92	62.60	8168.58	25.35	3307.32	2.45	319.68	4.44	579.33
1992	Mixed Mesquite	7.07	1334.88	27.05	5104.62	55.02	10383.20	1.20	226.89	3.27	617.58
	Barren	6.43	317.70	18.16	896.85	12.20	602.73	57.93	2860.83	4.83	238.50
	Urban	1.78	100.53	2.74	154.80	3.49	196.74	0.81	45.81	90.95	5131.08

Table 11. Land cover change transformation matrix, selected years.

	Average well depth (ft.)	Average water level (ft.)	Average pump rate (gal./min.)
Tract 14	281.88	182.69	293.91
Tract 15	277.60	257.38	483.33
Tract 16	546.06	403.53	280.21
Tract 17	236.81	145.45	345.30
Tract 18	567.02	374.14	173.71
Tract 19	226.76	125.41	28.00
Tract 20	269.71	174.66	54.28
Census Division	275.26	182.54	99.56

Table 12. Well attributes per census tract, 2000.

	Sensors (Platforms)		
	MODIS (EOS-AM)	ASTER (EOS-AM)	VEGETATION (SPOT 4)
Spectral Region (micrometers)	0.66-0.87(2 bands), 0.47-2.13(4 bands), 0.42-0.94(12 bands)	0.52-0.86(3 bands), 1.6-2.43(6 bands)	0.4-0.89(3 bands), 1.58-1.75 (1band)
Pixel Resolution	0.25 km (visible, NIR)	15 m (visible, NIR)	1.36 km (visible, NIR)
Orbital Characteristics	Polar-orbiting, sun-synchronous	Polar-orbiting, sun-synchronous	Polar-orbiting, sun-synchronous
Off-Nadir Repeat Cycle	1-2 days	5 days	48 hours
Time of Data Acquisition	10:30 AM	10:30 AM	Late-morning
Delivery time from acquisition	48 hours	48 hours	48 hours

Table 13. Satellite-based sensors along with their spectral region, pixel resolution, and orbital characteristics.

FIGURES

Figure 1. Political boundary of study area.

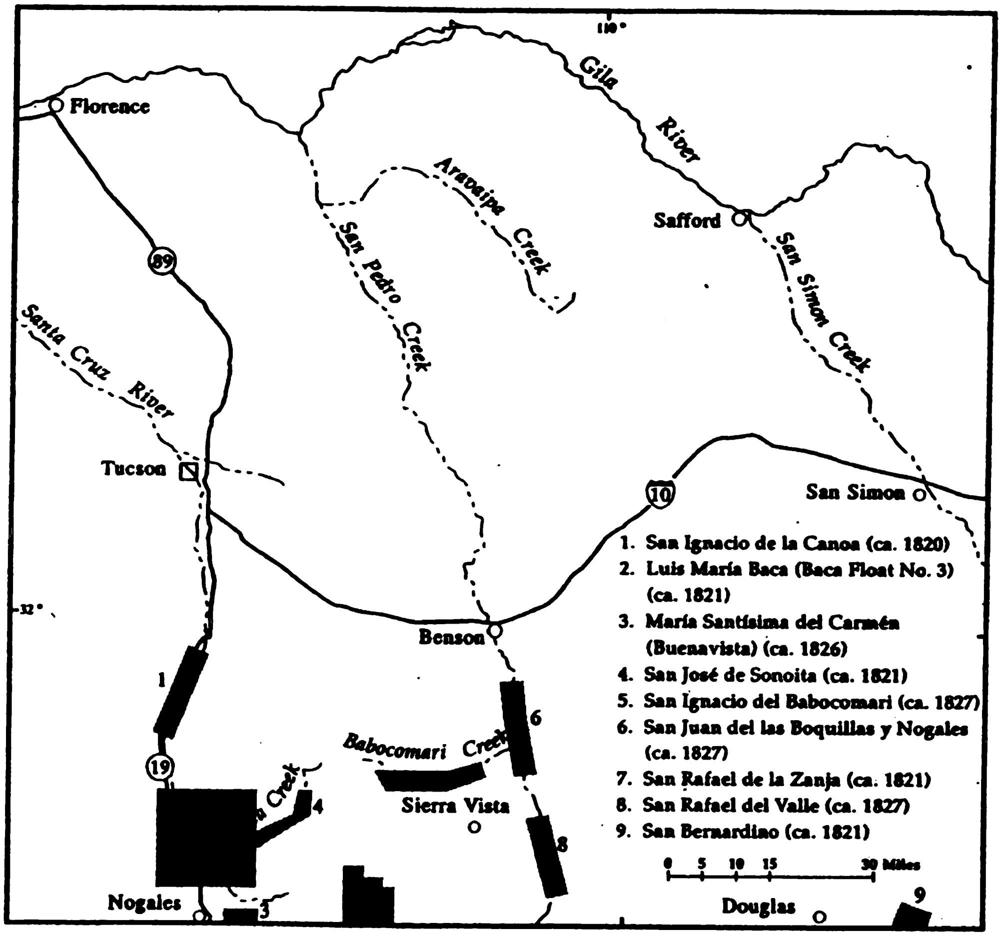

Figure 2. Authenticated Spanish and Mexican land grants in southeastern Arizona.

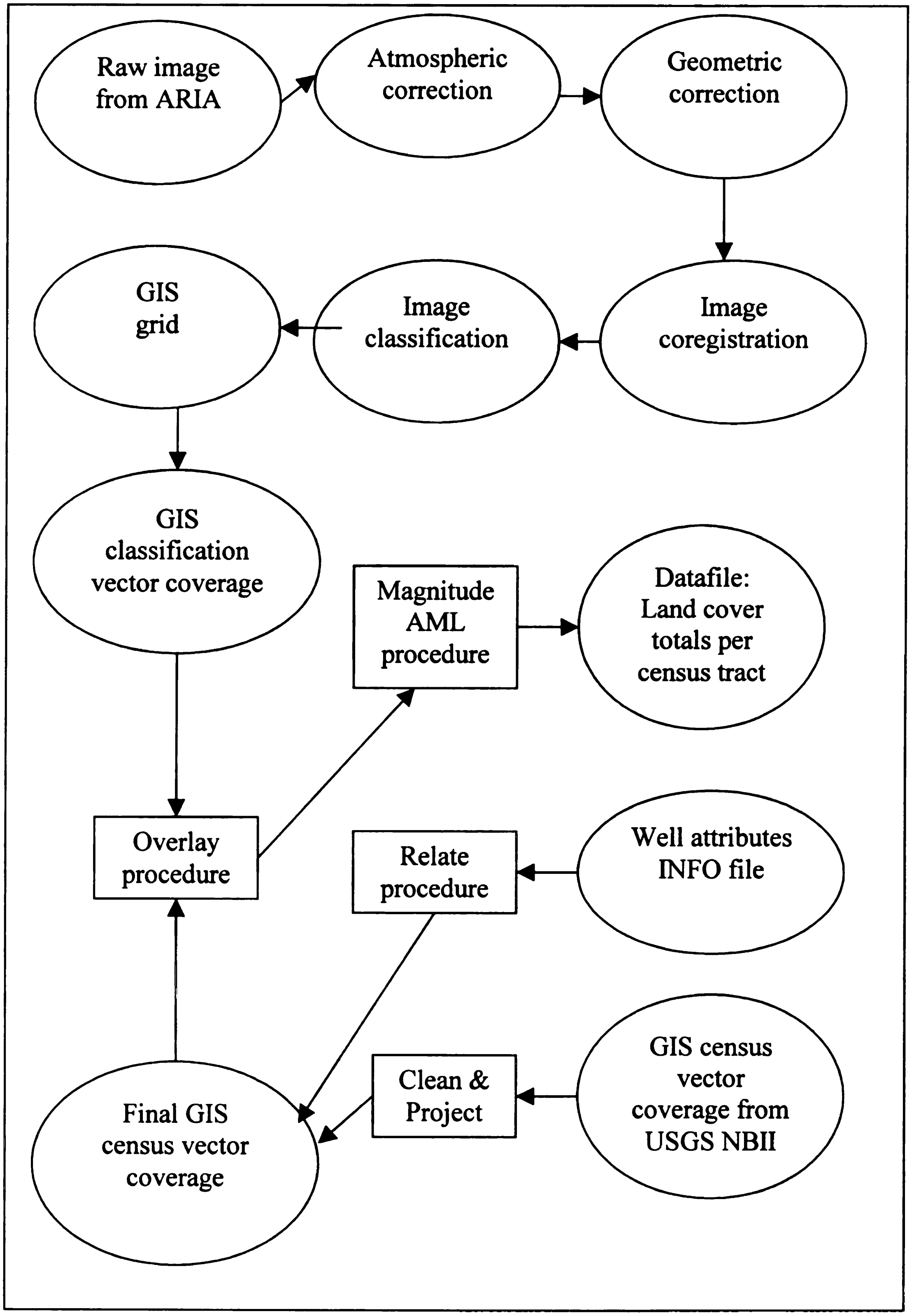

Figure 3. GIS and remote sensing processing and integration.

Landsat MSS image of Sierra Vista Census Division, 1973

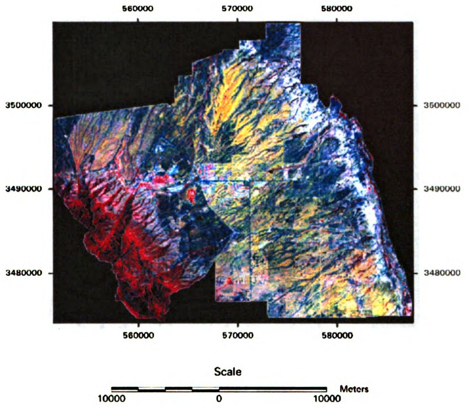

Image Metadata

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Datum:	NAD83
Spheroid:	GRS 1980
Units:	meters
Pixel Size:	80
Projection:	UTM
Zone:	12
Organization:	USGS
Department:	EROS Data Center
Address:	Sioux Falls, SD 57198

Figure 4. Landsat MSS image and metadata, 1973.

Landsat TM image of Sierra Vista Census Division, 1985

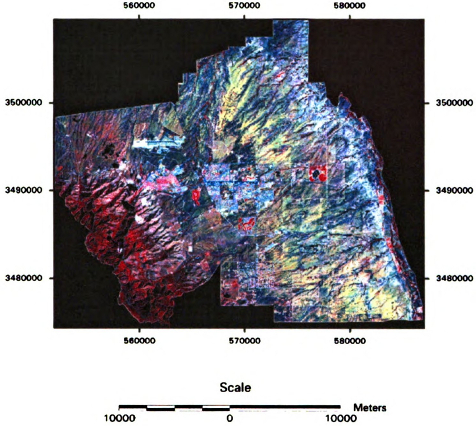

Image Metadata

Date of Acquisition:	09/27/1985
Datum:	NAD83
Spheroid:	GRS 1980
Units:	meters
Pixel Size:	30
Projection:	UTM
Zone:	12
Organization:	University of Arizona
Department:	Office of Arid Lands Studies
Address:	Tucson, AZ 85719

Figure 5. Landsat TM image and metadata, 1985.

Landsat TM image of Sierra Vista Census Division, 1992

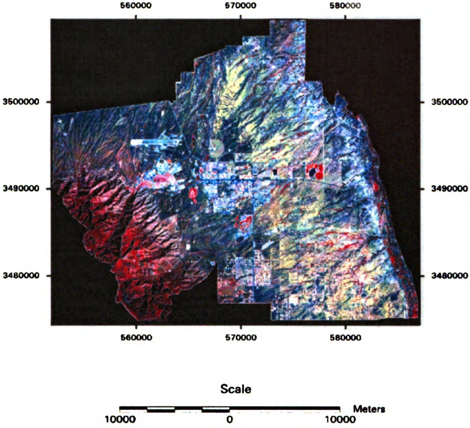

Image Metadata

Date of Acquisition:	09/30/1992
Datum:	NAD83
Spheroid:	GRS 1980
Units:	meters
Pixel Size:	30
Projection:	UTM
Zone:	12
Organization:	Space Imaging
Department:	Customer Service
Address:	Lanham, MD 20706

Figure 6. Landsat TM image and metadata, 1992.

Landsat ETM+ image of Sierra Vista Census Division, 1999

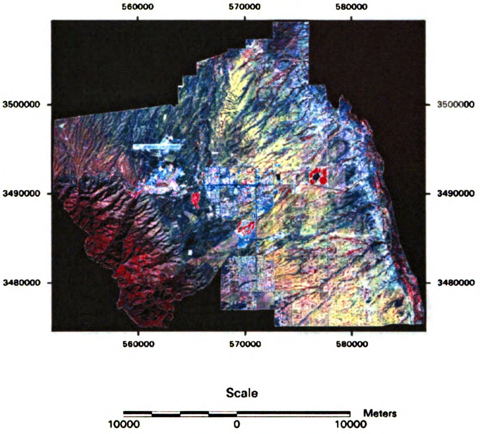

Image Metadata

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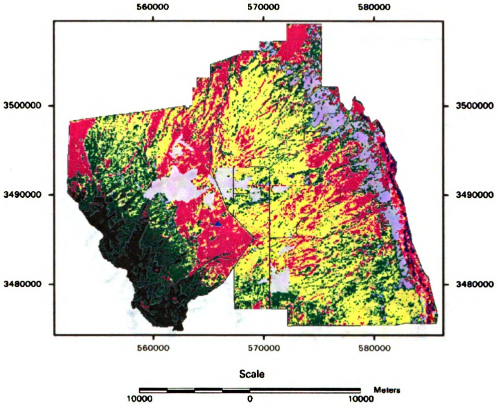
Datum:	NAD83
Spheroid:	GRS 1980
Units:	meters
Pixel Size:	30
Projection:	UTM
Zone:	12
Organization:	USGS
Department:	EROS Data Center
Address:	Sioux Falls, SD 57198

Figure 7. Landsat ETM+ image and metadata, 1999.

Sierra Vista Census Division Land Cover, 1973

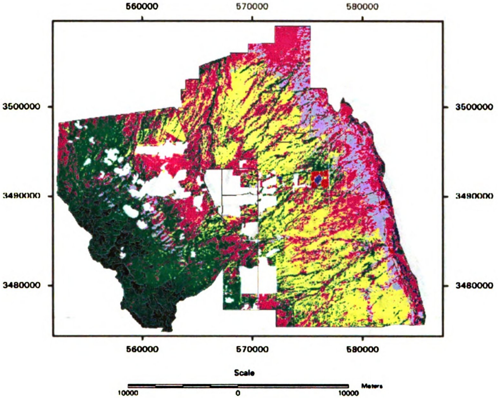


Area Totals in Square Meters

Land Cover Categories	Tract 14	Tract 15	Tract 16	Tract 17	Tract 18	Tract 19	Tract 20
Forest	37249200	0	0	0	0	0	0
Oak Woodland	19879200	0	0	0	0	0	0
Mixed Mesquite	65919600	421200	1108800	12949200	1713600	4953600	31370400
Grassland	97866000	802800	4309200	33886800	7905600	11714400	73094400
Scrubland	82357200	39600	309600	24184800	1000800	1422000	24505200
Riparian	0	0	0	1893600	0	0	2786400
Agriculture	0	0	0	295200	0	0	1713600
Barren	10969200	32400	201600	11617200	194400	144000	8020800
Water	244800	0	0	72000	0	0	0
Urban	13168800	3754800	1746000	777600	608400	291600	3992400

Figure 8. Classified land cover map and area totals per census tract, 1973.

Sierra Vista Census Division Land Cover, 1985

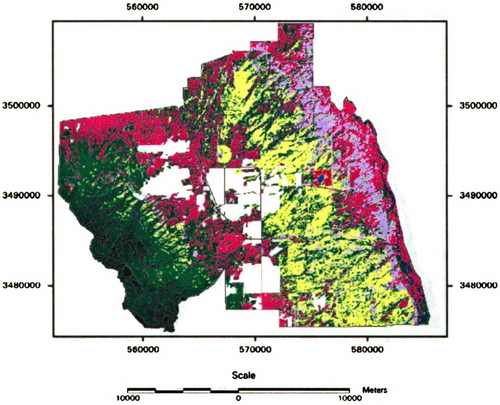


Area Totals in Square Meters

Land Cover Categories	Tract 14	Tract 15	Tract 16	Tract 17	Tract 18	Tract 19	Tract 20
Forest	30504600	0	0	0	0	0	0
Oak Woodland	15993000	0	0	0	0	0	0
Mixed Mesquite	104014800	109800	747900	13011500	1437300	8296200	18091800
Grassland	60339600	47700	898200	29068200	1718100	1258200	73130300
Desertscrub	80318700	135900	1195200	21788100	1730700	3402000	34300800
Riparian	0	0	0	534600	0	0	2471500
Agriculture	0	0	0	1521900	0	0	1518800
Barren	14840100	5400	183600	14112000	139500	176400	10267600
Water	242100	0	0	78100	0	0	0
Clouds	6982200	0	0	0	0	671400	0
Urban	14476500	4718700	4651200	5553900	6420600	4655700	5509800

Figure 9. Classified land cover map and area totals per census tract, 1985.

Sierra Vista Census Division Land Cover, 1992

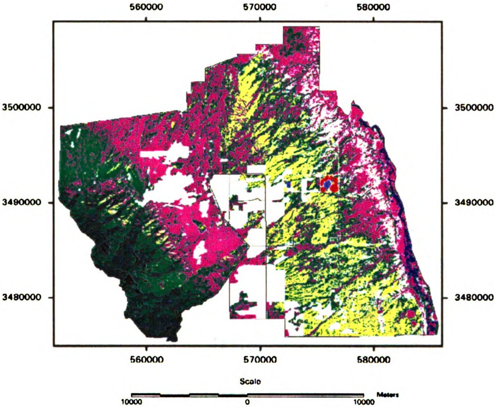


Area Totals in Square Meters

Land Cover Categories	Tract 14	Tract 15	Tract 16	Tract 17	Tract 18	Tract 19	Tract 20
Forest	33109900	0	0	0	0	0	0
Oak Woodland	12489500	0	0	0	0	0	0
Mixed Mesquite	130786500	87800	729000	13834700	1701000	6311700	35484300
Grassland	36450900	44100	598700	27784800	414000	586800	60724800
Desertscrub	80060400	132300	630100	17923600	1881900	4060900	26920000
Riparian	0	0	0	490500	0	0	1514700
Agriculture	0	0	0	1511100	0	0	0
Barren	17910000	5400	31500	16560900	208800	253800	14413500
Water	244500	0	0	79800	0	0	0
Clouds	0	0	0	0	0	0	0
Urban	16659900	4752900	5788800	7483500	7240500	7256700	7233300

Figure 10. Classified land cover map and area totals per census tract, 1992.

Sierra Vista Census Division Land Cover, 1999



Area Totals in Square Meters

Land Cover Categories	Tract 14	Tract 15	Tract 16	Tract 17	Tract 18	Tract 19	Tract 20
Forest	27546600	0	0	0	0	0	0
Oak Woodland	15999900	0	0	0	0	0	0
Mixed Mesquite	119379600	139500	861300	20366100	1489500	2175300	41081400
Grassland	21848400	12600	697900	19740600	728100	66800	46613700
Desertscrub	113167700	139500	219600	18522600	1452600	3586500	24997500
Riparian	0	0	0	1896300	0	0	4827600
Agriculture	0	0	0	1339200	0	0	0
Barren	11527200	18900	69300	14336100	299700	46800	13644900
Water	241300	0	0	79500	0	0	0
Clouds	1103400	0	0	0	0	0	0
Urban	16897500	4707000	5828000	9387900	7476300	12584700	14125500

Figure 11. Classified land cover map and area totals per census tract, 1999.

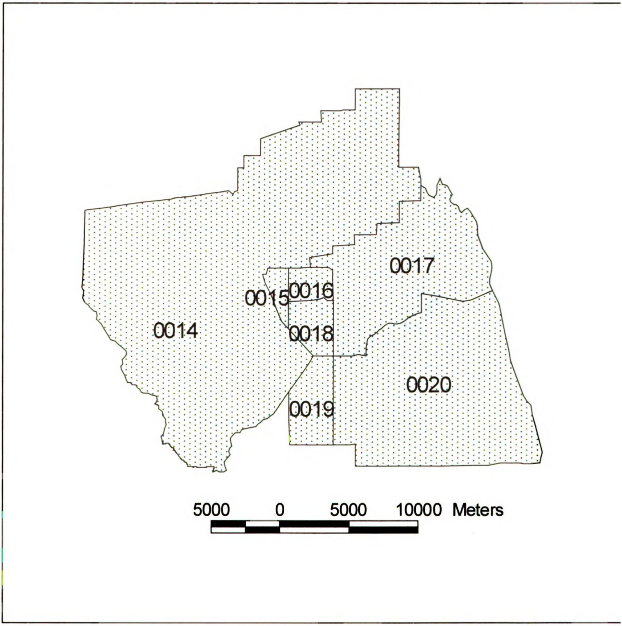


Figure 12. Sierra Vista Census Division (Tracts 14-20).

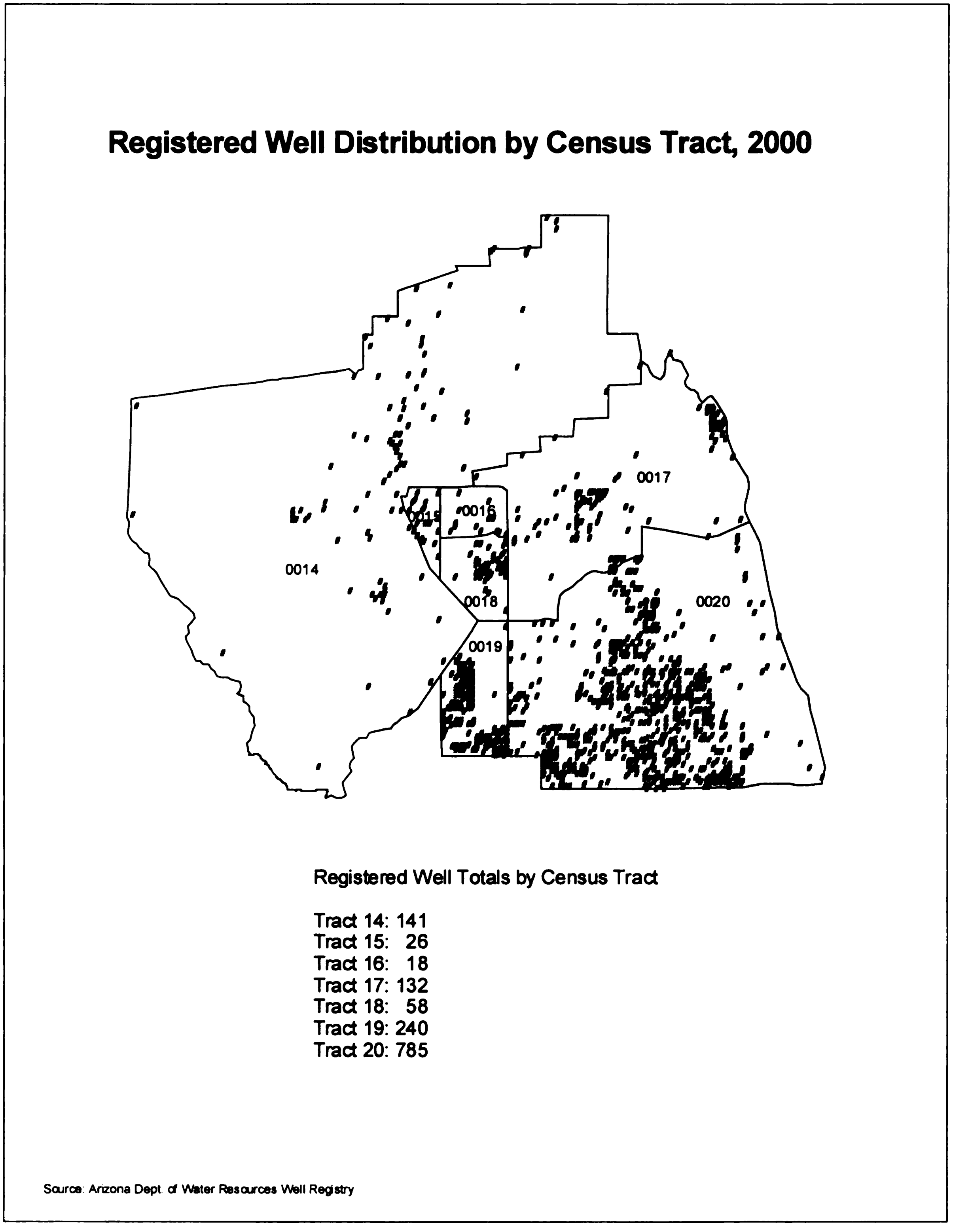


Figure 13. Registered wells in 2000 per census tract.

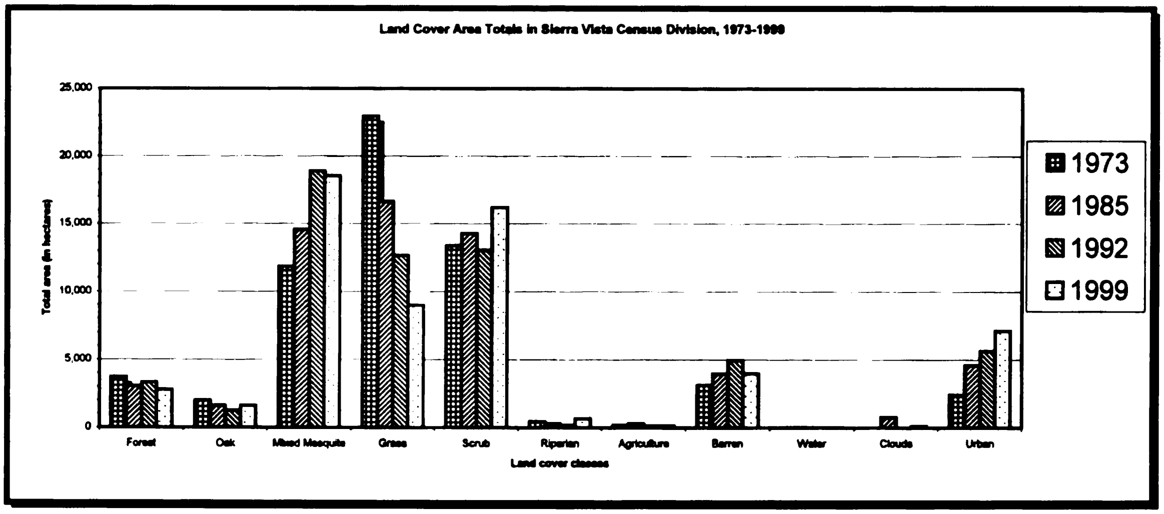


Figure 14. Land cover area totals in Sierra Vista census division, selected years.

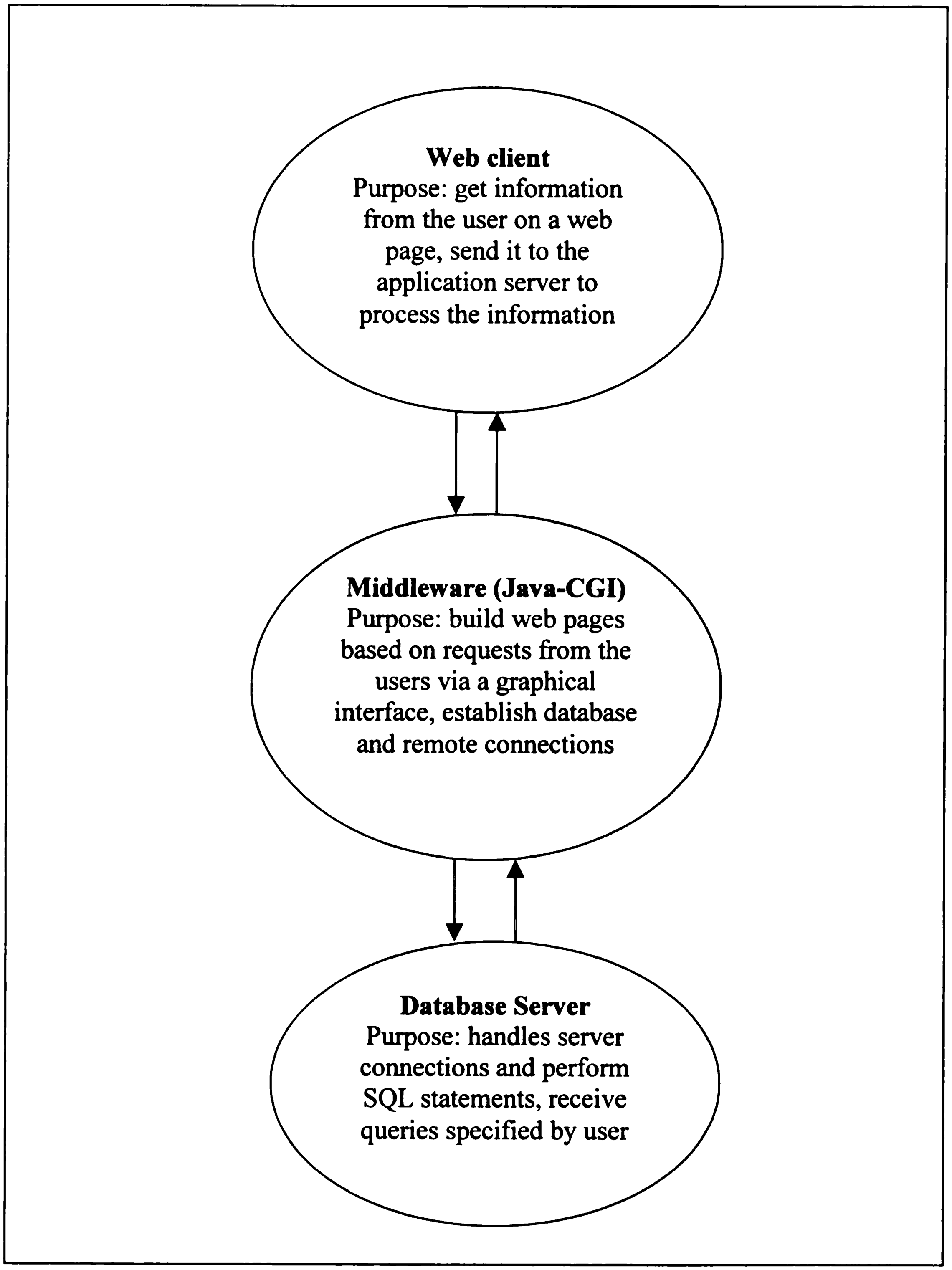


Figure 15. A simple three-tier DSS design.

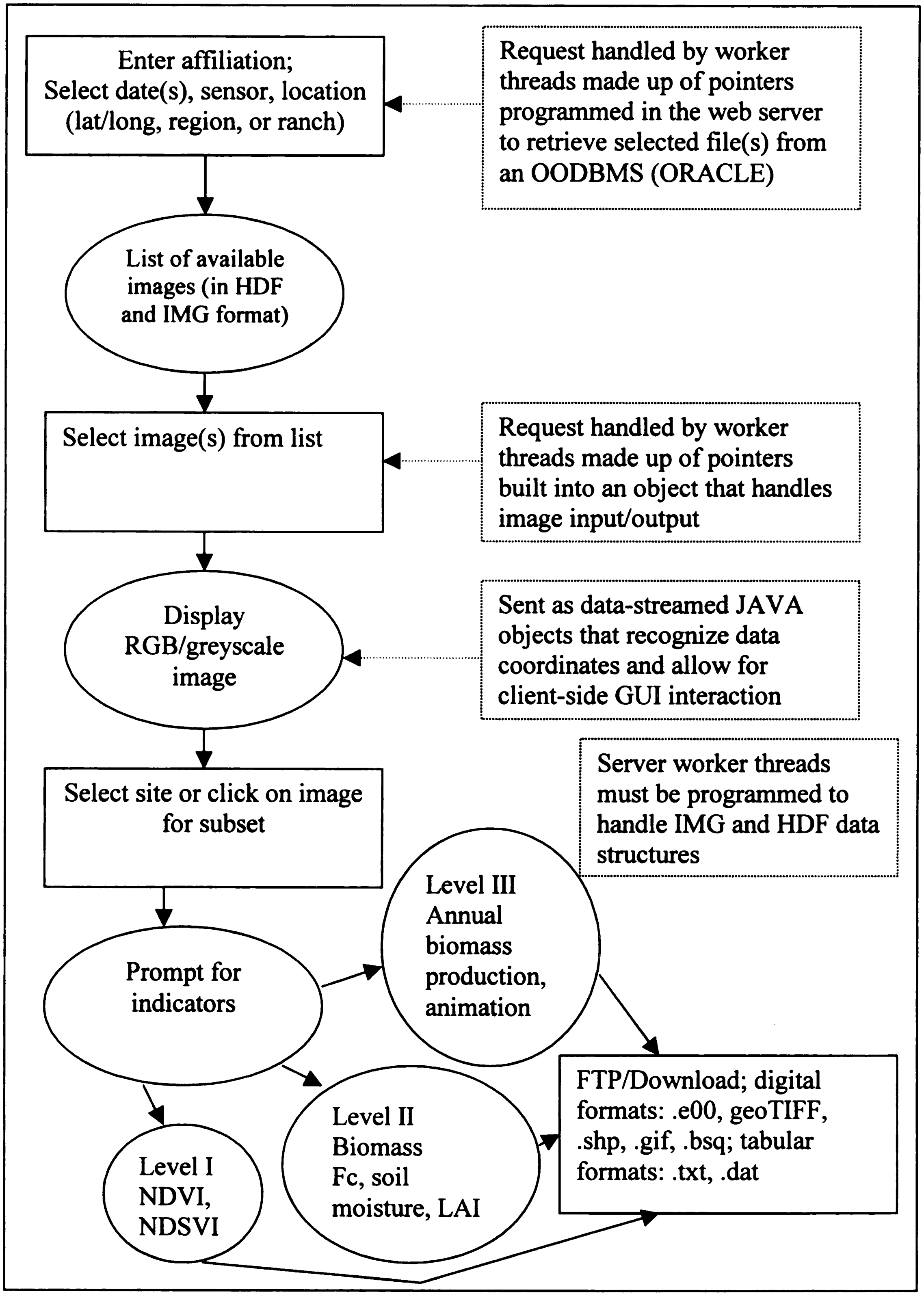


Figure 16. A simple GUI design for a rangeland DSS.

APPENDIX

```
/* AML tabulates land cover classes by census tract in Sierra Vista division
/* written by Osman Wallace
/* begin date: 09/08/00
/* end date: 09/08/00


&setvar year = [response 'enter year for tabulation (eg, 73): ']
intersect sv_ctracts3 sv%year%class classtract%year% poly .1
&setvar parc = classtract%year%.PAT
&setvar infi = MAGNITUDE
&call freq1
&data arc info
 arc
 select %infi%
&call zero_out
 select JUNK

 RELATE %infi% BY SV_CTRACTS3-ID



 RES GRID-CODE = 1
 CALC $1FOREST = AREA
 as
 RES GRID-CODE = 2
 CALC $1OAKWOODLAND = AREA
 as
 RES GRID-CODE = 3
 CALC $1MESQUITE = AREA
 as
 RES GRID-CODE = 4
 CALC $1GRASSLAND = AREA
 as
 RES GRID-CODE = 5
 CALC $1DESERTSCRUB = AREA
 as
 RES GRID-CODE = 6
 CALC $1RIPARIAN = AREA
 as
 RES GRID-CODE = 7
 CALC $1AGRICULTURE = AREA
 as
```

```
 RES GRID-CODE = 8
 CALC $1BARREN = AREA
 as
 RES GRID-CODE = 9
 CALC $1WATER = AREA
 as
 RES GRID-CODE = 10
 CALC $1URBAN = AREA
 as

select %infi%
 calc CHECK = 0
 calc DIFF = 0
 calc CHECK = FOREST + OAKWOODLAND + MESQUITE + GRASSLAND +
DESERTSCRUB + RIPARIAN + AGRICULTURE + BARREN ~
        + WATER + URBAN
 calc DIFF = AREA - CHECK
  select JUNK
  erase JUNK
  Y
 select %infi%
 calc $PRINTER-SIZE = 200
 &setvar ws = [show workspace]
 output %ws%\%infi%%year%RPT.dat init
 print 'Tract        Area        Forest        Oak        Mesquite        Grass
Scrub ~
     Riparian    Agriculture     Barren            Water        Urban        Check
   Diff'
 print
*W4,TRACT,*W14,AREA,*W14,FOREST,*W14,OAKWOODLAND,*W14,ME
SQUITE,*W14,GRASSLAND,*W14,DESERTSCRUB,*W14, ~
  RIPARIAN,*W14,AGRICULTURE,*W14,BARREN,*W14,WATER,*W14,UR
BAN,*W14,CHECK,*W14, DIFF
 Q STOP
&end
&return
/*****************************************************************
&routine freq1
/*****************************************************************
  frequency %parc% junk
          sv_ctracts3-id
          grid-code
          end
          area
          end
  &return
```

```
/*********************************************************************
&routine zero_out
/*********************************************************************
  CALC FOREST = 0
  CALC OAKWOODLAND = 0
  CALC MESQUITE = 0
  CALC GRASSLAND = 0
  CALC DESERTSCRUB = 0
  CALC RIPARIAN = 0
  CALC AGRICULTURE = 0
  CALC BARREN = 0
  CALC WATER = 0
  CALC URBAN = 0
  &return
```

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