Sustainability, arid grasslands and grazing: New applications for technology

Arian Pregenzer[1], Robert Parmenter[2], Howard Passell[1,2], Thomas Budge[3], John Vande Castle[4]

[1]Cooperative Monitoring Center, Sandia National Laboratories, P.O. Box 5800, M.S. 1373, Albuquerque, New Mexico, U.S.A., 87185-1373; [2]Department of Biology, University of New Mexico, Alb., N.M., U.S.A., 87131-1091; [3]Earth Data Analysis Center, UNM, Alb., N.M., U.S.A., 87131-6031; [4]Long Term Ecological Research Network Office, 801 University Blvd SE, Suite 104, Alb., N.M., U.S.A., 87106

Abstract

The study of ecology is taking on increasing global importance as the value of well-functioning ecosystems to human well-being becomes better understood. However, the use of technological systems for the study of ecology lags behind the use of technologies in the study of other disciplines important to human well-being, such as medicine, chemistry and physics. We outline four different kinds of large-scale data needs required by land managers for the development of sustainable land use strategies, and which can be obtained with current or future technological systems. We then outline a hypothetical resource management scenario in which data on all those needs are collected using remote and in situ technologies, transmitted to a central location, analyzed, and then disseminated for regional use in maintaining sustainable grazing systems. We conclude by highlighting various data-collection systems and data-sharing networks already in operation.

Introduction

As biodiversity, ecosystem function, and ecosystem services become more and more closely linked with human well-being at all scales, the study of ecology takes on increasing social, economic and political importance. However, when compared with other disciplines long linked with human well-being, such as medicine, chemistry and physics, the technical tools and instruments of the ecologist have generally lagged behind those of the others. This disparity is beginning to be overcome with the increasing use of biotelemetric techniques, satellite and airborne imagery, geographic information systems (GIS) and both regional and global data networks. However, we believe that the value and efficiency of ecosystem

DISCLAIMER

studies can still advance significantly with more wide-spread use of existing technologies, or with the adaptation of technologies currently used in other disciplines to ecosystem studies.

Arid land grazing systems play critical roles in supporting human social systems and economies in regions all over the world, and can be expected to play increasingly critical roles as human populations increase. The economic and political implications of grazing in arid lands, the controversy over its impacts, and the pressing need for resolving the controversies and for creating sustainable grazing systems make arid land grazing systems a prime focal point for the application of new technologies (Milchunas and Lauenroth 1993, Fleischner 1994, Bich et al. 1995, Nyakolartey and Baxter 1995, Memmott et al. 1998, Hiernaux et al. 1999, Belsky et al. 1999, Jones and Longland 1999, Rohner and Ward 1999).

We frame the discussion with the following questions: 1) What kinds of data about arid land grazing systems, biodiversity and sustainability are currently needed by researchers? 2) How are these data collection and analysis needs met currently? 3) How can the meeting of these needs be improved with technological innovations?

We will consider data needs for four sets of ecological variables, including grazing animals and wildlife, vegetation, soils, and climate; then we will present a scenario which shows how data on all these variables can be collected, analyzed and integrated into management strategies using currently or soon-to-be available technologies. The ideas expressed here about the application of technologies to arid land grazing systems transfer easily to other ecosystems and other research and management issues.

Data on grazing animals and wildlife

The maintenance of biodiversity, ecosystem function and sustainable grazing systems in arid as well as mesic environments requires data on: 1) routes and patterns of movement used by grazing animals, and their effect on vegetation, soils and water; 2) modification of wildlife species movements and behavior as a result of interaction with grazing animals; 3) effects of grazing on insect populations and behavior dynamics; 4) the effects of grazing systems on wildlife populations in neighboring regions.

The current standard for addressing these questions is through field observations. Though field studies ultimately provide the foundation for all ecosystem studies by linking theory with actual ecosystem function, they are constrained by limitations on personnel, time and the spatial scale of study. The rapidly advancing technologies of wildlife biotelemetry address these limitations by allowing the collection of data over great spatial scales on a wide range of animal taxa, which allows greater insight into animal habitat preferences, short- and long-term movements, activities and migratory routes (USGS 1997).

These technologies include sensors attached to animals that record and store information about the animal's location, movement and physiology (heart rate, body temperature, etc.) for later retrieval by researchers; sensors and transmitters that send those data to ground-based receivers; and sensors and transmitters that send the data to a satellite, from which they can be transmitted anywhere in the world. The development and miniaturization of the global positioning system (GPS) devices has revolutionized researchers' abilities to pinpoint animal locations via satellite technology (USGS 1997).

The range of animal taxa for which these various telemetric technologies have been used is broad, and includes amphibians, reptiles, rodents, passerine birds, raptors, bats, waterfowl, wolves, mountain lions and other large predators, various ungulates, fish, whales, and other marine mammals (Lewis 1994, Marzluff et al. 1994, King et al. 1995, Parker et al. 1996, Reading and Davies 1996, Sone and Kohno 1996, Shivik et al 1996, USGS 1997, Waller and Mace 1997, Adams et al. 1998, Lariviere and Messier 1998).

Other telemetric innovations include harmonic radar, which can record the positions over multiple time-steps of flying insects mounted with metallic tags that weigh less than 1 mg. This has special importance in monitoring the behavior of pollinators or outbreaks of pest species (Riley et al. 1996, Riley et al. 1998).

Data on Vegetation

Maintaining sustainable arid land grazing systems includes vegetation data on: 1) the rates of increase or decrease in vegetation biomass and/or net primary productivity due to grazing; 2) the changes in species composition due to grazing; 3) the affect of changes in species composition on grazing species.

The standard methods for obtaining such data are through field methods that include censusing of line transects, and similar techniques. However, optical and multi-spectral remote sensing from aircraft and satellites is being used increasingly to obtain spatially large-scale data on soils, biomass, vegetation patchiness, distribution of microbiotic crusts, leaf area index, vegetation indices, changes in species composition and net primary production (Anderson 1996, Reed et al. 1996, Karnieli 1997, Todd et al.

1998, Zhou 1998). Remote sensing is also being used to collect data on water quality and availability, mineral composition of soils and soil erosion patterns (Rao et al. 1996, Vande Castle 1998).

Remote sensing can be divided into the two broad categories of passive and active sensing. Passive sensing refers to the collection of optical and multi-spectral data from the reflection of the sun's electromagnetic radiation from an object; active sensing refers to technologies which project radiation at the object of interest and then receive the reflected radiation back. Synthetic aperture radar (SAR) is a common example of active sensing. Both types can be employed from aircraft or satellites, and both -- along with image-processing software applications that manage the data -- have increasingly important uses in ecological studies (Anderson 1996, Vande Castle 1998).

Three kinds of sensor resolution are important in matching a particular remote sensing technology to a particular study: spatial, spectral and temporal (Anderson 1996, Vande Castle 1998). Spatial resolution refers to the smallest-sized object that can be detected by a sensor. A sensor with a 28.5 m resolution, such as that available from the Landsat Thematic Mapper (TM) sensor for example, will average the spectral reflections for each 28.5 m^2 pixel in its view. This resolution is sufficient for providing data on coarse-scaled vegetation differences (grassland to shrubland to forest), and on geographic and topographic features. A TM image covers an area of 170 km x 185 km at a 1999 price of US$450 per scene. Other more expensive data already achieve spatial resolutions as high as 1m^2.

The second kind of resolution important to remote sensing is spectral resolution, which refers both to the number of spectral bands that a sensor can detect, as well as the total range of spectral wavelengths that the sensor can detect. Sensors with higher spectral resolution (including more bands and a larger range of wavelengths) can provide data that better discriminate between shades, colors and reflected heat, which can often be associated with different kinds of soils, different species, or different quantities of foliage. Landsat 7 TM images, for instance, include data on seven bands spanning wavelengths of the visible and infrared spectra. Future hyperspectral sensing technologies will cover up to 224 bands, greatly increasing data collection sensitivity.

The third kind of resolution is temporal resolution, which refers to revisit time, or the time between successive images. The revisit time for Landsat 7, for instance, is 16 days, but some satellites planned for launch in the near future will be able to revisit a site daily.

Satellite-borne radar sensors are becoming increasingly important in ecological monitoring. Radar systems project their own electromagnetic radiation at an object and are therefore not dependent on natural spectral reflectance, allowing them to operate at night. Because radar penetrates clouds and rain, it can also be used in inclement weather (Forster 1996).

A constant challenge facing all these remote sensing technologies is the development of efficient and reliable methods for "ground-truthing," or the correlation between spectral information in the data with actual species or assemblages on the ground. Ground-truthing is currently time-, energy- and labor-intensive, and seriously retards the speed at which the huge data sets provided by remote sensing can be processed.

Data on Soils

Maintenance of sustainable grazing systems include soil data on: 1) soil structures, textures and chemistries; 2) the relationships between soil temperatures, soil moisture and evapotranspiration, and the distribution of soil patches across landscapes; 3) the effect of grazing intensity on soil characteristics and soil microbial communities; 4) the effect of grazing on erosion rates.

Characterization of soil organic matter, soil texture, structure and chemistry (especially salinity and nutrient availability) currently involves laboratory analysis or laborious (and sometimes inaccurate) field techniques. In addition, laboratory analysis entails sample collection, storage and transportation, all of which can introduce errors and remove site-specific contextual information from the analysis process.

Optical remote sensing is currently used extensively to measure gully-formation and other effects of erosion, surface albedo, barren areas, water-logged soils, nutrient availability and water holding capacity . Synthetic aperture radar is currently used for mapping soil moisture and other soil and sub-surface geological and soil characteristics (Forster 1996), and burgeoning GIS technologies allow the organization and analysis of multiple layers of data for any given region (Anderson 1996).

In addition, new micro-capabilities for chemical detection and analysis developed for applications such as in-situ chemical and biological weapons detection, could be adapted for assessing nutrient availability, soil organic matter, soil chemistry, and other ecological data needs. Such in-situ soil characterization could also be an important first step in developing signatures for remote sensing. Some researchers have even suggested the use of mobile robotic technology for data collection, just as NASA's Mars Rover roamed the surface of Mars collecting, analyzing and transmitting geological data (B. Milne, personal communication).

Data on Climate

Maintaining sustainable grazing systems requires data on: 1) the amount, frequency and spatial scale of precipitation events; 2) the correlation between net primary production and precipitation in local and regional landscapes; 3) the use of indicators like lightning strikes to estimate precipitation patterns; 4) the correlation between atmospheric climate data with precipitation patterns and evapotranspiration.

Methods for collecting data on the questions above are already widely automated by meteorological stations with radio transmitters to local receivers or with satellite uplinks. Stations commonly monitor precipitation amounts, maximum, minimum and mean temperatures, relative humidity, vapor pressure, barometric pressure, wind speeds and directions and solar radiation, and some are outfitted to monitor gamma radiation as well.

NEXRAD ("NEXt Generation RADar"), is a nationwide U.S. National Weather Service system of ground-based radar stations that can track the movements, speed and intensity of precipitation events. One of the great advances already made in climate studies is the wide-availability of data at a wide range of spatial and temporal scales through the World Wide Web. The availability of these data through these various networks (further mentioned below) should be a model for the distribution of other kinds of ecological data as well. The efficient integration of all these data – on wildlife, vegetation, soils and climate -- into timely resource management is the pressing challenge.

Electronic ecological networks

The technologies described above comprise an extensive "tool kit" of both conventional and innovative technologies for measuring and evaluating physical and biological properties of arid ecosystems. How might these existing and future widely-available technologies be incorporated into an integrated ecosystem monitoring scheme to provide real-time information for management decisions?

The following example presents a hypothetical scenario for an ecosystem management scheme that utilizes an array of technological devices and approaches to provide real-time information for management decision-making. For the purpose of this exercise, the primary goal of the hypothetical managers – who could be ranchers, government officials, or scientists -- will be to conduct an efficient, cost-effective, sustainable livestock grazing operation on a large tract of arid and semi-arid land.

As a template for our hypothetical scenario, we will use the Sevilleta National Wildlife Refuge in central New Mexico, U.S.A., site of the Sevilleta Long-Term Ecological Research Program (LTER). The site is 100,000 ha in size, and encompasses many biome types found in the American Southwest -- Chihuahuan Desert shrublands, Great Plains grasslands, Colorado Plateau shrub-steppe, juniper savannas, and pinyon-juniper woodlands.

Prior to the implementation of a management plan for a region such as the Sevilleta, a series of baseline data sets must be acquired, including a series of GIS coverages for various factors, such as topography, drainages, soils, geologic formations, vegetation, the locations of political divisions and property boundaries, dwellings, transportation routes, agricultural fields, and other anthropogenic features. Examples of such GIS coverages made for the Sevilleta are shown in Figure 1. These maps represent GIS coverages of topography (Fig. 1a), vegetation (Fig. 1b) and an overall Landsat TM image (Fig. 1d).

A second required series of baseline data sets include climatic records, such as precipitation, temperature, humidity, solar radiation, wind speed and direction, and soil temperature and moisture at various depths. At the Sevilleta, meteorological data is collected at five stations spread across the reserve.

In addition to the collection of these baseline data sets, the managers must calculate estimates of forage production necessary for the nutritional maintenance and productivity of the livestock herd. From these data, the managers could estimate the maximum stocking rates within each vegetation association included in the GIS (Fig. 1c), assuming a particular level of net primary productivity (NPP). Baseline data sets will help managers understand conditions that provide higher or lower levels of NPP.

Estimates of NPP can be derived from correlations with various ecosystem parameters, including plant cover or density estimates derived from aerial photographs or ground-sampled plots. At larger scales, NPP estimates can be inferred through satellite imagery, using Normalized Difference Vegetation Index (NDVI) values or other reflectance indices (Todd et al. 1998, Vande Castle 1998). Some level of initial ground-truth classification must be undertaken to develop these correlations for the sites, but once validated, the requirement for ground-truthing is reduced.

Quantities of NPP will vary through space and time -- spatially, as one moves across soil types and elevations, and temporally, through seasonal or annual shifts of precipitation and temperature. The manager's task will be to observe and quantify these NPP changes – with the help of data inputs -- and adjust the grazing regimes to optimally utilize the available forage. This kind of adaptive management requires (1) a constantly updated database of the spatial distribution of NPP values, and (2) a detailed knowledge of the location of the livestock on the landscape. Temporal and spatial changes in NPP can be evaluated with frequent updates from satellite images. The NPP values typically respond to periods and locations of precipitation, which can be identified from an array of meteorological stations.

In the southwestern U.S., summer precipitation often occurs during intense, highly-localized, short-duration thunderstorms, that move across the landscape with a high degree of unpredictability. New technologies, such as lightning locator systems and NEXRAD radar, have been adapted to measure the spatial and temporal distributions of these summer storms. Correlations between the number and locations of lightning strikes and total precipitation amounts per strike can be established, allowing estimates of patchily distributed precipitation over large areas; for example, Sevilleta LTER researchers have determined that 36,190 m^3 of water falls within a 3 km radius of every cloud-to-ground lightning strike, or approximately 1.3 mm of precipitation (Gosz et al. 1995). This information can then be used to estimate the amounts and locations of thunderstorm rainfall events as storms move across the landscape; and by pooling data from longer time periods, site-specific seasonal, annual, or multi-year totals can be calculated. Similarly, NEXRAD radar images can indicate the spatial distribution of storms, although studies aimed at predicting precipitation amounts are still in the development stage.

Data on the location and amounts of precipitation can be integrated with remotely-sensed satellite data to determine the spatio-temporal patterns of NPP (Oesterheld et al. 1998). The NPP values can be estimated from NDVI reflectance indices using Landsat Thematic Mapper data. Temporal dynamics of NDVI values typically show increases following periods of moisture, such as the onset of summer monsoons, or decreases resulting from drought or winter senescence of vegetation. By analyzing areas of precipitation and NDVI on a daily or weekly time-step, managers can determine which sections of the land have experienced increases in NPP, and thus may support a higher level of herbivore activity. With such knowledge, managers can make decisions on livestock movements and stocking rates to optimize productivity and other considerations, such as soil conservation and pasture rotations.

This latter task of managing animal densities and movements across the landscape requires detailed knowledge of the locations, at any point in time, of the animals of interest (whether they are livestock or important wildlife species). Telemetric techniques, as described in sections above, can be adapted to such domesticated animals as cattle, sheep, goats, horses, oxen, camels or llamas.

Thus far, in this hypothetical scenario, the managers have used technological applications to establish baseline GIS databases, track the locations and amounts of precipitation on the landscape, determine levels of plant production, and monitor the movements of their livestock herds. From these databases, the managers can manipulate their livestock locations and stocking rates to optimize productivity. However, the managers are often confronted with other issues and criteria in their management strategies that also demand accurate information for management decisions.

For example, grazing by livestock typically is "uneven" on the landscape, and creates areas of severe disturbance (e.g., around waterholes or streamcourses) that may lead to erosional loss of topsoil and a decline in watershed quality; also habitat disturbances in critical areas may have detrimental effects on other native plant and animal species, causing local or regional reductions or shifts in biodiversity. Livestock activities also may interfere with activities of native game animals, particularly during critical breeding periods, or become targets themselves of native predators. Application of modern technologies can assist with the management of these problems as well.

In the case of "overgrazing" in local patches, remotely-sensed images can be used to estimate plant cover at pixel sizes now approaching 1 m^2. Estimates of leaf area index (LAI) also may be derived from imagery using mathematical modeling techniques. Soil characteristics, including mineral compositions and moisture levels, can be derived from spectral reflectance signatures and soil-penetrating synthetic-aperture radar images. Surface-reflecting radar, mounted in either aircraft or satellites, can be used to produce updates to topographic databases such as digital elevation models (Forster 1996), and identify surface erosion patterns, stream channel changes, or arroyo formations

(Vande Castle 1998). As areas with low vegetation cover values or high erosional rates are identified, management decisions can be made to move livestock or restrict access to the disturbed areas.

Management strategies for preserving biodiversity also can be enhanced with new technological applications. Areas of critical habitats, such as springs or marshes, can be identified, quantified, and monitored remotely as to size, productivity, water quantity and water quality. If changes through time are noted, ground teams of managers can be dispatched for on-site inspection of the problems. In the case of protected/regulated wildlife or predators, the GPS/radio-telemetry instruments can be used to measure the movements and activities of individual animals or family groups, and permit assessments of management practices and interactions with livestock (which can be monitored simultaneously as described above).

Pest species of grasshoppers and locusts can increase markedly in grazed ecosystems, presenting potential pest invasion problems for nearby agricultural regions (Gangwere et al. 1997). Similarly, grazing activities have been associated with changes in the densities of rodent and rabbit species (Bich et al. 1995, Nyakolartey and Baxter 1995, Jones and Longland 1999), which carry diseases (plague, hantavirus, Tularemia, rabies) transmissible to humans and livestock (Grenfell and Dobson 1995). As conditions on the landscape become more favorable to populations of these pests and disease vectors, satellite imagery would be able to detect the changing variables in vegetation and moisture, and provide data for predictive models of insect or disease outbreaks. Harmonic radar technology can be used to track swarms of locusts across the landscape (Riley 1998), and satellite data have been used to construct GIS models of patterns of hantavirus infection in humans (G. Glass, Johns Hopkins University, unpublished data, 1999), and grasshopper outbreaks in rangelands (Burt et al. 1995).

Currently operating networks

Various data sharing and communications networks that could contribute to a land use management scenarios like the one above are already in place and operating. The Argos Data Collection and Location Satellite System is operated under a joint partnership agreement with the U.S. National Oceanographic and Atmospheric Administration (NOAA) and the French Centre National d'Etudes Spatiales (CNES) to provide worldwide data collection on radio-tagged animals. The United States Geological Survey (USGS) Geostationary Operational Environmental Satellite (GOES) system downloads to the World Wide Web hydrology and water quality data in near real time from stations all over the United States. The U.N. Environmental Programme's Global Environment Monitoring System (GEMS) assembles global water quality data, and the Global Climate Observing System (GCOS), sponsored by the World Meteorological Organization (WMO), two U.N. organizations and the International Council for Science (ICSU) assembles data on long-term precipitation, atmospheric temperature, sea surface temperature, ENSO data and snow and ice data. Also, the World Data Center for Greenhouse Gases posts past and current concentrations of individual greenhouse gases from hundreds of locations globally at its web site.

A system that integrates all the technologies above – and others – is the Gap Analysis Program (GAP). GAP is a nation-wide program administered by the Biological Resources Division of the USGS. GAP uses GIS data on abundance and distribution of vertebrate species overlaid on data for land cover types to aid in land use and endangered species management decisions. Lastly, at least one commercial company, Agri ImaGIS, supports a website from which satellite imagery is advertised for sale to agriculturalists for large-scale analysis of farmland topography, yield variability and soil analysis. The company offers a free software package that enables analysis of the imagery, as well.

Global Terrestrial Observing System

A pioneering international effort to create a global "network of networks" for the applications of technology to large-scale land use questions can be found in the Global Terrestrial Observing System (GTOS). GTOS was established in 1996 by five organizations, including three from the U.N., the World Meteorological Organization (WMO), and the International Council of Scientific Unions (ICSU), and it includes participation from five international space agencies. GTOS is intended to provide data for detecting, quantifying, locating, and giving early warning of changes in the capacity of the Earth to sustain development and improvements in human welfare.

GTOS focuses on changes in land quality, freshwater resources availability, pollution and toxicity, loss of biodiversity, and climate change. The U.S. Long-Term Ecological Research network (LTER), one of the participating scientific networks, has established an affiliated international network (ILTER) that can help scientific organizations around the world establish ground-based ecological monitoring systems that can be coordinated with remote sensing systems accessed through GTOS.

In 1998, a new GTOS project known as GT-Net began to assess global primary land productivity. Under this project, participating countries will receive an ongoing stream of satellite data for their countries in exchange for ground-truthing performed by researchers in those countries on a small amount of that data. The ground-truthing information provided by the countries – on as little as one 3 km x 3 km site -- will be used to verify models of primary productivity metrics such as land cover, net primary productivity and leaf area indices (LAI). This project will also provide countries with an opportunity for training in data analysis and experiment design. As of this writing 11 nations have committed to 23 GT-Net sites, and more partnerships are planned.

Conclusions

Any attempt to better understand ecosystem function, the delivery of ecosystem services and the impacts made upon ecosystems by humans must be able to accurately identify and measure, over time, the most influential biotic and abiotic processes in the system. The ability to collect and analyze data on large spatial and temporal scales on these subjects becomes more crucial as human population and consumption increases, and as human needs for the products of ecosystem services increase. Historically, ecosystem studies have been labor- and time-intensive, such that a large amount of time and energy invested by researchers yielded a relatively small amount of useful data. We believe that new applications of the technological advances of the last half-century, used in conjunction with conventional techniques, can significantly increase the quality and quantity of data that can be collected and analyzed in ecosystem studies.

With increasing emphasis on the use of these technologies in ecological science, students will need systematic educational programs and training on the science and applications of the technologies. In addition, funding organizations should develop plans for integrating these technologies, and others, into ecological research. These plans would guide increased budgets for technological research and development and for incorporating technology into ongoing efforts. The high cost of landscape-scale data collection and regional networking will present one of the greatest challenges for integrating those technologies into day-to-day management routines; any research that will show ways to streamline systems and reduce those costs will be extremely valuable.

Acknowledgments

This project was completed with funding from the U.S. Department of Energy and the Cooperative Monitoring Center at Sandia National Laboratories. We would like to thank David Betsill, Sally Laundre-Woerner, Guarav Rajen, Moshe Shachak, Michael Vannoni and Andy Wilby for their various kinds of assistance in this project.

Literature Cited

Adams, N.S., D.W. Rondorf, S.D. Evans, J.E. Kelly. 1998. Effects of surgically and gastrically implanted radio transmitters on growth and feeding behavior of juvenile chinook salmon. Transactions of the American Fisheries Society 127: 128-136.

Anderson, G.L. 1996. The application of spatial technologies for rangeland research and management: state of the art. Geocarta International 11(3):5-11.

Belsky, A.J., A. Matzke and S. Uselman. 1999. Survey of livestock influences on stream and riparian ecosystems in the western United States. Journal of Soil and Water Conservation 54(1):419-431.

Bich, B.S., J.L. Butler, and C.A. Schmidt. 1995. Effects of differential livestock use on key plant species and rodent populations within selected *Oryzopsis hymenoides* -- *Hilaria jamesii* communities of Glen Canyon National Recreation Area. Southwestern Naturalist, 40:281-287.

Burt, P.J.A., J. Colvin, and S.M. Smith. 1995. Remote-sensing of rainfall by satellite as an aid to *Oedaleus senegalensis* (Orthoptera; Acrididae) control in the Sahel. Bulletin of Entomological Research, 85(4): 455-462.

Fleischner, T.L. 1994. Ecological costs of livestock grazing in western North America. Conservation Biology 8:629-644.

Forster, B. 1996. Current advances in radar remote sensing research and its application in South East Asia. Geocarto International 11(4):3-10.

Gangwere, S.K., M.C. Muralirangan, and M. Muralirangan. 1997. The bionomics of grasshoppers, katydids and their kin. CAB International, New York.

Grenfell, B.T., and A.P. Dobson. 1995. Ecology of infectious diseases in natural populations. Cambridge University Press, New York.

Gosz, J. R., D. I. Moore, G. A. Shore, and H. D. Grover. 1995. Lightning estimates of precipitation location and quantity on the Sevilleta LTER, New Mexico. Ecological Applications 5:1141-1150.

Hiernaux, P., C.L. Bielders, C. Valentin, A. Bationo and S. Fernandez-Rivera. 1999. Effects of livestock grazing on physical and chemical properties of sandy soils in Sahelian rangelands. Journal of Arid Environments 41:231-245.

Jones, A.L., and W.S. Longland. 1999. Effects of cattle grazing on salt desert rodent communities. American Midland Naturalist 141:1-11.

Karnieli, A. 1997. Development and implementation of spectral crust index over dune sands. International Journal of Remote Sensing 18:1207-1220.

King, D.T., J.F. Glahn, and K.J. Andrews. 1995. Daily activity budgets and movements of winter roosting double-crested cormorants determined by biotelemetry in the delta region of Mississippi. Colonial Waterbirds 18:152-157.

Lariviere, S., and F. Messier. 1998. The influence of close range radio-tracking on the behavior of free-ranging striped skunks, *Mephitis mephitis.* Canadian Field Naturalist 112:657-660.

Lewis, S.E. 1994. Night roosting ecology of pallid bats (*Antrozous pallidus*) in Oregon. American Midland Naturalist 132:219-226.

Marzluff, J.M., M.S. Vekasy and C. Coody. 1994. Comparative accuracy of aerial and ground telemetry locations of foraging raptors 96:447-454.

Memmott, K.L., V.J. Anderson and S.B. Monsen. 1998. Seasonal grazing impact on cryptogamic crusts in a cold desert ecosystem. Journal of Range Management 51:547-550.

Milchunas, D.G. and W.K. Lauenroth. 1993. Quantitative effects of grazing on vegetation and soils over a global range of environments. Ecological Monographs 63:327-366.

Nyakolartey, Q, and R.M. Baxter. 1995. The effects of different grazing regimes on the population dynamics of small mammals in the Eastern Cape. Transactions of the Royal Society of South Africa, 50:143-151.

Oesterheld, M., C.M. DiBella and H. Kerdiles. 1998. Relation between NOAA-AVHRR satellite data and stocking rate of rangelands. Ecological Applications 8:207-212.

Parker, N., A. Pascoe, H. Moller and R. Maloney. 1996. Inaccuracy of a radio-tracking system for small mammals: The effect of electromagnetic interference. Journal of Zoology 239:401-406.

Rao, B.R.M., R.S. Dwivedi, L. Venkataratnam and A.N. Singh. 1996. Monitoring salt-affected soils using remote sensing data. Geocarto International 11(4):41-46.

Reading, C.J. and J.L. Davies. 1996. Predation by grass snakes (*Natrix natrix*) at a site in southern England. Journal of Zoology 239:73-82.

Reed, B.C., T.R. Loveland and L.L. Tieszen. 1996. An approach for using AVHRR data to monitor U.S. Great Plains grasslands. Geocarto International 11:13-22.

Riley, J.R., A.D. Smith, D.R. Reynolds, A.S. Edwards, J.L. Osborne, I.H. Williams, N.L. Carreck, G.M. Poppy. 1996. Tracking bees with harmonic radar. Nature 379:29-30.

Riley, J.R., P. Valeur, A.D. Smith, D.R. Reynolds, G.M. Poppy, C. Lofstedt. 1998. Harmonic radar as a means of tracking the pheromone-finding and pheromone-following flight of male moths. Journal of Insect Behavior 11:287-296.

Rohner, C. and D. Ward. 1999. Large mammalian herbivores and the conservation of arid Acacia stands in the Middle East. Conservation Biology 13:1162-1171.

Shivik, J.A., M.M. Jaeger, and R.H. Barrett. 1996. Journal of Wildlife Management 60:422-430.

Sone, K. and A. Kohno. 1996. Application of radiotelemetry to the survey of acorn dispersal by Apodemus mice. Ecological Research 11:187-192.

Todd, S.W., R.M. Hoffer and D.G. Milchunas. 1998. Biomass estimation on grazed and ungrazed rangelands using spectral indexes. International Journal of Remote Sensing 19:427-438.

U.S. Geological Survey. 1997. Forum on Wildlife Telemetry: Innovations, evaluations, and Research Needs; 21-23 September 1997, Snowmass Village, Colorado. Program and Abstracts. U.S. Geological Survey and The Wildlife Society.

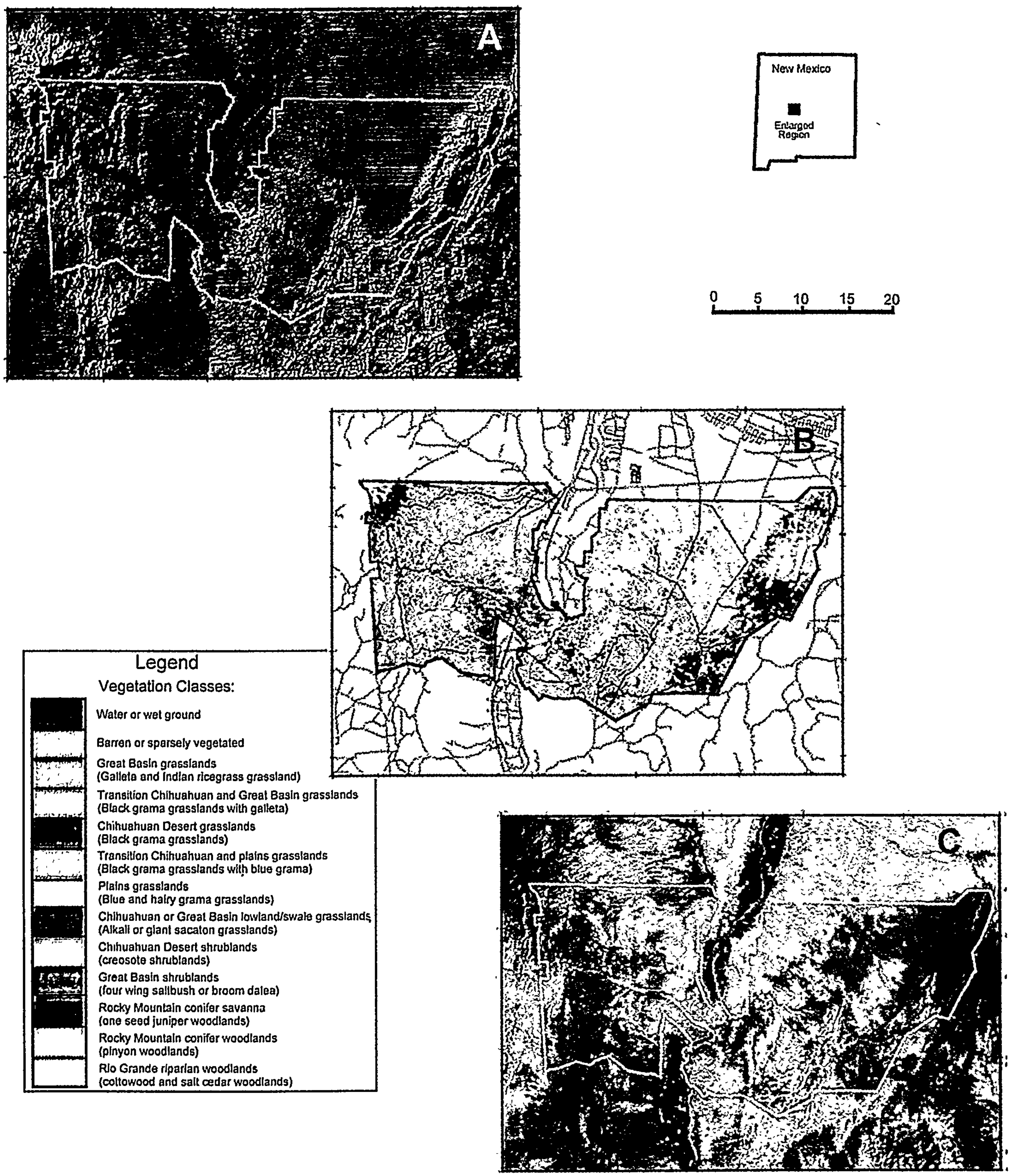
Vande Castle, J. 1998. Remote sensing applications in ecosystem analysis. Pages 271-287 in D.L. Peterson and V.T. Parker, editors. Ecological scale: theory and applications. Columbia University Press, New York.

Waller, J.S. and R.D. Mace. 1997. Grizzly bear habitat selection in the Swan Mountains, Montana. Journal of Wildlife Management 61:1032-1039.

Zhou, Q. 1998. Use of GIS technology for land resource inventories and modelling for sustainable regional development. Ambio 27:444-450.

Figure Legend

Figure 1. Geographic information system (GIS) data layers for the Sevilleta Long Term Ecological Research (LTER) site in central New Mexico. A. Topography (digital elevation model). B. Vegetation map based on unsupervised classification of computed Normalized Difference Vegetation Indices (NDVIs) of twelve composite Landsat TM images dating from 1987 to 1993. Validation of vegetation data was made at 252 field plots between 1994 and 1997. C. False color infrared image of the Sevilleta made by Landsat 5 TM sensor bands 2, 3 and 4 in August, 1992. Red represents vegetation.


A
New Mexico
Enlarged Region
0 5 10 15 20
B
Legend
Vegetation Classes:
Water or wet ground
Barren or sparsely vegetated
Great Basin grasslands
(Galleta and Indian ricegrass grassland)
Transition Chihuahuan and Great Basin grasslands
(Black grama grasslands with galleta)
Chihuahuan Desert grasslands
(Black grama grasslands)
Transition Chihuahuan and plains grasslands
(Black grama grasslands with blue grama)
Plains grasslands
(Blue and hairy grama grasslands)
Chihuahuan or Great Basin lowland/swale grasslands
(Alkali or giant sacaton grasslands)
Chihuahuan Desert shrublands
(creosote shrublands)
Great Basin shrublands
(four wing saltbush or broom dalea)
Rocky Mountain conifer savanna
(one seed juniper woodlands)
Rocky Mountain conifer woodlands
(pinyon woodlands)
Rio Grande riparian woodlands
(cottowood and salt cedar woodlands)
C