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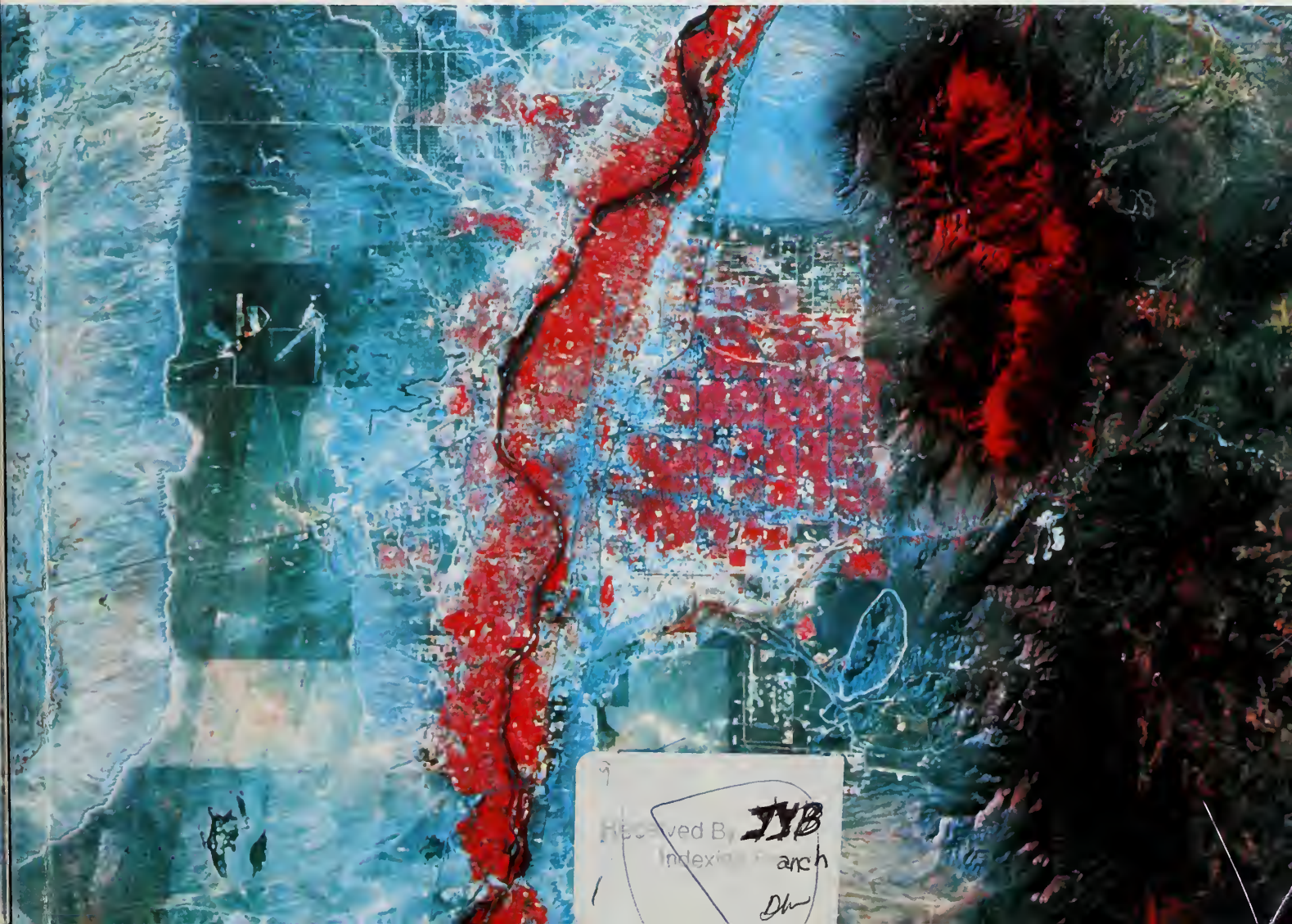Forest Service

Rocky Mountain
Forest and Range
Experiment Station

Fort Collins
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General Technical Report
RM-GTR-268

Ecology, Diversity, and Sustainability of the Middle Rio Grande Basin

Abstract

This book synthesizes existing information on the ecology, diversity, human uses, and research needs of the Middle Rio Grande Basin of New Mexico. Divided into nine chapters, the volume begins with reviews of the environmental history and human cultures in the Basin, followed by an analysis of the influences and problems of climate and water. Later chapters focus on ecological processes, environmental changes, management problems, and current conditions in Basin ecosystems identified as being especially susceptible to damage: pinyon-juniper woodlands, grasslands and shrublands, and the riparian bosque of the Rio Grande. Research needs associated with land management problems are identified for each of these ecosystem types. Many interrelated factors, identified here, have contributed to deteriorating environmental conditions in the Basin. Concluding chapters on the belowground ecology of specific Basin ecosystems and on declining populations of native fish species highlight topics in need of further attention. Each chapter seeks to identify studies that can supply information to mitigate environmental problems, rehabilitate ecosystems, and sustain them in light of human values and needs.

Keywords: Rio Grande, sustainability, riparian, environmental history, climate change, pinyon-juniper, desert grasslands, ecosystem restoration

Ecology, Diversity, and Sustainability of the Middle Rio Grande Basin

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Chapter 1
Introduction: Ecosystem Research in a Human Context

Deborah M. Finch and Joseph A. Tainter

USDA Forest Service, Rocky Mountain Forest and Range Experiment Station,
Albuquerque, New Mexico

THE RIO GRANDE: RIVER OF LIFE

The Rio Grande/Rio Bravo Basin, which drains a 355,500 square mile area in the southwestern United States and northern Mexico (Fig. 1), encompasses numerous land ownership boundaries, vegetation types, desert and woodland ecotones and edges, and urban and rural cultures, forming a complex array of interactive ecological systems. Historically known as the Southwest's "River of Life," the Rio Grande has lately become a subject of controversy over water resources and biological diversity. It earned the name in 1993 of "The Most Endangered River in North America" as proposed by the environmental organization American Rivers, Inc. Not only does the river form a geopolitical border between an industrialized country and a developing one, but human dependency on its waters, lands, and biotic resources reflects the traditions, economies, and social values of Hispanic, Anglo, and American Indian cultures. Sustainability of the Rio Grande's socioeconomic and ecological systems is a goal that has united diverse institutions, agencies, scientists, and private groups throughout the Southwest. This has resulted in numerous partnerships and initiatives designed to conserve the river and its way of life.

Nowhere is this controversy so heated as in the Middle Rio Grande Basin, an area frequently defined as the stretch between Cochiti Dam (southwest of Santa Fe) and Elephant Butte Reservoir (south of Socorro) in New Mexico (Fig. 2). Pressing middle Basin issues include water resource problems related to water quality, quantity, and rights; conservation of natural resources; restoration of ecosystems including control of exotic plant species and maintenance of biological diversity; overgrazing by livestock; urban expansion and human population growth; and impacts of anthropogenic changes on natural ecosystems. One of the biggest challenges facing researchers in the Basin, however, is developing new knowledge that integrates methodologies and data from different disciplines to solve complex problems that currently threaten sustainability of the middle Rio Grande Basin's ecosystems. To sustain the river and its people, it is necessary to understand (1) how historical and existing resource needs and uses by different human cultures have affected ecosystem and watershed processes, and (2) how ecosystem and watershed responses to natural and human-induced perturbations have influenced water resources, soil processes and stability, vegetation growth and ecotonal movement, riparian dynamics, biological diversity, and human use of lands.

THE MIDDLE RIO GRANDE BASIN RESEARCH PROGRAM

To address some of these issues, the Rocky Mountain Forest and Range Experiment Station of the USDA Forest Service initiated a research program in 1994 called "Ecology, Diversity, and Sustainability of Soil, Plant, Animal and Human Resources of the Rio Grande Basin." This program is funded by an Ecosystem Management grant from Forest Service Research and has a five-year duration (1994–1999). Its mission is to develop, synthesize, and apply new knowledge to aid in understanding processes, interactions, and sociocultural uses of upland and riparian ecological systems for sustaining diverse, productive, and healthy plant, animal, and human populations and associated natural resources in the Rio Grande Basin. The four problems defined by the program are: (1) knowledge is needed on short-term and long-term responses of upland soils, water, nutrients, mycorrhizae, and vegetation to historic perturbations caused by factors such as climate, grazing, fire, fuelwood harvesting, recreation, or farming, and how such responses influence dynamics, stability, and productivity of upland ecosystems; (2) research is

The Rio Grande Basin

N

100 Miles

Source: The International Boundary and Water Commission

Colorado

Alamosa

Rio Grande

Santa Fe

Albuquerque

New Mexico

Pecos River

Elephant Butte

Roswell

Caballo

Las Cruces

USA
Mexico

El Paso

Ciudad Juarez

United States

Texas

Devils River

Big Bend National Park

Rio Grande

Rio Bravo

Chihuahua

Chihuahua

Conchos

Rio

San Antonio

Corpus Christi

Rio Salado

Coahuila

Falcon

Brownsville

Gulf of Mexico

Mexico

Nuevo Leon

Matamoros

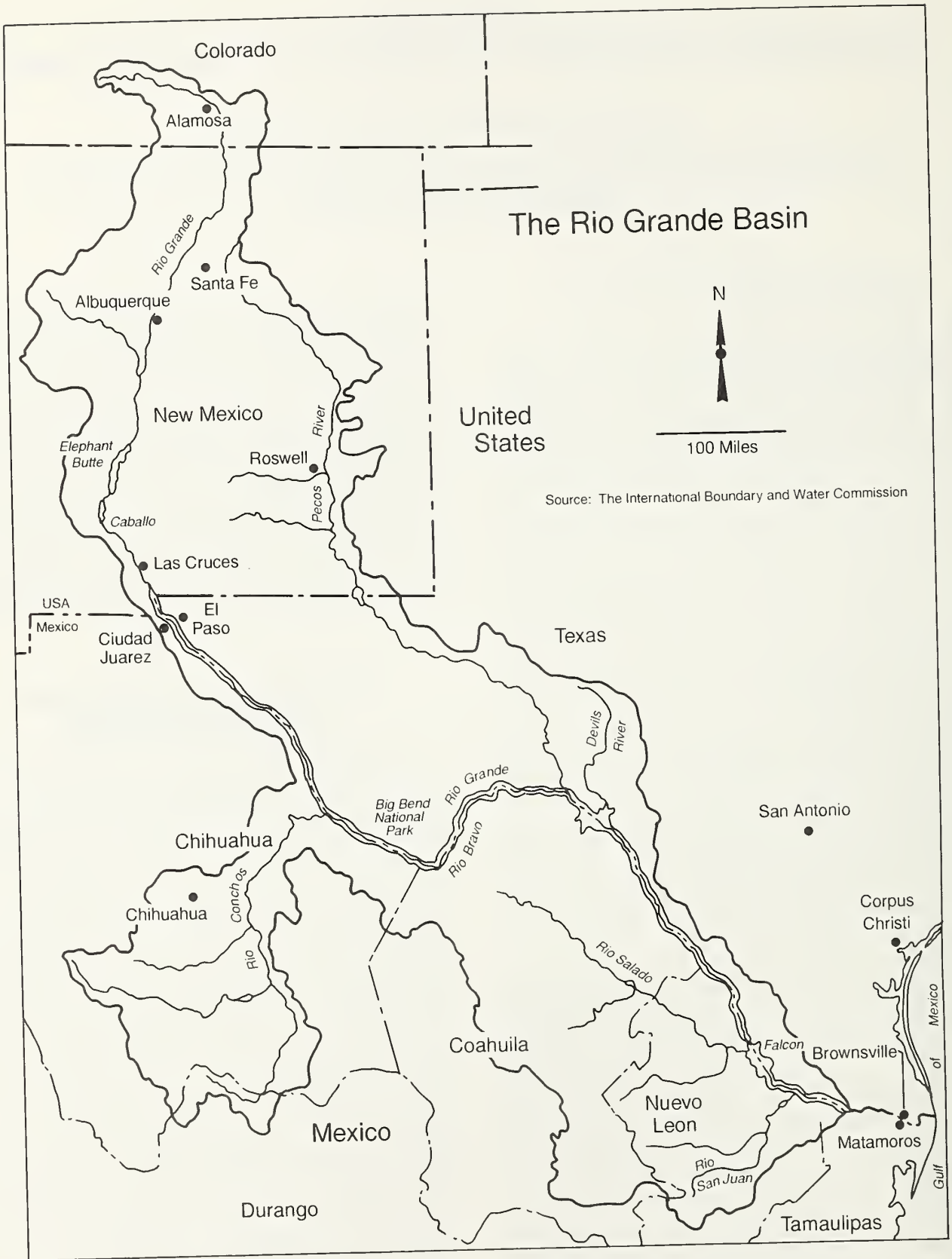Rio San Juan

Durango

Tamaulipas

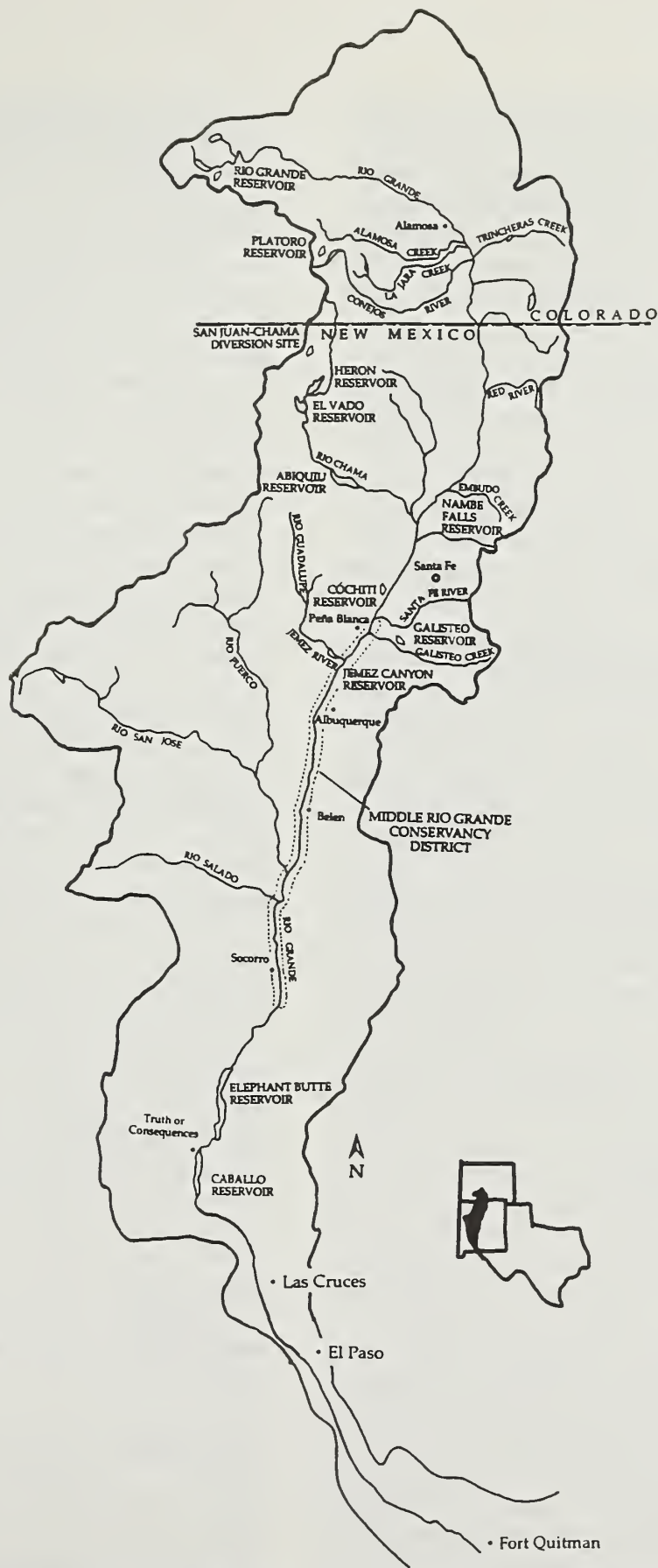**Figure 1.—The Rio Grande/Rio Bravo Drainage Basin.**

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Figure 2.—The Rio Grande Basin in Colorado, New Mexico, and Northern Texas, including the Middle Rio Grande study area from Cochiti to Elephant Butte.

3

needed to describe spatial and temporal processes within fluvial ecosystems, past and present, that form major linkages between upland catchments (watersheds), the Rio Grande, and its floodplain bosques; (3) research is needed to determine how plant and animal species respond to barriers in dispersal, migration, and reproduction along the Rio Grande and selected tributaries; to identify those species most sensitive to corridor edges and barriers; and to develop methods for enhancing movement and survival of sensitive, threatened, and endangered species; and (4) research is needed to improve understanding of the environmental history of the Rio Grande Basin, the historic and contemporary human role in Basin ecosystems, the nature and extent of anthropogenic disturbances to the Basin, and the sustainability of cultural diversity in the Basin.

To address these four problem areas, the existing literature was reviewed and synthesized to identify high priority research and management topics in the middle Rio Grande Basin. This volume is a product of that effort, commonly called a "problem analysis" in Forest Service Research. Because Basin problems are so complex and numerous, a team of experts agreed by consensus to write separate problem analyses on a number of priority topics identified during a series of planning meetings held in Albuquerque, New Mexico, in 1994. These meetings were attended by participants and cooperators in this research program, including researchers and natural resource managers from the Forest Service, the U.S. Fish and Wildlife Service, the National Biological Service, the National Park Service, the University of New Mexico Biology Department, the University of New Mexico Natural Heritage Program, the City of Albuquerque, the U.S. Geological Survey, Wingswept Research, Inc., and the Terrestrial Ecosystems Regional Research and Analysis Laboratory. The authorship of chapters for this volume reflects the diversity of cooperators in our research program. Biographical sketches of the authors are included in the front of the volume.

Our prioritization process identified three major forces that drive ecosystem processes and dynamics in the middle Rio Grande Basin: people, water, and climate. The first three chapters in this volume explore these driving forces. Such forces cannot be adequately understood, however, without a historical context. The first chapter therefore is a brief environmental history, documenting Basin changes in ecology, biology, and human land use over time. It also identifies needed information to fill in gaps in this history. Understanding the history of a region is critical for comparing current environmental conditions to past and future conditions and for recommending solutions to natural resource problems. This is especially true in the middle Basin where native human cultures have influenced the environment for thousands of years prior to European contact, leaving behind a complex archaeological record of artifacts, architecture, and other remains; and where Hispanic people settled hundreds of years earlier than European exploration of most other parts of North America.

The second three chapters synthesize information and identify research needs pertaining to natural resource problems in major vegetation types of the middle Basin: pinyon-juniper woodlands, desert grasslands and shrublands, and the Rio Grande riparian woodland, locally known as the "bosque" (Spanish for "forest"). While higher-elevation vegetation types such as ponderosa pine and subalpine spruce-fir forests also occur in the middle Basin, problems pertaining to them were not found to be as directly linked to the integrated complex of cultural, agricultural, and biotic problems associated with the river, its tributaries, and its people. Therefore, given our limited human and financial resources, we did not address them in detail here.

The last two chapters highlight aspects of ecosystems that are often neglected in natural resource assessments and management. The southwestern United States has more threatened and endangered native fish species than most other regions of North America. In the middle Rio Grande Basin, several fish species that were historically present in the river itself are now found primarily in headwater streams. The reasons for these faunal changes are discussed and research needs identified in Chapter 8. Chapter 9 focuses on the below-ground fauna of ecosystems, a critical component contributing to ecosystem functioning, and one that is seldom managed.

In the following three sections, we review in greater detail the four problem areas and associated elements addressed by the Middle Rio Grande Research Program.

PROBLEM 1: UPLAND BASIN ECOSYSTEMS

Rio Grande Basin ecosystems have evolved under human influence for at least 12,000 years. Since 1540, the Basin has experienced increasing anthropogenic changes, including human population growth, introduction of new plant and animal species, changes in

land use, and environmental degradation. The human population in the middle Rio Grande Basin is predicted to double by the year 2020 (Crawford et al. 1993). To maintain the diversity of native grasslands, shrublands, woodlands, and forest in the overall Basin, it is necessary to identify ways to sustain human populations in the space- and resource-limited environments along the Rio Grande and its tributaries. An understanding of the history, ecology, and responses of ecosytems is dependent on the creation, synthesis, modeling, and transfer of research knowledge that describes the functional processes, structural components, and interactions of ecological systems in the context of extreme climate variability, changing human social values, and expected population growth within the Rio Grande Basin.

Fluctuations in the functional health and productivity of the Basin's arid and semiarid ecosystems are largely driven by changes in climate, water, animal, and human disturbance, including native herbivory, livestock grazing, agricultural conversion, and recreation. Extreme disturbances to grassland, shrubland, and pinyon-juniper ecosystems in the Basin contribute to soil compaction, sheet and gully erosion, reduced soil and plant productivity, desertification, invasion of exotic plants and animals, and reduced biological diversity. These problems are exacerbated by severe and unpredictable climatic fluctuations that affect water flow dynamics, nutrient availability, and energy availability along gradients of slope and vegetation. To understand how human use of the Basin's upland environments affects overall ecosystem functioning and structure, knowledge is needed concerning ecosystem responses to historic and current perturbations caused by climate, grazing, and fire, and how such responses influence dynamics, stability, and productivity of upland ecosystems.

Pinyon-juniper ecosystems occur on approximately 23 million acres in New Mexico. On National Forests alone, close to 50 percent of pinyon-juniper watersheds (about 3.5 million acres) contain degraded soils and vegetation (Henson 1993). Indeed, the Forest Service's Southwestern Region established a Pinyon-Juniper Initiative in the early 1990's for the purpose of restoring pinyon-juniper watersheds to a healthy state (Henson 1993). Degraded conditions associated with historical and current overgrazing in the middle Rio Grande Basin are especially visible at the interface between pinyon-juniper woodlands and desert grasslands and shrublands. Pinyons and junipers in these transitional zones or ecotones

may have been historically subjected to higher fire frequencies than interior pinyon-juniper woodlands, owing to frequent lightning-caused fires in grasslands (Tom Swetnam, personal communication). Without the restoration benefits of fire, soils and cover of grasslands and adjacent ecotones can deteriorate, especially under heavy livestock use. In grasslands with juniper as an overstory species, grazing results in a competitive advantage to juniper and a reduction in grass production (McPherson and Wright 1990). Removal of grass cover and degraded soil conditions, including soil compaction and accelerated erosion, can lead to reduced long-term soil productivity and impaired water quality. These upland ecosystem processes and dynamics are addressed in more detail in Chapters 4, 5, 6, and 9.

PROBLEMS 2 AND 3: WATER, WATERSHEDS, AND RIPARIAN ZONES

Climate change, and corresponding patterns of rainfall and drought, can cause further havoc in ecosystem processes controlling water flow and vegetation distributions. The amount and quality of runoff entering the Rio Grande and its tributaries from pinyon-juniper and desert grassland watersheds influence the dynamic connections among river water, the riparian zone, and biotic diversity. The reproductive and nutritional state of native vegetation in the Rio Grande's riparian zone reflects the magnitude and chemistry of seasonal flooding, which is a function of watershed runoff. Unsatisfactory watershed conditions contribute to increased overland flows, eroded stream banks, and non-point source pollution.

From an ecosystem perspective, managing the quantity and quality of nutrients and sediments delivered from upland watersheds to the Rio Grande and its tributaries should be a major goal of Basin management. The second and third problems defined under our research program deal more specifically with water, riparian habitats, and associated wildlife and fish. The literature related to these problems is reviewed in Chapters 4, 7, and 8.

Historic and contemporary land use practices, especially grazing, mining, and fuelwood harvesting, coupled with severe drought periods, have led to high rates of surface runoff and sediment yield from upland grassland and pinyon-juniper watersheds into Basin tributaries such as the Rio Puerco. This has jeopardized the health and regenerative capacity of riparian plant and animal populations and com-

munities. Sediment pollution detrimentally affects native fish populations. Current livestock grazing in the uplands, if managed poorly, can reduce herbaceous cover and compact soils, leading to erosional and runoff problems that ultimately impact riparian zones. Overgrazing within the riparian zone can also reduce the regeneration capacity of native cottonwoods and willows, potentially deteriorating habitats used by wildlife and people. Loss of native riparian vegetation owing to overgrazing, agricultural and urban conversion, and replacement by exotic woody plants may ultimately disrupt the migration and breeding dynamics of neotropical migratory birds along the Rio Grande flyway and may explain the population decline of the endangered southwestern willow flycatcher (*Empidonax trailii extimus*).

The Rio Grande has long provided many resources, including drinking water, travel pathways, fuelwood, and fish and game for indigenous and recent human populations. Today, a continuous corridor of transportation and communication links contemporary urban environments along the main stem of the Rio Grande. Europeans built water diversion structures, cleared riparian vegetation, planted non-native species, and constructed dwellings and villages in the Rio Grande bosques. Dams, groundwater pumping, agricultural developments, and urban centers along the main river valleys have impacted the nature, extent, distribution, and regenerative health of floodplain bosques. Exotic plant species have invaded most river systems in the Basin, forming potential barriers to dispersal, migration, and reproduction of native plant and animal species. Water pollutants from urban centers, non-point source pollution from overgrazed uplands, and introduction of exotic salmonids and bullfrogs have eliminated native fisheries along the Rio Grande, endangering some fish species by isolating them in headwater streams or in remnant pockets of the river itself. Although the middle Rio Grande bosque appears continuous, in actuality it is "fragmented" by centers of human habitation, the presence of exotic plant and animal species, dams and diversion structures, and a system of protected parks and wildlife refuges interspersed by nonprotected stretches used by livestock. Chapter 7 explores the dynamics of the Rio Grande bosque, emphasizing the relationships among three taxonomic groups and trophic levels, while Chapter 8 focuses more specifically on the fish fauna in the Basin.

In the final section, we explore in greater depth the human dimensions part of our program because it is the integration of human needs and values that makes our program especially valuable and unique in the arena of environmental research.

PROBLEM 4: HUMAN DIMENSIONS

Environmental Issues as Human Values

In the United States today and throughout the world, there is increasing disagreement over policies of land management and natural resource use. Many of these disagreements concern basic political and economic goals. Others, more subtle and difficult to understand, are expressed as differences in cultural values and perceptions, or as traditional ways of using land. Disputes and conflicts that are expressed in cultural terms have become common over the past three decades. This is a worldwide phenomenon. Such disputes over culture and environment manifest themselves in a continuous spectrum. At one end of this spectrum are the comparatively benign land disputes fought mainly in the courtrooms and legislatures of the United States, Australia, and Canada. At the opposite extreme there are the terrible conflicts that we see in Rwanda, Liberia, and Bosnia. Because these disputes are global in their occurrence and continuous in their expression, they are best comprehended in a comparative framework. In the United States, agencies that manage public lands experience one part of this global pattern. This is part of the reason why comparative cultural research is of importance to the USDA Forest Service and other land-managing agencies. The human dimensions component of the Rio Grande Basin research program will be a major part of that comparative research.

Conflicting cultural perceptions and goals in land use underscore an important point: environmental problems are essentially human problems, and solutions to them require more than the traditional biophysical approaches. Too often, those who work in natural resource management have not foreseen that their work has social and cultural consequences. Especially in places where cultural diversity is high, and where land and resource use differ by cultural group, how people use the land can easily become a part of cultural identity. It can also be part of a strategy to resist assimilation. The issues that arise from threats to traditional land use are more than merely economic. Subsistence practices and other uses of land may be no easier to abandon than any other aspect of cultural identity. These issues are particu-

larly salient in the southwestern United States, including the Rio Grande Basin.

Amidst today's cacophony of land-management appeals, litigation, and contentious political discourse, one point should be clear: sustainability is a human value judgment. There are no absolute standards to which ecosystems should be maintained or restored. People assign meaning to landscapes (Greider and Garkovich 1994), and those meanings may be quite different from how a biologist or a forester sees a landscape. What we perceive as a desirable landscape condition reflects social values as much as it reflects ecosystem characteristics. Confounding matters, such values change over time. To illustrate, consider some historical changes in how our ancestors and ourselves have viewed landscapes.

In the world of the ancient Mediterranean, peasant agriculture was the basis of society and the source of most wealth. The most valued landscape was therefore an agricultural one: small peasant farmers using the land intensively to produce wealth for the elites, taxes for the state, soldiers for the army, and food for all. Writers of the period always commented favorably on such landscapes. Conversely, a landscape not filled with productive peasants, being allowed to revert to natural conditions, was considered to indicate a society in decline (Alcock 1993). The economic conditions that favored such a landscape ideal persisted until the Industrial Revolution. They are essentially the economic conditions and landscape values that formed the Jeffersonian theory of American democracy.

Implicit in such ideals is the assumption that lands that have not been culturally transformed are without value. Such lands may even be seen as vaguely threatening. At one extreme this produced the medieval European view that old-growth forests were places to be feared. They were dark and forbidding, and the home of witches, wolves, and robbers. Forests were where culture stopped and nature began. To enter such a place was to risk one's life. The medieval folklore reflecting such fears is still repeated today in tales told to children.

Consider how these views have changed as industrialism has transformed our economic base. The people of medieval Europe would have been astonished by the notion that old-growth forests are to be valued, protected, and actually entered for enjoyment. Thomas Jefferson could hardly have foreseen the wilderness philosophy that would emerge from the writings of Henry David Thoreau. Since the founding of this country, the view that many people have of valuable landscapes has changed profoundly. It will do so again in times to come.

What we perceive to be an ecosystem worth maintaining or restoring has much to do with what we value in landscapes. Neither ancient Romans nor medieval Europeans, not to mention Thomas Jefferson, would ever have thought to preserve land as wilderness. Sustainability is a flexible and changing judgment of human values, and managers must approach it as such.

Human Dimensions Research in the Rio Grande Basin

Including the human dimension in ecosystem research and management greatly increases the complexity of our work. Yet to leave people out is to guarantee political discord and continuing expenditure of public funds on land-management appeals and litigation. Recognizing that environmental issues are substantially human issues, many scientists and administrators have concluded that ecological problems require human solutions as much as they require strictly biophysical ones (e.g., Allen and Hoekstra, in press). The human dimensions component of the Rio Grande Basin research program reflects this growing realization. A few years ago, such a program would have been likely to include little or no human dimensions research. More recently, a brief discussion of human dimensions might have been included as an afterthought. The fact that a strong component of human dimensions research was planned into this program at the outset is an indication of how research and administration are changing in land-management agencies.

Several principles have guided the development of the human dimensions component of the Rio Grande Basin research program. The first is that there are in the world today few "natural" ecosystems, or perhaps even none, in the sense of existing without human influence. All ecosystems are anthropogenic to one degree or another. Rio Grande Basin ecosystems have evolved under human influence for at least 12,000 years, and this has particularly been so for the last 450 years. The Rio Grande Basin cannot be understood without considering the role of humans in ecosystems and human responses to environmental problems.

Recognizing that past human populations have modified ecosystems, sometimes to significant de-

grees (e.g., Lewis 1973), does not, of course, legitimize callous environmental destruction. What it should do is to change the terms of debate over historical and contemporary changes to ecosystems. Calling for the "restoration" of ecosystems to "pristine" conditions (as some environmental advocates do) exacerbates the political conflict in the United States over environmental laws. It may also be historically misguided.

A second principle concerns scale and complexity. Environmental problems occur at all levels, from local to global. Systems for managing environmental issues match this range. They can be found at every level, from local, ad hoc associations to international agencies. To consider issues of culture and environment in the Middle Rio Grande Basin requires a view that sees the Basin in context. This context involves such matters as immigration; Albuquerque's success at attracting business; economic conditions at the state, national, and international levels; the state and federal budgets; the price and availability of fossil fuels; climate; and other factors. To develop a comprehensive understanding of cultural diversity in New Mexico in its relationship to environmental factors requires research into all of these topics, as well as into the position of the Rio Grande Basin in the global economy and in the global environment.

A third principle is the importance of knowing where we are in history (Tainter 1995). Historical trends develop over periods of generations or even centuries. Because these trends cannot be comprehended in a single lifetime, it is difficult to know from personal experience where we are in the long-term cycle of human-environment interactions. The production and prices of natural resources, for example, often depend on a capital investment cycle with a lag time of up to several decades. So does employment in resource production (Watt 1992). Do current low levels of employment in the timber products industry reflect the effects of environmental laws, technological change, global economic forces, or the capital investment cycle? Unless the timber products capital investment cycle is considered, the question cannot be answered. It is important to know where we are in history.

Historical research sometimes produces surprising results. As pointed out by Dan Scurlock in this volume, the Anglo-American trader Josiah Gregg suggested in 1844 that the grasslands of the Southwest would eventually be replaced by trees and shrubs due to suppression of range fires (Gregg 1844). To en-

counter such a statement in the historical literature is both illuminating and disturbing. One has to wonder why it took us 150 years to rediscover that lesson.

A final principle involves the role of social and political organization in both creating and resolving environmental problems. Frank Wozniak (this volume) has described how irrigation agriculture in the Middle Rio Grande Basin had declined by the early 20th century due to a variety of environmental problems. In the 1920s the Middle Rio Grande Conservancy District (MRGCD) was organized to drain waterlogged soils, reclaim unused lands, and provide water for irrigation. This involved a reorganization of irrigation systems, a renovation of facilities, and the development of a new agency to manage irrigation. The new system brought with it an infusion of outside influences and a tremendous escalation in the costs of irrigation. Much of the latter impact was absorbed by the Federal government, which massively subsidized the cost of irrigation in the Rio Grande Valley. Many of the old problems of flooding, sedimentation, waterlogging, alkali poisoning, and unreliable water supply were resolved or at least held in check, but they were replaced by problems of financing the new system.

The formation of the MRGCD illustrates the role of political organization in human-environment interactions. Today the Middle Rio Grande Basin is embedded within larger political and financial systems at the national and international levels. While this allows the people of the Basin to tap higher political levels for financial support, it also means that the stability of the Basin depends on the stability of the larger system. There are historical examples that should be considered in appraising this stability. In the first millennium A.D., the regimes that ruled the Mesopotamian alluvium greatly intensified irrigation and agricultural production. Irrigation systems were developed that were beyond local abilities to manage and repair. State control and financing were required. In the late ninth and tenth centuries A.D., however, the political hierarchy became unstable, and the irrigation system declined catastrophically. Fields became salinized and production plummeted. By the eleventh to twelfth centuries A.D. the total occupied area had dropped by about 94 percent. Populations declined to the lowest levels in five millennia. Tax revenues plummeted by 90 percent within a few decades. People rebelled and the countryside became ungovernable. For centuries afterward, this catastrophe eliminated the basis for urban life in 10,000

square kilometers of Mesopotamia (Adams 1981; Waines 1977).

The point of this illustration is not to suggest any direct parallel between ancient Mesopotamia and the Middle Rio Grande Basin. The analogy is more subtle. It lies in the dependency of local systems of production and management on higher levels in a complex system, and the risks that this dependency entails. The very highest levels in political systems have always been prone to failure. This is because problem-solving in such systems displays a characteristic historical pattern of increasing complexity, the creation of costly institutions, and ultimately diminishing returns to problem-solving. This simple pattern has profound implications. In a system of problem-solving that develops in this way, eventually the point is reached where it is no longer feasible or beneficial to try to solve problems. In time such systems are either terminated or they collapse (Tainter 1988, 1995), as happened in ancient Mesopotamia. Systems for managing environmental and cultural issues are no exception to this. In these days when we know that the cost of government is not sustainable, it is probably unwise to depend on the political hierarchy to solve local problems with financial subsidies. It is worth noting that the MRGCD has received no federal funds for the past several years.

Working within these principles, the human dimensions portion of the Rio Grande Basin research program contains five elements.

The first research element is to improve understanding of the human role in Rio Grande Basin ecosystems, including historic and contemporary human ecology, and human responses to climatic and other environmental changes. When land managers consider the human role in ecosystems, it is usually as a dichotomy: human dimensions or natural ecosystems. This dichotomy is misleading and channels discussion in unproductive directions. Human populations are *of course* parts of ecosystems. The relationship of culture to environment is reflexive: Each influences and conditions the other. North American ecosystems have developed under varying degrees of human influence. At the same time, both prehistoric and historic North American cultures have been influenced by environmental conditions. To debate whether to include human populations in the analysis of ecosystems is like debating whether ecosystems include both flora and fauna.

What we do not yet know is the extent to which the historic conditions of Rio Grande Basin ecosystems were conditioned by prehistoric human activities. In some parts of North America, Indian populations deliberately manipulated ecosystems to select for early seral stages (e.g., Lewis 1973). Research is needed to determine if this was also the case in New Mexico. Our conception of such matters as the range of historic ecosystem variation will depend substantially on the outcome of such research.

The second research element is to establish historical information on changes in the Rio Grande Basin and to improve understanding of the evolution of Basin ecosystems since 1540. Dan Scurlock's contribution to this volume falls within this research element. It is a prologue to a much longer work in progress that he is preparing for both the Rio Grande Basin research program and the Cultural Heritage Research Work Unit of Rocky Mountain Station. This report will be a full synthesis of the documentary evidence for environmental change in the Middle Rio Grande Basin since 1540. Such knowledge should be the basis of any attempt to understand current environmental conditions.

The third research element is to develop an integrated understanding of the relationships among environmental, cultural, political, and economic factors and processes within the Rio Grande Basin. The Rio Grande Basin is noted for its cultural mosaic. The cultural identity of some Basin groups is formed in part through their relationship to the land, while maintaining cultural identity depends on an adequate economic return from use of the land. An integrated understanding of the relationships among environmental, cultural, and economic factors and processes within the Basin is needed to sustain both human populations and natural resources. Where perceptions and uses of land vary by culture, this may lead to conflict over land and resources. Ecosystem management, which is a concept of European analytical thought, is increasingly constrained by values and perceptions arising from other cultural contexts. To predict human responses to changes in land management and to manage conflicts resulting from change, we need to understand better the perceptions and values of nature, land use, and land management held by different cultural groups in the Rio Grande Basin. We also need to improve understanding of the relationship of cultural sustainability to changes in climate, energy, population, land use, the national and global economies, and the environment. We need to understand alternative cultural responses to changes in these factors. The contribution by Frank

Wozniak in this volume explores some of these relationships.

The fourth research element concerns developing or refining methods to assess the impacts of alternative resource-allocation decisions within the Basin. It also concerns how adverse social and cultural impacts of allocation decisions can be mitigated. Existing models of conflict resolution, mediation, and prevention should not simply be applied untested to the Rio Grande Basin. Their suitability to Basin conflicts needs to be determined. If necessary, new models should be developed that are specific to the characteristics and problems of this area. Such new methods may be needed to help the people of the Basin visualize and understand better the impacts of alternative resource allocation decisions

The final research element is closely related to the fourth. It is to improve ways to obtain consensus on, and commitment to, the desired future conditions of the Basin from the area's many interest groups, agencies, and institutions. The Rio Grande Basin is one of the most culturally diverse parts of North America. That diversity must be recognized to achieve a consensus on future conditions of the Basin.

Cultural Diversity in Context

As noted above, we are experiencing a dramatic increase in the formation and expression of cultural identity. This is nearly global in its occurrence, and in its present form it is a phenomenon largely of the last 30 years. It is something nearly unique in human history. This global intensification of cultural identity and cultural conflict manifests itself in the Rio Grande Basin, as it does elsewhere.

We understand poorly the basis of cultural identity or the reasons for cultural conflict. Journalists, among others, seem to assume that cultural differences lead automatically to violence. Commonly in the media one encounters attempts to explain violence as the sad but inevitable result of "ancient tribal feuds." Violence is thus assumed to be something intrinsic to cultural differences. Such is the picture of cultural diversity that is presented to the public. It is a great oversimplification and a terrible misunderstanding of the basis of cultural conflict.

Two recent conferences, one of which was organized by the Cultural Heritage Research Work Unit of Rocky Mountain Station,[1] have shown that these popular "explanations" of cultural conflict are fundamentally incorrect. The results of these conferences suggest that many so-called "cultural" conflicts may not really have cultural origins or cultural solutions. In the discussions at these conferences it was consistently clear that contemporary incidents of violence, each supposedly a clash of cultural identities, are closely linked to political struggles in the relations of local groups to central governments or are actually about control of central governments. Cultural differentiation in today's conflicts is flexible and shifting, and it responds to both external stimuli and deliberate manipulation.

To an outsider or casual observer it is easy to suppose that conflicts between different cultural groups are conflicts *about* culture. In fact, in many of the conflicts occurring around the world today, people struggle not for their culture but for more fundamental economic and political issues that happen to be expressed in cultural terms. To phrase an economic or political claim (such as a claim to have a role in managing public lands) in cultural terms raises the moral authority of the claim and taps profound emotions. It is an effective strategy of public discourse.

This point has important implications for addressing cultural disputes in land management. If such disputes have an economic or political basis, but are expressed in cultural terms, then to address only the cultural issues is not to resolve the problem. The underlying economic or political conflict may remain. This is not to deny that people often have strong feelings for traditional uses of land. Such uses are often a central part of cultural identity and may be no easier to abandon than religion, language, or community. The point is that if attempts to mediate disputes address only expressed cultural issues, the attempts will fail. The fundamental economic and political disputes must be resolved as well. This is as much the case in the Rio Grande Basin as it is in Bosnia, Rwanda, or Tajikistan. The label "cultural conflict" may conceal much more than it reveals.

CONCLUDING REMARKS

It is clear that resolution of environmental problems must come from integrated research by natural

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[1] *The first conference was* The State Under Siege: Political Disintegration in the Post-Cost War Era, *organized by R. Brian Ferguson,*

[1] *(continued) New York Academy of Sciences, April 22–24, 1994. The second was* Environmental Dimensions of Cultural Conflict, *organized by Joseph A. Tainter and R. Brian Ferguson, Xerox Document University Training Center, Leesburg, Virginia, June 18–22, 1995.*

and social scientists working together. Leaving out either component of this mix will result in failure. The level of interdisciplinary research in the Rio Grande Basin research program, exemplified in this volume, is unique in our experience. It points the way to the future. If we find solutions to the problems of the Rio Grande Basin, it will be because we find new ways of organizing research so that it is truly interdisciplinary, integrated, and synthetic. We need multidimensional research and management to understand and solve multidimensional problems.

ACKNOWLEDGMENTS

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Chapter 2
Environmental History

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HISTORIC PERIODS	
Spanish Colonial	A.D. 1540–821
Mexican	A.D. 1821–1846
Territorial	A.D. 1846–1912
Statehood	A.D. 1912–present

INTRODUCTION

Humans are a major component of the environment, and all human activities impact the environment, which includes other humans. Researchers have only recently focused on spatial and temporal impacts of historic human activities on the land and water of the Middle Rio Grande Basin. Interrelationships of these and the effects of periodic severe cold periods, early or late frosts, droughts, insect infestations, and other "natural disasters" such as epidemic diseases, earthquakes, fires, and floods have been minimally explored but not systematically studied. Furthermore, the equally complex history of plant and animal introductions and extinctions by humans, although generally understood, still need additional research of their temporal and spatial occurrence and impact on other biotic components. Finally, the role of world view exhibited by various groups as related to environmental impact, change, and future resource management needs must be considered.

Various groups in the Middle Rio Grande Basin ecosystems have greatly affected the processes and evolution of plant and animal communities during the historic period, A.D. 1540 to the present. The human-generated impacts and changes, through activities such as farming, hunting, ranching, mining, logging, stream impoundment, and recreation, have affected ecosystems' structure, function, and ecodynamics over the past 450 years. Some of these activities have reduced vegetative cover and, combined with periodic droughts and fires, have resulted in high rates of surface run-off due to precipitation and associated erosion. Silt from this process has, generally, increased through time and the resulting impacts

on riparian plant and animal communities have been severe in places such as the Middle Rio Grande Valley and Rio Puerco. Other impacts such as introducing exotic species of plants, animals, and toxins, diverting water for irrigation, and constructing dams have also brought dramatic changes to riparian ecosystems. This chapter summarizes human impacts and their interaction with the Middle Rio Grande Basin.

OVERVIEW OF ENVIRONMENTAL HISTORY

Climate

Weather records dating from the late 19th century to the present indicates that most of the region (excluding the mountains) is a continental plateau with arid to semi-arid climate. Salient characteristics include an average annual precipitation below 15 inches; high solar radiation; low relative humidity; moderate, but wide ranges of diurnal/nocturnal and seasonal temperatures; and high evaporation and transpiration rates (Taft 1980: 1; Tuan et al. 1973: 185–189). In the higher mountain ranges flanking the river valley, adjacent mesas, and foothills, subhumid and humid climatic conditions prevail. Average annual precipitation is higher, up to 30 inches; in contrast to the lower elevations of the region, not all available moisture is evaporated or transpired (Tuan et al. 1973: 192–195). Higher winds and lower seasonal temperatures occur here also.

Almost half of the average annual precipitation for the Rio Abajo falls from July to September or during the growing season (Tuan et al. 1973: 30, 33, 50). Precipitation fluctuates widely about the mean, and most summer rain is of high intensity and associated with thunderstorms. Average annual precipitation ranges from 7.25 inches at Peña Blanca to 8.31 inches at Las Cruces (Gabin and Lesperance 1977: 114, 327–364). Mean monthly (July) high temperatures for the Rio Abajo range from 76.2° F at Peña Blanca to 82.2° F at Las Cruces. Mean lows (December) for these two locations are 31.1° F and 37.6° F. The growing season

ranges from 189 days at Cochiti to 198 days at San Marcial (Bennett 1986: 46–47).

Winds in the summer are predominantly southerly, in the winter they are northerly, and in the spring northwesterly to southwesterly. March and April are the windiest months; Albuquerque averages 16 severe dust storms during this two-month period (Bennett 1986: 42–45; Tuan et al. 1973: 111).

Detailed climatic records before 1850 are limited, although tree-ring data provide some understanding of climate fluctuations and long-term patterns. Chronicles of Hispanic expeditions, missionary reports, and some government documents from the Colonial Period (A.D. 1540–1821) mention or describe some weather phenomena such as droughts, floods, severe cold, and deep snow. These environmental factors influenced or directly impacted many activities, notably travel, agriculture, livestock raising, warfare, hunting, and gathering. Drought and otherwise sporadic short-term and long-term precipitation were significant limiting factors and were interrelated with such environmental conditions as soil erosion, decreases in wildlife populations, changes in plant community species density and composition, and changes in surface water hydrology.

Extended cold winters, or shorter periods of below normal temperatures associated with high winds and snow (blizzards) and above normal snowfalls, had significant impacts. Events of these kinds commonly occurred during the "Little Ice Age," which gripped New Mexico from about the mid-fifteenth to early 19th centuries. Adverse effects of this cold period included human fatalities, crop and livestock losses, and general unrest and suffering. The warming period and relatively frequent droughts that followed, especially from the 1860s to the 1950s, adversely impacted ranching economics, farming economics, and human population shifts and trends.

No comprehensive systemic study has been made of scientifically recorded climatic records, which date from the late 1840s to early 1900s in the Middle Rio Grande Basin. Associated data, such as stream flow records of the last 120 years or so, are just now being synthesized and analyzed. Comparative climatological data from tree-ring studies await attention as well.

In general, local climate and available construction materials dictated selection of building materials, with *terron*, or sod blocks, extracted from riverine wetlands, adobe bricks and/or stone used in the lower to mid-range elevations, and logs used in the higher, temperate, mountain locations.

Floods

Floods, due either to spring runoff resulting from the melting mountain snowpack or from intense summer rains, have played a significant environmental role in the Rio Grande's hydrology and associated land-use activities during the historic period. Before the construction of major flood control structures on the upper Rio Grande and major tributaries in the 1930s, late spring and summer flooding of stream valleys was common. Maintenance of various climax plant communities was, in part, dependent on these seasonal floodwaters. This relationship will be discussed later in this chapter.

Reports of adverse impacts of these floods on Rio Grande Pueblos date as early as 1591, when De Sosa visited a flooded Santo Domingo village (White 1935: 12). Destruction of mission churches and farmlands was the most commonly documented impact of flooding during the Colonial Period.

Droughts

Probably the singlemost significant climatic factor affecting human populations negatively during the historic period was drought. Occurring regionwide, droughts damaged or destroyed crops and rangelands, devastated wildlife populations, and depleted water supplies. These impacts sometimes resulted in widespread loss of human life and the shifting of human populations. For example, the dry years of 1561–90, 1640, and 1663–69 contributed to or caused the abandonment of pueblos along the Galisteo drainage and in the Salinas Province (Abo, Quarai, and Gran Quivira) (Hackett 1937: 17; Schroeder 1972: 48; Vivian 1964: 153).

Historical documentation from the mid-seventeenth century to the late 19th century corroborates analyses of more recent detailed weather records, which suggest the occurrence of a major drought in the region every 20 to 25 years (Tuan et al. 1973: 64). These periodic droughts, increasing use of surface and ground waters, and intensive grazing have generally resulted in dramatic changes in the flora. These changes will be discussed later in this chapter.

Fire

Wildfires caused by lightning are a common phenomenon from July to September. American Indians used fire as one method of clearing the bosque for

cultivation. Woodland and range fires in the Rio Abajo were not suppressed until this century. In the prehistoric and historic periods, American Indians burned grasslands and woodlands to drive game animals to a location where they might be more easily killed, as well as to stimulate new plant growth (Cooper 1960: 138; Harris 1966: 416).

Woody shrubs and small tree species such as fourwing juniper, saltbush, and pinyon encroached on semi-desert grasslands near the valley as a result of fire suppression. Range fires usually kill small woody species, while grass regeneration is stimulated. Removal of dense stands of dry grasses by overgrazing also reduced available fuel for range fires and decreased competition from grasses, allowing propagation and growth of woody plants (Harris 1966: 416–418; Lymbery and Peiper 1983: 14–15). Interestingly, Josiah Gregg (1966: 202) in 1844 suggested that the grasslands of the Southwest would eventually be replaced by shrubs and trees due to suppression of range fires.

Infectious Diseases

The impact of introduced European diseases such as smallpox on American Indians has been relatively well documented in New Mexico; more Indians died of epidemics in the Colonial Period than from any other single cause. These serious maladies contributed significantly to unrest in the province, some of which resulted in several Pueblo revolts in the 1600s and increased raiding by nomadic Indian groups. The latter phenomenon was related to severe, extended drought conditions in the 1640s, 1660s, and 1770s to early 1780s, and it produced the most catastrophic periods of conflict and war in the Colonial Period. The annual Pueblo calendar of religious events was interrupted, and socioeconomic systems were fragmented due to these two environmental factors.

RESOURCE USE IN THE SPANISH COLONIAL AND MEXICAN PERIODS

The Spanish brought with them new technologies and many new domesticated plants and animals that had a decisive impact on Pueblo, Navajo, and Apache diet and landscape. Introduced livestock included sheep, goats, horses, mules, burros, oxen, cattle, hogs, and chickens. Introduction of metal tools such as the axe, which made cutting green wood easier and faster, as well as iron-tipped plows and weapons, had

an increasingly significant adverse impact over time on habitats of native fauna, flora, and soils. New cultigens included wheat, barley, cabbage, onion, lettuce, radish, cantaloupe, watermelon, and several species of fruit trees, as well as native Mexican Indian crops such as chile, cultivated tobacco, tomato, and new varieties of corn and beans. Some introduced non-cultigens, such as alferillo and horehound, became established in fields and other disturbed areas.

Spanish Colonial settlement land use patterns generally were similar to those of the indigenous, sedentary American Indians in the region (the Pueblos). Settlers chose land with good soils along or near water sources that could be used for ditch irrigation, domestic water, and livestock watering. The community land grant system used in northern New Mexico accentuated this pattern, with the principal concentration of settlers in a plaza, watered by an *acequia madre-sangrias*, fed by streams or springs, and with agricultural fields stretching between the *acequia madre* and the river or stream source. Irrigation farming of some lands led to salt buildup in soils, and clearing lands impacted local plants and animals.

Spanish villagers constructed dwellings at the upper ends of their fields, above the *acequias*, forming a settlement pattern resembling a string of beads, or *cordillera*. Often this occurred on the north slope of the river valley, to take advantage of solar radiation in the colder months.

Ejidos, or the common lands of grants, were the sources for wood (for building as well as fuel), building stone, and grasslands as summer forage for livestock. Hunting and gathering activities also occurred in the *ejidos*. Commonly hunted animals included deer, elk, and rabbits. Fuelwood, building stone and wood, medicinal plants, and edible plants were collected in these areas as well. The cycle of adverse impacts on biotic communities in these areas, which would greatly accelerate in the Territorial Period, was put into motion in the Spanish Colonial era.

After the Spanish-Comanche Peace of 1786 gave some respite to conflicts with nomadic Indians, the *ciboleros*, or buffalo hunters, who had adopted the annual fall hunting tradition of the Pueblos, increased their trips onto the eastern plains from the Middle Rio Grande Basin. An estimated 12,000 bison were harvested annually from this time into the first half of the 19th century. Combined with the market for buffalo robes created by Anglo traders after 1821, virtually all the buffalo were exterminated or driven from the eastern plains of New Mexico.

Limited mining in the Colonial Period by both Spaniards and Pueblos impacted local areas. The best known of these locales are the turquoise and lead mines in the Cerrillos area and north of the Sandia Mountains. Pinyon, juniper, and oak were cut for "smelting" fuelwood, mining timbers, and structures. Some local water pollution was generated by these mining activities.

During the Mexican Period, some of the effects of settlement and land use on the natural environment were recorded by both government and ecclesiastical officials. Overgrazing around old settlements and nearby valley and upland rangelands, begun in the Colonial Period, intensified. Some of the choice grazing areas in the region were cienegas and other wetlands, which were heavily impacted by livestock during this period. Livestock trails turned into linear arroyos, and silt-laden run-off increased.

Padre Martinez of Taos complained about the effect of both hunting and trapping on the wild animal populations of the traditional use areas of Taos Pueblo and the Jicarilla Apaches. Trappers, including some Mexican and newly arrived Franco- and Anglo-Americans, began intensively harvesting beaver pelts in the rivers and streams throughout northern, central, and southwestern New Mexico in the early 1820s. Beaver populations were quickly decimated overall in the region and even extirpated in some streams; in response, the Mexican government issued a moratorium on trapping in 1838.

Anglo-American traders, such as the Bent brothers, directly contributed to the decimation of fur animals across southern Colorado and northern New Mexico. American Indians, especially nomadic groups such as the Plains Indians, eagerly hunted and trapped to obtain goods offered by traders. With this focus on hide harvesting and processing, day-to-day and season-to-season elements of their way of life were disrupted.

Around the gold, silver, and copper mines in the Ortiz, Sandia, and Jemez mountains, the land was denuded of trees by wood cutters to make support timbers and charcoal for the mines. The relatively sharp increase in livestock numbers, especially sheep, during this period was due to the growth in mining markets to the south in Mexico (and later California). This intensive and widespread grazing resulted in loss of vegetative cover in various locales. Grass shortages on Spanish land grants led, in part, to encroachment of Mexican flocks and herds on Pueblo crop and range lands, erosion of hillsides, and the siltation of river and stream beds.

RESOURCE USE IN THE TERRITORIAL PERIOD

The arrival of relatively large numbers of Anglo-American military personnel, ranchers, and settlers, beginning in 1846, had a significant impact on New Mexico's environment. Although these groups did not introduce many new domesticated plants and animals, their implementation of more intensive land-use patterns, coupled with a new technology, increasingly contributed to the ongoing erosion of hillsides and siltation of river beds, as well as the extermination or reduction of several animal species. Military forts, mining camps, and railroad construction made heavy use of natural resources such as trees for both building and fuel supplies, harvesting of native grasses for "hay," and killing local game, such as grizzly bears, black bears, bighorn sheep, deer, elk, pronghorn antelope, and several species of birds for food and sport. Major stream pollution occurred at many mining sites, killing associated fauna and flora and poisoning water supplies. Many of these mining sites were abandoned, leaving open pits and shafts and toxic spoil deposits. Air quality was also negatively impacted by the railroad and mine smelters. These technologies were the first serious sources of noise pollution in the Territorial Period.

Early saw mills in or near such settlements as Santa Fe, Taos, and Albuquerque resulted in the first extensive clearcutting of forests. As a result, soil erosion was accelerated at these locales, and habitat loss contributed to the reduction of game animal populations.

The growth of the range cattle industry in New Mexico after the Civil War led to increased grazing of grasslands. Cattlemen employed a strategy of securing sections of the public domain having water sources to control larger areas for grazing. During the mid-1880s, a severe winter followed by a drought and another cold winter led to the massive reduction in livestock numbers and ultimately the range cattle industry. After the introduction of barbed wire and windmills, open range gave way to fenced pastures. Overgrazing along streams, at other wetland sites, and at windmill tanks occurred.

Anglo ranchers, unlike Native and Hispano Americans, suppressed range fires. This action, combined with overgrazing, caused native plant species such as broomweed, cholla, prickly pear cactus, sagebrushes, and less desirable grasses to spread and increase on pristine grasslands. The exotic Russian thistle and several introduced grasses also prolifer-

ated. Consequently, the carrying capacity of New Mexico's rangelands was reduced significantly during this period.

Intensified irrigation farming impacted stream hydrology and increased salinization and waterlogging of soils in the Middle Rio Grande Basin in the late 19th and early 20th centuries. This resulted in the loss of thousands of acres of agricultural land by the early Statehood Period and was a factor leading to the creation of the Middle Rio Grande Conservancy District in 1926. The drainage systems, dams and reservoirs, and levees which followed produced a new set of environmental problems, such as a rapid drop in shallow ground waters, flooding of habitat, and diminution of native *bosques*, all of which have only recently begun to be addressed.

Toward the end of the 19th century, homesteaders claimed and farmed much of the public domain, with population growth centered in central and eastern New Mexico. They plowed virgin shortgrass plains and dry-farmed crops such as broom corn, milo, maize, and pinto beans. These newcomers also raised livestock on their small claims, which generally contributed to overgrazing, and in some areas these land-use practices contributed to the environmental impacts which resulted in the Dust Bowl of the 1930s.

Railroads were both influenced by and, in turn, affected the environment in several adverse ways. Topography, in particular the requirement for low grades and the need for water for steam engines every ten miles, played a significant role in the choice of route. Rail routes generally followed stream valleys, causing damage to riparian biotic communities and polluting streams. Train engines were often the cause of range or forest fires (ignited by ashes and sparks) and other environmental changes.

Railroad construction also impacted forests (mainly for ties and locomotive fuel) and streams (siltation from exposed soils). Animal populations were subjected to additional pressures as commercial hunters harvested meat animals to feed the railroad construction crews. Deer, pronghorn antelope, and elk were the main game species; elk populations were eradicated in some areas.

Hot springs, long visited by both American Indians and Hispanics, were used for medicinal and recreational purposes; often Anglo promoters built hotels or spas near the springs, and some lobbied successfully for a railroad connection. Cold water springs were tapped for irrigation, domestic use, or livestock water. Many springs were impacted, both in terms of water quality and quantity. Some no longer flow today due to intensive mining of water and periodic droughts.

Commercial, subsistence, and sport hunters during the late 19th and early 20th centuries had sharply reduced or exterminated populations of native game animals such as pronghorn antelope, elk, bighorn sheep, and Rio Grande turkey. This over harvesting resulted from the lack of regulatory game laws, more efficient firearms and ammunition, an increasing number of hunters, and a philosophy that there would always be wild animals of any kind to hunt. In response, the New Mexico Game and Fish Department was created by the territorial legislature in 1904. Both state and federal regulatory laws were subsequently passed. These regulatory actions supported by hunters went on to help restore populations of many native game species.

RESOURCE USE IN THE STATEHOOD PERIOD

During the preceding period farmers, ranchers, and the general hunter population had killed large numbers of predators, notably the grizzly bear, gray wolf, Mexican wolf, coyote, and mountain lion. Beginning in the second decade of this century state and federal agencies joined in an effort to exterminate the grizzly and the two wolf sub-species. By the 1930s, they had almost eradicated two of the three; a few Mexican wolves survived in extreme southwestern New Mexico until the 1950s.

Under the management of federal and state agencies, several animal species (bighorn sheep, elk, and wild turkey) were reintroduced to wildlife preserves established at various locations in the 1920s through 1940s. At a later time the Game and Fish Department introduced the ibex, barbary sheep, and oryx. Some wildlife specialists view these animals as detrimental to indigenous species such as the bighorn sheep.

Other exotic animal species and many plants were introduced and naturalized during this period and became, or have become, ecological-economical problems by the 1950s. These species were either inadvertently or purposefully introduced. Some of the introduced animals included the Norway rat, house mouse, burros, horses, and several species of amphibians and fish. The most troublesome plants are tree-of-heaven, Russian olive, Russian thistle (tumbleweed), Siberian elm, and tamarisk.

During the New Deal, a massive effort at reforestation and environmental conservation was initiated

through several programs, most notably the Civilian Conservation Corps (CCC), the Grazing Service, and the Soil Conservation Service. The Grazing Service was merged with the General Land Office and became the Bureau of Land Management in 1934.

With the passage of the Antiquities Act of 1906, a number of outstanding natural and archeological areas were set aside for preservation management by the National Park Service and the Forest Service. Also, the state legislature created the New Mexico Parks Commission, later renamed the State Park and Recreation Commission, and some "natural" areas were established under its administration.

In the last three decades several federal and state agencies, as well as private organizations, have assumed responsibilities for restoring and managing indigenous ecocultural resources through bioremediation, restoration, and/or preservation. Progress has been made, but much remains to be done to restore overgrazed rangelands and riparian areas, to stop leaching of toxic materials from historic mining sites, to arrest soil erosion in intensively grazed and logged locations, to increase populations of rare and endangered plants and animals, to foster continuance of traditional ecocultures, and to improve water quality in all of these areas. The burgeoning population and attendant development contribute to and exacerbate the adverse environmental impacts of the past and produce new problems for all New Mexicans today.

LITERATURE REVIEW

Only those sources, published and unpublished, that specifically focus on the environmental history of the Middle Rio Grande Basin are briefly reviewed here. Generally, little investigation has been directed at the interrelationship of humans and their biological-physical environment. Most striking is the lack of a reconstruction of the climatic regime and its impact during the historic period. Although fire suppression is usually regarded as adversely affecting species composition, in fact the relationship of natural and incendiary fires to biotic communities is not sufficiently understood. Some recent fire history studies, such as those by Baisan (1993) and Foxx (1981) for the Sandia and Manzano mountains do, however, provide starting points and direction.

No serious attempts have been made to identify and document all introduced plant species into the region and their impact. There are, however, many

studies on the environmental history and ecological impact of tamarisk (Campbell and Dick-Peddie 1964; Crawford et al. 1993; Harris 1966; Robinson 1958, 1965).

General histories of human populations and the river are found in: Baker et al. (1988); Calvin (1934); Gilpin (1949); Kelley (1952), Sargeant (1987), Sargeant and Davis (1986), Schroeder (1968, 1972, 1979), Tucker (1992), and Welsh (1985). Eastman et al. (1971) have published a paper on attitudes toward land, and Oberg (1940) focused on cultural factors and land-use planning.

Finally, there are a number of archival guides and references for the study region: Beers (1979), Bureau of Land Management (1979), Burger (1990), Chavez (1957), Colley (1972), Gallacher (1986), Jackson and Teeples (1978), Jenkins, Simmons and Martinez (1967), Jenkins (1968, 1969, 1970), National Archives and Records Service (1973), O'Connor (1989), Rex (1991), and Tyler (1984).

Data on human demography in the historic period for central and northern New Mexico include:
Pueblo: Dozier (1983), Earls (1992), Simmons (1979a and b), Thornton (1987);
Spanish: Bailey and Haulman (1977), Carroll and Haggard (1942), Jones (1979), Nostrand (1992), Olmstead (1975, 1981) Tainter and Levine (1987); and
Anglo: U.S. Census Bureau (1850–1990).

Overviews of the late prehistoric-historic Pueblos in the basin, which address settlement patterns and land-water use, are found in Abbink and Stein (1977), Cordell (1979), and Riley (1987). Hodges (1938) reported on irrigation water supply for each Pueblo. DuMars et al. (1984) have published an in-depth study of Pueblo water rights. Ford (1972) has done a detailed view on the regulatory role of ritual systems in counteracting environmental crises and stressful periods of Eastern Pueblos and their environment. Studies on the environmental adaptations of Zia and Tewa Pueblos also have been published (Euler 1954; Ford 1972, 1987). An early 20th-century study of the relationship of Rio Grande Pueblos and valley physiography was conducted by Hewett et al. (1913). Hewett and Dutton (1945) published a general study of Pueblos and their physical surroundings. Zubrow (1974) produced a published study of the interrelationships of population, climate, and contact with Euroamericans on the historic Pueblos. His work, including construction of a deductive model, found that from post–1800 to the recent past the Pueblos

experienced some resource-related problems due to Spanish and Anglo encroachment and resource usage. The historical data used by Zubrow, although limited, corroborate Puebloan subsistence difficulties during this period.

Many studies on the interrelationships of Hispanic and Anglo land-water use and management from 1846 to the recent past have been published. Briggs and Van Ness (1987), deBuys (1985), Harper et al. (1943), and Hernandez et al. (1971) have addressed Hispanic land grantees and their resources. Meyer (1984) has published an in-depth overview of Hispanic use of water, focusing on community use, water rights, irrigation, and litigation. Other settlement pattern-resource use studies have been conducted by Kelley (1955), Maes and Fisher (1937), Moir et al. (1971), Simmons (1972, 1974), Sunseri (1979), Tainter and Levine (1987), and Westphall (1983). Historic management studies have been produced by Rothman (1992), among others.

Many reports and papers on water control and management exist for the basin. Some of the general ones, including treatment of problems and issues, are Albuquerque National Trust and Savings Bank (1936), Burkholder (1928), Clark (1987), Dortignac (1956, 1963), Follansbee and Dean (1915), Forsling (1950), Hay (1972), Linford (1956), Nickerson (1945), and Wortman (1971). Follett (1898) and Yeo (1910) wrote a report on the conditions of water control systems in the Middle Rio Grande with emphasis on water use facilities and irrigation. Welsh (1985) has published a paper on management of the Middle Rio Grande Basin water resources by the U.S. Corps of Engineers.

The earliest written descriptions of the Middle Rio Grande Basin, albeit general, were, of course, the Spanish, beginning with Coronado in 1540 and others in the late 1500s (Hammond and Rey 1940, 1966). Other early colonial (to 1680) observers include Vargas (Bailey 1940; Kessell and Hendricks 1992), Benavides (1965), and Hodge et al. (1945). Observations on the general environment from Spaniards in the 18th and early 19th centuries are found in Adams (1954), Adams and Chavez (1956), Carroll and Haggard (1942), Hackett (1937), Kessell (1992), and Simmons (1982).

There are numerous journals and diaries of Anglo explorers, settlers, military personnel (Abert 1962; Bell 1965; Calvin 1968; Davis 1982; Frazer 1981; Gregg 1966, Pattie 1966; Wislizenus 1969) and state and federal resource investigators (Bailey 1913; Bryan 1927,

1928; Burkholder, 1928; Cockerill et al. 1939; Cooperrider and Hendricks 1937; Follansbee and Dean 1915; Hodges 1938; Ligon 1927; Maes and Fisher 1937; Matthew 1897; Middle Rio grande Conservancy District 1928; Poore 1893; Pynch et al. 1911; and Wooton 1908) describing landscape, water, fauna, flora, etc., dating from the mid and late 1800s and the early 1900s. These provide the first relatively detailed descriptions of fauna and flora, floods, grazing, farming, and mining in the region. Some include the first illustrations, drawings, lithographs, and photographs of fauna, flora, farming activity, etc. The first detailed maps of the region appear with early U.S. Army reports. Scurlock (1988b, 1988c, 1993a, 1993b) has used many of these sources in recent publications.

A major study of irrigation system development from the late prehistoric period to 1945 in the Rio Grande Valley was prepared by Wozniak (1987) for the Historic Preservation Division. Evidence is presented to show that irrigation was a major influence in the "development and character of New Mexico society in the Rio Grande Valley from 1700 to the early 1900s." Wozniak's report also deals with government reclamation projects and related socioeconomic changes since the early 1900s. Simmons (1972) has addressed Spanish irrigation practices for the basin. A major unpublished study on water use and development in New Mexico after 1846 was written by Linford (1956), including discussion of federal and state water projects.

A voluminous work on historic water use in the state, primarily on the sociopolitical and management aspects, was authored by Ira Clark (1987). R.E. Clark (1958) has produced a paper on water law and traditional Pueblo and Hispanic communities. Reports on water statistics, irrigation, drainage, etc., have been published by Burkholder (1928), Follett (1898), Middle Rio Grande Conservancy District (1928), Poore (1893), Pynch (1911), Welsh (1985, 1987), and Yeo (1910).

Fritts (1965), Gabin and Lesperance (1977), Scurlock (1994), Swan (1977), Taft (1980), Tuan et al. (1973), and Zubrow (1974) have all published reports on historic climate and human interrelationships with climatic events in central New Mexico. Zimmerman Library has many volumes of published U.S. Weather Bureau records from the late 1800s for the region.

River hydrology and morphology, including floods, are found in Bryan (1927, 1928), Bowen and Sacca (1971), Carter (1953), Calkins (1937), Crawford

et al. (1993), Sargeant (1987), Sargeant and Davis (1986), and Scurlock (1993b). Land grant records, early government documents, and early maps, photographs, aerial photos, etc. contain untapped information on these topics.

Historic and recent flora are treated in Allen (1984), Bailey (1913), Brown (1982), Cooper (1960), Crawford et al. (1993), Dick-Peddie (1993), Freehling (1982), Gross and Dick-Peddie (1979), Harris (1966), Hink and Ohmart (1984), Manthey (1977), Leopold (1951), Minckley and Rinne (1985), Robinson (1958), Scurlock (1988a, 1993a and b), Van Cleave (1935), Watson (1912), and Wislizenus (1969). Data on the use of indigenous plants by the Pueblos are found in Hewett and Dutton (1945). Spanish use of native woods is found in Jones (1932).

The only historical vegetative studies of the research region using paired photographs have been done by Klett et al. (1984) and Sallach (1986). There are, however, several studies of the surrounding region that will serve as models for paired photo research in the Middle Rio Grande Basin (Athearn 1990; Baars and Buchanan 1994; Bureau of Land Management 1979; Humphrey 1987; Rogers 1982, 1984; Veblen and Lorenz 1991; Zaidliez 1979). A major drawback in using historic photographs is that even the earliest images date after major vegetation changes caused primarily by intensive grazing and fire suppression had occurred.

Faunal studies of protohistoric sites in the basin contain data on vertebrate species present and their usages by American Indians. A few of the more important ones are Akins (1987), Crawford et al. (1993), Marchiando (1977), Sublette et al. (1990), and Young (1980). For the historical period, there are data on mammals recorded by Allen (1903), Bailey (1971), Carroll and Haggard (1942), Gregg (1966), Findley et al. (1975), Ligon (1927), Linford (1967), Matthew (1897), Moore (1986), Pattie (1966), and Warren (1942). Historical data on birds are found in reports by Abert (1962), Bailey (1928), Freehling (1982), Henshaw (1875), Hubbard (1978), and Ligon (1927, 1961). The works of Koster (1957) and Sublette et al. (1990) contain historical data on Rio Grande fish, as does Crawford et al. (1993).

Livestock numbers and grazing are covered by Baxter (1987), Baydo (1970), Carlson (1969), deBuys (1985), Denevan (1967), Eastman and Gray (1987), Rothman (1989), Rowley (1985), Smith (1953), and Wooton (1908). A survey of ranches and farms is found in Cockerill (1959) and Cockerill et al. (1939).

Siltation and erosion problems related to intensive grazing are discussed in Bryan (1927), Cooke and Reeves (1976), Denevan (1967), Dortignac (1956, 1963), Harper et al. (1943), Nickerson (1945), Pynch et al. (1911), Wooton (1908), and Yeo (1910).

This investigator (Scurlock 1993b) has written an overview of environmental history of the Rio Abajo (the Rio Grande Basin from La Bajada-Cochiti to San Marcial) for the Biological Interagency Team of the Middle Rio Grande Bosque Management Project (Crawford et al. 1993). Scurlock (1988c; 1993c) has also published papers on the historic environment of the Camino Real and changes in the Middle Rio Grande bosque, and co-authored two regional studies of northwest and southwest New Mexico which included some environmental history (Scurlock 1988a; 1991). A monograph manuscript of an overview on the environmental history of pinyon-juniper in the Southwest was recently completed and is being reviewed for possible publication (Scurlock 1993a).

RESEARCH NEEDS, STRATEGIES, AND GOALS

Extant and new historical and archeological data may provide the environmental context and baselines to address the following problems:

1. Need a better understanding of the long-term responses of ecosystem components—soils, nutrients, water, flora, and mycorrhizae—to past and present perturbations caused by climate change, fire, herbivore grazing, irrigation and dry farming, logging, fuelwood harvesting, and other human activities. Secondarily, these historical data will shed light on how such responses influence ecosystem dynamics, stability, and productivity of upland communities.

2. Need better understanding of upland biotic communities, including the historic, spatial, and temporal interrelationships with fluvial ecosystems.

3. Need better understanding of how humans adapted to changing environmental conditions, both "natural" and human-induced, and to determine when and how these perturbations occurred and what the consequences were. These data will be used to determine sustainability of traditional land-water activities today and more importantly in the future.

4. Need better understanding of the evolution of basin ecosystems in terms of human interactions related to cultural elements—"world view," use

of resources, and economics—and how these land-water use histories relate to conflicts between specific groups. Collected data for use in planning future management for sustainability of resources as related to differing group views will afford a more sound basis for such decision-making.

To assist in addressing these four major problems, the following research sub-goals will be explored:

a. Reconstruction of historic climatic regimes for the overall basin and specific locales.
b. Reconstruction of morphological dynamics of the Rio Grande and major tributaries related to floods and human-use management.
c. Reconstruction of water flow data and interrelationships with climatic fluctuations and human use.
d. Reconstruction of historic fire occurrence spatially and temporally.
e. Reconstruction of human-induced changes in ecosystem components.
f. Reconstruction of overall and site-specific spatial-temporal grazing history and impacts.
g. Reconstruction of spatial-temporal overall and site-specific farming history.
h. Reconstruction of changes in plant and animal communities and particular species populations over time related to human use, climatic change, and exotic species introductions.
i. Reconstruction of human responses to these changes.
j. Reconstruction of adaptations of various groups to the same subregional, or area, environments.
k. Examination of the similarities and/or differences in Pueblo agricultural techniques and production along streams such as the Rio Grande and Las Huertas Creek.
l. Delineation of eco-cultural areas based on spatial-temporal distributions of specific groups related to identifiable ecosystems.
m. Comparisons between the exploitation strategies of different populations, e.g. Hispano and Anglo livestock raisers utilizing the same resource area, as well as the impacts of utilization.
n. Construction of spatial-temporal models of ecosystems, including humans as a major factor in the dynamics and change of these systems (i.e., the Santa Fe River, Rio Puerco, Las Huertas and Tijeras Arroyos, and sections of the Rio Grande, such as the Bosque del Apache and Isleta Pueblo areas [including the wetlands]).

Models

The following four spatial and temporal models of the Middle Rio Grande Valley historical ecosystem will be tested using data collected and analyzed. The resulting revised models will provide a context for better bioremediation, evaluation of sustainability of land-use practices, and development of appropriate management programs.

Model I: Middle Rio Grande Basin in 16th century
Historic river hydrology-morphology:
- Perennial flows; relatively deeper, larger volume of water.
- Transport of relatively low sediment load.
- Braided, slightly sinuous, aggrading, shifting sand substrate.
- Overbank flooding with two peaks—April to early June (snowpack melt, highest water flow); August to September (intense precipitation on watershed).
- Shifting river channel and movement across floodplain (avulsion).
- Island and sand bar formation-destruction.

River-floodplain biological-ecocultural components:
- Grass meadows, *cienegas*, *charcos* (ponds or small lakes).
- Varied, changing age structures of cottonwood-willow stands.
- Wildlife diverse and relatively abundant.
- Some life forms present—wolf, river otter, mink, whooping crane, Rio Grande turkey, shovelnose sturgeon, and 11 other fish species (now extinct).
- Limited Pueblo diversion of river for irrigation.
- Ca. 30,000 acres of floodplain under Pueblo cultivation.

Model II: Middle Rio Grande Basin in 18th to mid 19th centuries
Historic river hydrology-morphology:
- Somewhat decreased stream flows.
- Flow widening and becoming more shallow.
- Braided, sinuous, increasing aggradation.
- Overbank flooding and avulsion more frequent and severe.
- Increased frequency of channel shifting resulting from intense floods.

- River banks and islands less stable.
- Increasing sediment load due to various land-use practices.

River-floodplain biological-ecocultural components:
- More fragmented and reduced stands of cotton-wood-willow communities due to intense floods.
- Increased alkalinity and waterlogging of soils.
- Increased numbers of grass meadows, *cienegas*, and *charcos*.
- Less stable and decreasing populations of faunal communities.
- Increase to ca. 100,000 acres under cultivation by Pueblos and Hispanos.

Model III: Middle Rio Grande Basin in late 19th century to early 20th century

Historic river hydrology-morphology:
- Continued decrease in flows, increase in sediment load, and aggradation of river.
- Flood frequency and intensity increased.
- Some scouring and incising of river channel due to floods.
- Increased soil alkalinity and waterlogging.
- Rising water table, then lowering water table.

River-floodplain biological-ecocultural components:
- Highest (?) number of wetlands and associated plant communities, then severe reduction to lowest in historic period.
- Cultivated acreage increased to perhaps 125,000 acres by Euroamericans and Pueblos, then decreased to 35,000 acres due to environmental changes.
- Increased alkalinity and waterlogging of valley soils.
- A number of wildlife species extirpated.
- Less stability and severe decrease in wildlife populations.

Model IV: Middle Rio Grande Basin in mid to late 20th century

Historic river hydrology-morphology:
- Decrease in sediment load and aggradation of river.
- Flood frequency and intensity decreased dramatically due to construction of major dams.
- Continuing lowering of water table.
- Channel straightened and bermed, channel shifts virtually halted, and banks stabilized.

River-floodplain biological-ecocultural components:
- Cultivated acreage increased to 58,000 acres.
- Floodways cleared and channel modified.
- Continued reduction of wetlands.
- Construction of several ponds.
- Some wildlife populations increased.
- A few exotic plant and fish species introduced.
- A few wildlife species extirpated.

BENEFICIARIES OF RESEARCH

In addition to potential data uses by various public ecocultural resource management personnel and agencies, this study would be useful to a myriad of other basin communities and organizations: Pueblos, Hispanic land grant associations, the Middle Rio Grande Conservancy District, universities and schools, environmental groups, and private firms and individuals involved in Middle Rio Grande Basin research. Potential uses include evaluating current resource use and management, planning for bioremediation of specific locales or areas, evaluating sustainability of current land-use practices, locating field trip-study area sites, and identifying critical environmental issues.

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Chapter 3
Human Ecology and Ethnology

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HISTORIC PERIODS	
Spanish Colonial	A.D. 1540-1821
Mexican	A.D. 1821-1846
Territorial	A.D. 1846-1912
Statehood	A.D. 1912-present

INTRODUCTION

The relationship of humans with Middle Rio Grande Basin ecosystems is complex. In historic times, humans had a critical role in the evolution of environmental landscapes and ecosystems throughout the Middle Rio Grande Basin. The relationship of humans with the land is based on and regulated by resource availability, environmental conditions, levels of technological knowledge, political and socioeconomic structures, and cultural values regarding the use of land and water. The general and specific impacts of historic human activities on Middle Rio Grande Basin ecosystems have only recently become a focus of researchers.

Three groups utilized the natural resources of the Middle Rio Grande Basin during historic times: American Indian, Hispanic, and Anglo-American. Each group had its own cultural values regarding the land and water, which influenced and regulated exploitation of the Middle Rio Grande Basin. Most studies of cultural values regarding the land and water tend to be simplistic. Studies of cultural values that do not romanticize certain groups and demonize others are a fundamental foundation for any systematic and integrated understanding of the relationship between humans and Middle Rio Grande Basin ecosystems.

Though the general outline of the political, socioeconomic, and technological history of the Middle Rio Grande Basin is available, exploration of the specific historical relationships between human impacts and the Basin's ecosystems has barely begun. Stud-ies similar to that of de Buys (1985) on the Sangre de Cristos would contribute significantly to our understanding of the human role, human impacts, and human relationships with the land, water, and other resources of the Middle Rio Grande Basin during historic times. Farming, ranching, hunting, mining, logging, and other human activities have significantly affected Basin ecosystems in the last 450 years.

Most of the research on resource availability and its role in regulating human impacts on the Basin has focused on the 20th century. Some work has been done on the second half of the 19th century but very little on the 300 years of the historic era preceding the Treaty of Guadalupe Hidalgo in 1848. This chapter summarizes the available historic information.

OVERVIEW OF HUMAN IMPACTS

The principal factor influencing the human relationship with Basin ecosystems is the location and availability of water. Because the Basin is located in a semi-arid environment, the quality, quantity, and accessibility of water have always profoundly and decisively influenced human settlement in and exploitation of the Middle Rio Grande Basin.

Fluctuations and broad scale changes of the Basin's climate have influenced human activities such as hunting, gathering, farming, livestock raising, travel, and warfare. Drought and erratic precipitation patterns have been important limiting factors in the extent and intensity of human exploitations of Middle Rio Grande Basin ecosystems. The majority of the historic period in the Basin fell within the "Little Ice Age," which affected New Mexico from the mid–15th to the mid–19th century.

Though the broad outlines of the climatic history of the Middle Rio Grande Basin are available, several factors constrict our present understanding. While tree-ring data provide some information on climatic fluctuations and long-term climatic patterns, the amount of climatic data for the period before 1850

is very limited. For the second half of the 19th century and the early 20th century, substantial amounts of scientifically recorded climatic data exist but have not been systematically studied. Climatic records and studies for the 20th century are in general voluminous and well known.

The role of European introduced diseases such as smallpox and their impact on local populations have been relatively well documented in New Mexico as a whole. The interrelationship of disease and politico-ideological motivated concentrations of early historic Puebloan populations by Spanish colonial authorities are well known if not systematically studied. However, the devastating epidemics of the 1780s profoundly altered the population dynamics and relationships in all of settled New Mexico. The beginnings of the intermixing of Hispanic and Puebloan populations on the rich agricultural lands of the Pueblo land grants are to be found in the aftermath of the 1780s epidemics. The historic epidemics of the 17th century and the late 18th century coincided with periods of severe, extended drought and catastrophic periods of warfare that interrupted and fragmented Puebloan religious life and socioeconomic systems.

LAND UTILIZATION IN THE SPANISH COLONIAL AND MEXICAN PERIODS

When the Spanish settled in New Mexico at the end of the 16th century, they brought new technologies and new domesticated plants and animals. These introduced species along with the new political, socioeconomic, and ideological structures imposed by the Spanish significantly altered not only Puebloan but also Navajo and Apache diets, economic structures, and land use patterns. Puebloan and nomadic Indian land-use patterns prior to Spanish settlement can be reconstructed through archeological research and from the records of Spanish *entradas* (Hammond and Rey 1928, 1940, 1966; Hackett 1937).

Given the vital relationship between water and settlement in all semi-arid environments of the North American West, including New Mexico, it is not surprising that the Spanish of the 17th century, but particularly those of the 18th and 19th centuries, gravitated into the Rio Grande Valley and its tributaries. Spanish settlement depended upon irrigation agriculture for its economic base and, therefore, for its survival. Extensive development and expansion of irrigation systems accompanied the introduction of community land grants in the Rio Grande Valley af-

ter the Reconquest of 1693–1697. What is surprising about irrigation agriculture is its relative rarity among the Pueblo Indians before Spanish settlement in the late 16th century. Spanish missionaries and encomenderos imposed an irreversible reliance on irrigation agriculture upon the Pueblo Indians during the 17th century. This combined socioeconomic and technological change irretrievably undermined and altered traditional Puebloan subsistence systems, land use patterns, and ways of life. In addition to a plethora of domestic livestock (sheep, goats, cattle, horses, mules, hogs, chickens, etc.) and new cultigens (wheat, barley, oats, onions, lettuce, watermelon, fruit trees, etc.) the Spanish also introduced native Mexican Indian crops such as tomatoes, chiles, cultivated tobacco, and new varieties of corn and beans. These introduced species along with the introduction of metal tools such as axes, metal tipped plows, and weapons had a significant and sometimes adverse impact on native flora, fauna, and soils. The role of metal tools and their impact on ecosystems before the 19th century should not be exaggerated since metal tools were generally in short, even critically short, supply throughout the 17th and 18th centuries in New Mexico.

With the colonization of New Mexico by the Spaniards, irrigation entered into a new era in the Rio Grande Valley. The introduction of new crops such as wheat, which required irrigation to produce harvests in semiarid New Mexico, encouraged the development and/or expansion of Pueblo Indian irrigation. The Spaniards insisted that the Indians grow these crops, particularly wheat, so that the Spaniards could obtain their customary food stuffs even in New Mexico. At least part of the tribute that the Spanish regime required from the Puebloans was exacted in the form of wheat, so the Indians had to irrigate to meet these demands. Other tribute demands for food stuffs would also push the Puebloans toward intensive (i.e., irrigation) agriculture during the 17th century, with considerable disruptive consequences for both Puebloan and Spanish society in New Mexico. The Spanish reliance on Puebloan agricultural labor was due not only to politics, economics, and demographics, but also to cultural factors. In the 17th century, Spanish colonists tended to reject agriculture as a fitting occupation. Even herding was seen as being fit for native Puebloan but not Spanish labor.

During the 17th century, the Spanish settlers in New Mexico survived on tribute in food and labor collected from the Puebloans under the *encomienda*

and *repartimiento* systems (Scholes 1937, 1942). (*Encomienda* is a grant of Indians who are entrusted to the care of a Spaniard, in return for which the Spaniard provides military services to the government. *Repartimiento* is a grant to a Spaniard of the right to exact certain labor services from an Indian village or villages.) The Spanish missions or *reducciones* concentrated Puebloan populations into a much smaller number of pueblos than had been occupied before the arrival of the Spaniards. The *reducciones* were established for religious, political, economic, and military reasons and served to enhance Spanish control and supervision over the native Indian populations (John 1975: 65–67; Scholes 1937, 1940). Concentration of the heretofore scattered Puebloan settlements also enabled both ecclesiastical and secular authorities to exploit the Indian labor force more effectively and to levy tribute. Tribute demands and the *reducciones* themselves often drove the Puebloans to escape Spanish control by withdrawing into the mountains or joining the nomadic Indian tribes (Hammond and Rey 1953: 659–692).

Throughout the 17th century the Spaniards steadily increased their demands for native labor and goods while the labor force was being progressively reduced by disease and warfare. Missionization appears to have produced the first of the major population declines that then continued as a result of epidemics and drought. Demands for native labor by both the encomenderos and the friars along with the increasing European population placed strong pressures on the Puebloans to improve their productivity to supply food for both groups. These pressures led to an increased and in some cases a virtually exclusive reliance on irrigation agriculture. The Spaniards encouraged the development of Puebloan irrigation farming not only to ensure the increased productivity that would supply them with food and to obtain introduced European crops, but also because irrigation agriculture made possible the concentration of Puebloan populations in the *reducciones*. The friars thus intended both to increase Puebloan productivity and to maintain a newly imposed sedentism among the New Mexico pueblos. Dry farming was replaced by more intensive agricultural strategies involving fields irrigated by artificial diversions of water through ditches. At the same time hunting virtually disappeared, to be replaced by livestock herding. The gathering of wild plants and plant products declined as the Puebloans were tied to their irrigated fields in their efforts to meet the demands of the colonists and missionaries.

Agricultural intensification through irrigation demanded much labor, and the requirements of the system were difficult to meet owing to the decline in Indian populations. Such intensification was necessary, however, if the alimentary demands of the friars and encomenderos and the simultaneous demands for other goods and services were to be met. Contrary to Ellis's (1970) contention that the Spaniards found irrigation widespread and flourishing in the Rio Grande Valley, it was the institution of the *reducciones* that produced a rapid change in the Puebloan subsistence system from expansive to intensive agriculture. This increased and heretofore unnecessary dependence on agriculture led to a decrease in hunting, gathering, and trade in subsistence goods with the nomadic tribes. Mineral deposits, although present in several areas of New Mexico, were insignificant and unexploited in the 17th century. Apart from an erratic pinyon crop, and the relatively unimportant collection of wild animal skins and cotton textiles, there were virtually no exploitable natural resources that were not already available in quantity in the mining districts of Chihuahua, New Mexico's only potential market.

Conditions began to deteriorate seriously in New Mexico in the third quarter of the 17th century. In 1659, the first major region-wide famine occurred (Hackett 1937: 272); between 1666 and 1668, and in 1670 and 1671, famine once again struck the New Mexican pueblos (Hackett 1937: 302). In the early 1670s the suffering of the Puebloans was exacerbated by disease and the onset of devastating Apache raids (John 1975: 92–95).

Economic exploitation, religious persecution, and the failure of the Spaniards to protect the Puebloans from nomadic raiders culminated in the Pueblo Revolt of 1680 (Hackett 1942: 1: 1–82; John 1975: 96–97). After decimating the Spanish settlements and driving the remaining settlers from the northern Rio Grande Valley, the Puebloans shed Spanish religion and culture but retained Spanish crops and technology, both civilian and military (Hackett 1942: 1: 12–18, 1942: 2: 235). The continuing legacy of Spanish colonization could be seen in the residual importance of irrigation agriculture. Once the Spaniards were gone, the Pueblos quickly broke up into warring factions.

Puebloan factionalism and calculated economic warfare ultimately enabled Diego de Vargas to reduce the Pueblos once again to Spanish rule between 1692 and 1694 (Espinosa 1942: 85–208). Only Vargas himself was authorized to have an *encomienda* after

the Reconquest; all other Spanish settlers were to support themselves by their own labors. Economic conditions, however, forced the newly returned Spaniards to rely upon a system of tribute in food and labor from the exhausted pueblos that, in its operations and efforts, resembled the discredited *encomienda* and *repartimiento* system. These exactions drove most of the Puebloans into a second revolt in 1696 (Espinosa 1942: 228–246). The Spaniards crushed the new revolt with the assistance of those pueblos that did not join the rebellion (Espinosa 1942: 296–303). After 1697, a new economic regime was established in New Mexico, one that centered on community land grants rather than *encomiendas*. Internecine warfare among the Puebloans during the Revolt and Reconquest led to the abandonment of many 17th century pueblos, particularly in the Middle Rio Grande Basin. These abandonments had a profound effect on 18th century resettlement and land-use patterns.

The century following the reconquest is crucial to an understanding of the cultural diversity of the Middle Rio Grande Basin. Throughout most of the 18th century, New Mexico was not an active participant in the developing colonial world system, of which it was an almost forgotten part. More significant were raids by and warfare with New Mexico's nomadic neighbors: the Navajos, the Apaches, the Utes, and the Comanches. The alternating periods of war and peace had a major impact on settlement patterns and resulted in periods of expansion followed by periods of settlement contractions and abandonments. Warfare among the nomadic Indians, the Spanish, and the Puebloans affected land uses in the Middle Rio Grande Basin until after the American Civil War.

The 18th century also witnessed the gradual compartmentalization of Puebloan culture and society. On the one hand, Puebloan communities needed to co-exist with the dominant Hispanic culture. On the other hand, there was the equally obvious desire to maintain individual Puebloan traditions and identity. Out of the 18th century, there developed the Puebloan and Spanish Colonial cultural traditions which are still evident on the landscapes of the Middle Rio Grande Basin. Both traditions had to co-operate and interact to survive in the semi-arid environment of New Mexico, and to defend themselves against attacks by the semi-nomadic Indian tribes that surrounded New Mexico.

With the reconquest of New Mexico, the Spaniards instituted a new settlement system that transformed the way they utilized the resources of New Mexico. Before the Pueblo Revolt the Spaniards had occupied New Mexico with a small number of settlers who held large tracts of land. These 17th century settlers grazed livestock and depended upon the Puebloans to produce surpluses of food as well as products such as woven goods, salt, and pinyon nuts. After the Reconquest, because a secure hold on New Mexico had a higher value than extraction of economic wealth, the Spanish government made grants of land (*mercedes*) to ensure the effective occupation of New Mexico by means of self-sufficient farming and herding communities.

In place of a small number of exploitive *encomiendas*, which had proved to be a political, military, and economic disaster, the Spanish authorities established an ever-expanding number of land grants on which the Hispanic settlers supported themselves through agriculture and stock-raising. In the early days after the Spanish reconquered New Mexico, a number of individual land grants were given to people who had been prominent in the Reconquest. Though given to individuals, these were not *encomiendas*; the recipients were expected to support themselves by their own endeavors and those of their extended families and servants. Indian labor was virtually unavailable owing to the catastrophic population decline of the late 17th century. This decline continued at a reduced level in the 18th century, while the non-Indian population steadily expanded. At the same time, the Spaniards were prohibited from exploiting what little Indian labor might have been available (Simmons 1969: 10–12). The Indian pueblos settled into a system of local self-sufficiency under the religious (but not economic) supervision of the mission friars (Adams and Chavez 1956). Most land grants in the 18th century were given to groups rather than individuals, to settle as many people as possible on the land and provide for defensible settlements (Simmons 1969; Westphal 1983: 3–23). New Mexico became a region of small, self-sufficient Puebloan and Hispanic communities, held together by fear of nomadic raids and by the necessities of mutual defense.

For a settlement to succeed, irrigable land was necessary (Ressler 1968: 10). The accessibility of water to cultivate bottomlands was a primary consideration in the grants of land by the Spanish government. Subsistence agriculture employing irrigation and livestock herding was the economic basis for these settlements. Consequently, land grants were made

primarily along the Rio Grande and the Rio Chama and their perennial tributaries. The irrigable lands on each grant were divided among the settlers, while the rest of the land was held in common for pasture and woodland (Westphal 1983: 3–23). While Spanish colonial ordinances required that settlements be compactly organized for defense, most New Mexico land grant settlements were straggly communities of dispersed ranchos (Simmons 1969: 12–20). Formal plazas were rare, despite the threat of Indian raids. Even the villas of Santa Fe, Santa Cruz, and Albuquerque were scattered over large areas so farmers could live near their irrigable fields (Simmons 1969: 10–12; Snow 1976: 47–48).

The development of irrigation systems for agriculture was a primary consideration in the foundation or resettlement of villas after the Reconquest. Two *acequias madres* (main ditches) that had existed at Santa Fe since approximately 1610 were rehabilitated after the resettlement in 1693 (Simmons 1972: 139). When the Spaniards resettled Santa Cruz de la Cañada in 1695, they dispossessed the Tanoan residents and took over their irrigation system (CPLC, Cases #110 and 194; SANM I: #882). At Albuquerque in 1706, one of the first tasks of the new settlers was the construction of *acequias* (Hackett 1937: 379; SANM II: #124).

It is true that an atmosphere of expediency surrounds the development of land grants and land grant settlements in 18th century New Mexico. On the other hand, the prohibition of *encomiendas*, combined with the government's expressed desire to have the province securely occupied by Hispanic settlers who could defend it, means that some thought had been given to the requirements for settlement.

The long-lot system that prevailed on most land grants was developed to accommodate community land grants and as a response to local conditions in the Rio Grande Valley of northern New Mexico. However, this system of property division did not resemble the Puebloan field systems of the 17th or 18th centuries. Long-lot farms developed as a means of growing introduced crops that required irrigation in a semiarid environment where both land and water resources were limited. The system assured settlers of maximum access to limited water resources and proved to be a practical and equitable method of partitioning irrigable lands among the large numbers of settlers required by military necessities. The resulting small subsistence farms never produced significant agricultural surpluses nor were they intended to do so. Colonial policy was not directed toward economic prosperity but toward the successful occupation of New Mexico, which the defense of New Spain was deemed to require (John 1975).

In the Rio Abajo, where Puebloan populations south of the confluence of the Rio Grande and Rio Jemez had virtually disappeared, arable land was more plentiful, particularly along the Rio Grande; extensive grazing lands were also available in the Middle Rio Grande Basin. Water, also, was more securely available and more manageable for irrigation purposes in the Rio Abajo than in the Rio Arriba, especially south of San Felipe Pueblo. The continual threat and often devastating impact of raids by nomadic Indians limited expansion, however, except in the Bernalillo and Albuquerque areas.

Little changed in the formalities of obtaining land grants under the Mexican regime, and the vicissitudes of settlement remained much the same as well. The total area given in land grants between 1821 and 1846, however, probably exceeded that granted during the preceding 125 years (Westphall 1983: 25–65). Most of these grants were outside the Rio Grande Valley and placed large areas of grazing land under the control of individuals in what can only be termed an orgy of deliberate fraud and rapacity by prominent New Mexicans, aided and abetted by Mexican government officials in New Mexico. This raid on the public domain had precedents in the grazing grants west of the Rio Puerco in the 1760s. The Mexican Period grants set the patterns for land use that would prevail in the Middle Rio Grande Basin throughout the 19th century and into the 20th. Trade with the Anglo-Americans, the incipient development of a livestock industry, and some mining began the gradual transformation of the economy of the Middle Rio Grande Basin and changes in land use patterns. These changes included both more extensive and intensive utilization of resources outside of the main valley.

In the northern Rio Abajo only one grant in the Rio Grande Valley was made during the Mexican Period. On November 17, 1840, the constitutional *alcalde*, Antonio Montoya, gave Salvador Barreras and his associates possession of the Tejon or Arquito tract that lay in the uplands to the east of the abandoned pueblo of Tunque (CPLC, Case #145). In the Albuquerque area the only grant dating to this period was made to Antonio Sandoval for the area of Las Laqunitas (U.S. Surveyor General 1855–1987, Case #154). By 1827 Sandoval occupied the area and had dug an *acequia* along the foothills south of Las Barelas.

On the Rio San Jose, Rafael Sanchez and other vecinos petitioned for land below the Pueblo of Laguna in 1829. Before he could give possession of the land, the constitutional *alcalde* of Laguna was required to investigate whether cultivation of this area would depend upon water already being used for irrigation by the Indians of Laguna and Acoma (SANM I: #1291).

In the southern Rio Abajo, an Antonio Sandoval (probably not the same one who acquired the Arquito grant near Albuquerque in 1827) petitioned Governor Armijo for land at Bosque del Apache, which he needed for grazing sheep but which he also intended to cultivate. On March 7, 1846, Sandoval was placed in possession of the Bosque del Apache grant by the *alcalde* of Socorro, Vicente Piño (U.S. Surveyor General, Case #35).

The arrangement of field systems and the nature of land ownership were very different among the Pueblos and in the Hispanic land grant communities. The Pueblo irrigation systems, however, were similar in engineering and organization to the Spanish ditches (Simmons 1972: 144).

Throughout the 18th century and first half of the 19th century, the Indian pueblos suffered from declining populations and had to compete with Hispanic settlers for arable land, and to a lesser extent for water. Unfortunately information regarding Puebloan irrigation systems is scarce and spotty, but enough can be derived from ecclesiastical reports to provide an adequate picture of Puebloan irrigation during the Spanish and Mexican Periods. The best and most extensive report on the Pueblo Indians was that of Fray Dominguez from the latter part of the 18th century, but other, less comprehensive reports also exist (Adams 1954; Adams and Chavez 1956; Morfi 1932).

LAND UTILIZATION IN THE TERRITORIAL AND STATEHOOD PERIODS

When the Americans occupied New Mexico in 1846, they found a largely agrarian society that was concentrated in the Rio Grande Valley and depended for its survival upon irrigation agriculture and raising livestock. Both Hispanic and Puebloan communities controlled and managed the irrigation systems that covered most of the irrigable lands along the mainstream of the Rio Grande and its tributaries.

Just prior to the annexation of New Mexico by the United States, Josiah Gregg visited the territory on several occasions during the 1830s. Gregg (1954: 104) noted the fertility of the bottomlands and the barrenness of the unirrigated uplands. New Mexican agriculture was primitive by American standards. The crude plows were used only on loose soils; most land was cultivated with the hoe alone (Gregg 1954: 107). Nearly all of the farms and settlements in New Mexico were located in valleys with perennial streams. In some valleys, crops were regularly stunted by the seasonal depletion of stream flows. One *acequia madre* was generally sufficient to convey water for the irrigation of an entire valley or the fields of one town or settlement (Gregg 1954: 107–108). Community ditches were most common; private ditches were relatively rare (Gregg 1954: 108). New Mexicans in the late Mexican Period grew mostly corn and wheat under a system of subsistence agriculture (Gregg 1954: 108). While the scope and extent of irrigation activities in the Rio Grande Valley had steadily expanded in the Spanish and Mexican Periods, the nature of irrigation agriculture had remained very much the same. Expansion of irrigation systems in the Rio Grande Valley was strictly a response to population growth. The primary focus on subsistence agriculture and livestock herding persisted in the Rio Grande Valley for some time after the American annexation of New Mexico under the Treaty of Guadalupe Hidalgo.

After the arrival of the railroads, irrigated acreage in the Middle Rio Grande Basin expanded substantially until the 1890s when drought, upstream development, salinization, defective drainage, and a development embargo by the federal government brought expansion virtually to a halt. Although irrigated acreage had expanded, the actual irrigation systems and their organizations had changed very little between 1846 and 1910. In the upper Rio Grande Valley, virtually all of the irrigable acreage was under ditch before 1846; in the middle valley (i.e., White Rock Canyon or Cochiti to San Marcial) most expansion after 1846 took place in areas where raids by nomadic Indians had caused earlier attempts at settlement to fail.

The vast majority of farmers in 1910 were still Puebloans or Hispanic New Mexicans. Increasing numbers of Anglo-Americans had begun to engage in irrigation agriculture, but most were too poor or inexperienced to introduce modern irrigation technology. The real impact of Anglo-Americans on the New Mexican economy during the Territorial Period was in the development of a livestock industry with

its accompanying infrastructure of railroads and market towns. Most of the essential developments in the livestock industry in the Territorial Period took place away from the Rio Grande on the uplands and plains that surrounded the valley. The emergence of large scale sheep and cattle herding had significant impacts on ecosystems of the Middle Rio Grande Basin, particularly on soils, native vegetation, and water resources.

With the American acquisition of New Mexico came the beginning of the end of the economic stability that New Mexican subsistence farmers had experienced for over a century. While the stability of this adaptation gradually disappeared, the technology of irrigation and the methods of irrigation agriculture that were used changed very little for most farmers in the Rio Grande Valley until after the turn of the century. The Anglo-Americans introduced changes in the New Mexican economy that altered settlement systems, land-use patterns, and the utilization of natural resources not only along the mainstream of the Rio Grande but also in the more marginal areas of the Middle Rio Grande Basin. Exploitation of minerals, grasslands, and forests as a part of the new, commercial economy of New Mexico opened portions of the ecosystems of the Middle Rio Grande Basin to more intensive use than the preceding subsistence economy had found possible or necessary.

However, the most immediate and profound impacts of the new economics of the Anglo-Americans came along the mainstream of the Rio Grande itself. By the early 1890s, serious problems had emerged in the irrigation agriculture of the Rio Grande Valley. Drought, which had struck sporadically in the 1880s, became acute in the early 1890s (Wortman 1971: 17); by 1889 the Rio Grande below Albuquerque literally dried up for four months of the year. Stream flow had been seriously depleted by rapid development of irrigation agriculture in the San Luis Valley of Colorado; the effects on downstream users were dramatic and ultimately led to federal intervention (Follett 1896; Harper et al. 1943; Harroun 1898; Yeo 1910, 1929).

Ironically, at the same time that the Rio Grande was being seasonally depleted, lands in the middle Rio Grande Valley from Cochiti to San Marcial, especially between Bernalillo and La Joya, were becoming waterlogged and thus not amenable to cultivation (Conkling and Debler 1919: 77; Harper et al. 1943; Harroun 1898: 2; Natural Resources Committee 1938: 70). Sedimentation in the Rio Grande resulting from

decreased flows had caused the bed of the main channel to aggrade; as a result, the water table in many parts of the valley had begun to rise. Waterlogged lands had always been a problem near the Rio Grande itself owing to poor drainage and wasteful irrigation practices. Under traditional agricultural methods, excess water in the *acequias* was simply dumped onto low-lying lands at the end of the *acequia*. Only a small percentage of ditches had facilities for returning the excess flow to the Rio Grande or delivering the water to downstream ditches. Each ditch system, of which there were dozens, was independent; no plan or organization to integrate the multitude of irrigation systems in the middle Rio Grande Valley existed or was deemed necessary.

Though more urbanized and subject to outside influences than their neighbors to the north, residents of the middle Rio Grande Valley maintained patterns of agriculture that were remarkably traditional in the period before 1910 (Harper et al. 1943). After the early 1880s and the arrival of the railroad, some commercial agriculture was introduced into the area around Albuquerque, Belen, and Socorro, but for the most part irrigation agriculture preserved its traditional orientation toward subsistence farming. At least 90 percent of the farmers were Hispanic or Puebloan, and approximately 90 percent of the irrigated acreage was farmed by them (Natural Resources Committee 1938). Nonetheless, irrigated acreage did expand in the middle Rio Grande Valley in the 1860s to early 1890s.

Beginning in the mid 1890s, droughts, sedimentation, aggradation of the main channel, salinization, seepage, and waterlogging caused an overall decline in irrigable acreage in the middle Rio Grande region. The total amount of actual irrigated acreage remained relatively stable as previously uncultivated lands were brought into production to replace adversely affected acreage.

Much of the potentially irrigable acreage in the middle Rio Grande Valley had been damaged by poor drainage and the rising water table, and had been retired from production by the early 20th century (Wortman 1971: 17- 18). Thousands of acres were rendered unusable by the related problems of waterlogging and alkalinization; at the same time floods were frequent and often devastating. The flood of 1874 destroyed almost every building between Alameda and Barelas (Carter 1953). In 1884, Tome, Valencia, and Belen were under water during the spring floods. The flood of 1886 wiped out part of the pueblo of

Santo Domingo, and a new church had to be built. In 1904 most of the bridges on the Rio Grande were destroyed by a late summer flood. The spring flood of 1905 washed away the community of Tomé.

As early as the 1890s, the desirability of reorganizing the middle Rio Grande Valley irrigation systems was recognized by a few individuals. The need for a unified and rationalized system of irrigation and drainage was great, but such a development was hampered by misunderstanding and mistrust (Linford 1956: 277). Local residents who were mostly Hispanic or Puebloan were naturally reluctant to surrender or assign water rights to private irrigation companies, which were mainly Anglo-American enterprises, in return for the promise of a more secure water supply. Such a hesitancy was well founded; 90 percent of the private irrigation companies in the western United States went bankrupt—hardly a record to engender confidence in a privately sponsored reorganization of the middle Rio Grande Valley's irrigation systems.

In the second half of the 19th century, a mining industry developed in the mountains of the Middle Rio Grande Basin with the usual accompanying impacts on water and timber resources. The latter were also affected by the construction of railroads with their large demands for timber in construction and operations. Other forested areas than the mountains of the Middle Rio Grande Basin were more systematically exploited then those of the Basin; the environmental effects were nonetheless demonstrable if generally localized. Of broader impact on the extensive grasslands of the Middle Rio Grande Basin was the development of the livestock industry. The emergence of a commercial livestock industry was encouraged and made possible by the construction of transcontinental railroads through New Mexico that opened national markets for sheep and cattle that utilized the Basin's grasslands. These uses had important impacts on nature vegetation, water, and soil, and the uses produced deteriorations in grasslands throughout the Basin beginning in the late 19th century and continuing into the 20th century. Transformation in Middle Rio Grande Basin ecosystems such as arroyo cutting and desertification were due not only to human activities, but also climatic changes following the end of the "Little Ice Age" in the mid–19th century.

The late 19th and early 20th century also witnessed the breakup of community land grants and the common lands (ejido) as an indirect consequence of land grant adjudications by the U.S. Surveyor General and the Court of Private Land Claims. Except for the construction of larger flour mills and the centralization of distribution networks as a result of railroad constructions, agriculture in the Middle Rio Grande Basin changed very little before the 1920s from its centuries old system of irrigation farming. Frustrated in that area by antiquated farming methods, Anglos were constantly advocating "modern" techniques of farming.

In 1879, the long-awaited railroad arrived in New Mexico. The railroads immediately superseded the limited trade on the Sante Fe Trail and were able to transport larger masses of goods more quickly then the old system of wagon transportation. Connections with the eastern United States spurred the growth of new industries in New Mexico, including the Middle Rio Grande Basin. These included the livestock industry in sheep and cattle, and natural resource extraction in minerals and lumber. The railroads also directly spurred population growth through employment in construction and operations; by 1920 over half of Albuquerque's male heads-of-households worked for the Santa Fe railroad.

Physical resources deteriorated in the middle Rio Grande Valley from the 1890s to the mid 1920s (Harper et al. 1943: 28). Water shortages resulting from drought, and especially from over-exploitation of surface water for irrigation in the San Luis Valley, were frequent throughout the period after the early 1880s (Conkling and Debler 1919; Follett 1896; Gault 1923; Hodges 1938; Yeo 1910). These shortages were often tragically combined with devastating floods (Carter 1953; Yeo 1943). Water shortages particularly affected the annual flows on the middle and lower Rio Grande, producing increased sedimentation and dramatic channel aggradation in the early 20th century that choked the ditches (Harper et al. 1943: 36–40). The aggradation of the main stream channel increased the frequency and destructiveness of floods and also contributed to the waterlogging of arable lands in the middle and lower valley through lateral seepage and raised water tables (Burkholder 1928: 34; National Resources Committee 1938: 70). Waterlogging was frequently accompanied by salinization and alkali poisoning of soils (Conkling and Debler 1919: 77; Harper et al. 1943: 36–40). The changes in the hydrology of the valley were not the only causes of waterlogging and its accompanying effects on arable lands. Traditional irrigation practices in the middle valley encouraged and frequently were a pri-

mary immediate cause of arable acreage going out of production (Stewart 1936). The combined effect of all of these factors was a decline in irrigation agriculture in the middle Rio Grande Valley (Harper et al. 1943: 51). Drought in the 1920s and 1930s had similar effects on the grasslands of the Middle Rio Grande Basin. Overgrazing reduced the cover grasses and contributed to serious soil erosion.

Concern over the deterioration of conditions in the middle Rio Grande Valley gradually grew in the 1920s (Burkholder 1928; Linford 1956: 287–289). In 1921, the State Legislature created the Rio Grande Survey Commission, which was to study conditions in the middle valley in cooperation with the U.S. Reclamation Service (Hedke 1925). Finally in August 1925, the Middle Rio Grande Conservancy District was organized. When the district was organized, two-thirds of the arable bottomlands within its boundaries were subject to seepage or were waterlogged (Burkholder 1928: 45–55; Conkling and Debler 1919: 77).

Over the next three years an official plan for reclamation, flood control, and irrigation was developed; the plan was presented in its final form by the chief engineer of the district, Joseph L. Burkholder, in 1928. The plan covered flood and river control, irrigation (especially diversion dams and main canals), drainage, water supply (a reservoir at El Vado), management of Indian Lands belonging to five pueblos (Congressional legislation was needed in order to include Pueblo lands within the Middle Rio Grande Conservancy District), and sedimentation control (dealing with aggradation of the Rio Grande, channel shifts, lateral seepage, and waterlogged lands). In March 1928, Congress authorized the Secretary of the Interior to enter into an agreement with the Middle Rio Grande Conservancy District for irrigation, drainage, and flood control on the lands of the pueblos of Cochiti, Santo Domingo, San Felipe, Santa Ana, Sandia, and Isleta. The MRGCD and its projects would transform Middle Rio Grande Basin agriculture in the 1920s, 1930s, 1940s, and 1950s.

The arrival of modern irrigation technology not only meant a reorganization of the irrigation systems, a renovation of the facilities, and a rationalization of the structure of irrigation, but also the infusion of outside influences and a tremendous escalation in the costs of irrigation. Much of the latter impact was absorbed by the largesse of the federal government, which wrote off or massively subsidized the costs of irrigation agriculture in the Rio Grande Valley as it did in the rest of the arid American West. The changes

in the character of irrigation agriculture in the middle Rio Grande Valley of New Mexico included: (a) the appearance of modern, surveyed ditch alignments to replace the old meandering systems; (b) the construction of a few concrete diversion structures to replace the multitudes of primitive head works; (c) construction of large water storage structures to provide a virtually guaranteed source of water during the irrigation season; and (d) the institution of operation and maintenance methods using heavy machinery to replace human beings with shovels. Many of the old problems of flooding, sedimentation, waterlogging, alkali poisoning, and unreliable water supply were resolved or at least held in check, but they were replaced by new problems related particularly to finances, especially maintenance costs and reimbursement of construction costs. The new problems have proved to be much more intractable than the old ones.

The organization of the U.S. Forest Service and the U.S. Bureau of Reclamation in the 20th century introduced federal involvement in land uses and land management to the Middle Rio Grande Basin. The formation of federally mandated grazing districts on public lands in the 1930s and the related organization of the Bureau of Land Management brought similar federal involvement with the grazing resources of the Basin. The role of these and other federal agencies in resource utilization on public lands has increased throughout the 20th century in the management of grazing, mining, forestry, recreation, water, soil, and other areas of resource utilization.

LITERATURE REVIEW

The following literature review briefly summarizes previous research on the human role in the ecosystems of the Middle Rio Grande Basin during the historic period. The environmental history of the Basin is reviewed elsewhere (Scurlock this volume). In general, only limited attention has been given to the complex relationships of humans and ecosystems throughout New Mexico, including the Middle Rio Grande Basin.

Overviews of human activities in the Basin can be found in the following studies: Berman (1979); Cordell (1979); Dick-Peddie (1993); Dyerson (1971); Flores (1992); Horgan (1954); National Resources Committee (1938); Tainter and Gillio (1979); Tainter and Levine (1987); and USDA Soil Conservation Service (1936a,b). A unique body of information on eco-

systems in the historic period is contained in the records of the Wheeler surveys. The published records are contained in Wheeler (1875–1889), while the extremely important unpublished records are held at the National Archives and at Yale University.

Many archival guides and references exist to assist the researcher in the study of the region: Beers (1979); Burger (1990); Chavez (1957); Colley (1972); Gallacher (1986); Jackson and Teeples (1978); Jenkins (1968, 1969, 1970); Jenkins, Simmons and Martinez (1967); National Archives and Records Service (1973); O'Connor (1989); Rex (1991); and Tyler (1984). The fundamental primary records for the Spanish and Mexican Periods are contained in the Spanish Archives of New Mexico and the Mexican Archives of New Mexico, which are available on microfilm at the State Archives and Records Center (Santa Fe) and at the University of New Mexico (Albuquerque). Also of primary importance in the study of land uses in the 17th, 18th, and 19th centuries are the records of land grants in the Spanish and Mexican archives, and the American Period investigations of Spanish and Mexican land grants; these records are contained in the proceedings before the U.S. Surveyor General of New Mexico (1855–1887) and the Court of Private Land Claims (1891–1904). For the study of land use by Indians and non-Indians on Pueblo Indian Land grants, the records of the Pueblo Lands Board (1926–1932) provide considerable information on the 19th century and the first part of the 20th century.

The interrelationships of human populations and the river valley itself have been explored in Abbink and Stein (1977); Bowen and Sacca (1971); Burkholder (1928); Carter (1953); Debler (1932); Hernandez (1971); Kelley (1969); Kelley (1955); Leopold (1951); Linford (1967, 1968); Marshall and Walt (1984); Moir et al. (1971); Nickerson (1945); Sargeant (1987); Sargeant and Davis (1986); Scurlock (1988a, 1988b, 1988c, 1993b); and Wortman (1971).

Population studies and human demography for the historic period in northern and central New Mexico are provided for the Pueblos by: Creamer (1994), Dozier (1970), Earls (1992), and Thorton (1987); for the Hispanics by: Bailey and Haulman (1977), Carroll and Haggard (1942), Jones (1979), Nostrand (1992), Olmsted (1973, 1975, 1981), and Tainter and Levine (1987); and for the Anglos by: Johansen (1971, 1972).

The largest, longest, and most profound human impacts in the Middle Rio Grande Basin during the historic period have been upon the riparian ecosys-

tems as a result of irrigation agriculture. The role and impacts of irrigation in the human history have been more studied than any other human roles and impacts. This investigator (Wozniak 1987) has written an overview of the development of irrigation systems in the Rio Grande Valley of New Mexico (including the Middle Rio Grande Valley) during the historic period. A comprehensive history of irrigation and its impacts in the Middle Rio Grande Basin is still needed. The study of irrigation agriculture and of agricultural water uses has been undertaken in a series of studies: Clark (1987); Clark (1958, 1971); Conkling and Debler (1919); Downing and Gibson (1974); Ellis (1970); Follett (1896); Hodges (1938); Hutchins (1928); Meyer (1979); Meyer and Deeds (1979); Ressler (1968); Simmons (1972, 1983); Sunseri (1973); Swan (1977); Wortman (1971); and Yeo (1910a, 1910b, 1929).

Puebloan settlement patterns, land use, and irrigation agriculture for the historic period are addressed in Abbink and Stein (1977); Bandelier (1892); Cordell (1979); Dozier (1970); Du Mars et al. (1984); Earls (1985); Euler (1954); Ford (1972, 1984); Hewett and Dutton (1945); Hewett et al. (1913); Hodges (1938); Lange (1951 and 1959); Michael (1976); Nelson (1914); Ortiz (1979); Poore (1893); Ressler (1968); Riley (1951 and 1987); Sando (1982); Scurlock (1991); Snow (1981); and White (1935). Marshall and Walt (1984); Schroeder (1968, 1972, 1979); Vivian (1932); and Wozniak (1987) have addressed the question of Pueblo abandonments in the Middle Rio Grande Basin during the historic period. Zubrow (1974), in this study of the relationships of climate, populations dynamics, and Euroamerican contacts, has examined the problems for the Pueblos of Hispanic and Anglo-American settlements on Puebloan land grants and resource bases. An ecological perspective on the Eastern Pueblos has been offered by Ford (1972).

Perspectives on Hispanic settlement patterns, land use, and agriculture has been provided by Bailey and Haulman (1977); Briggs and Van Ness (1987); Campa (1979); de Buys (1985); Greenleaf (1972); Hall (1982); Hernandez (1971); Jones (1979); Kelley (1955); Kutsche (1979); Leonard (1943); Nostrand (1992); Rothman (1989); Simmons (1969, 1972 and 1983); Snow (1976, 1979); Sunseri (1973); Swan (1977); Tainter and Levine (1987); Van Ness and Van Ness (1980); Westphall (1983); Widdison (1958); and Wozniak (1987). The results of the USDA Soil Conservation Service's Human Dependency Surveys of the 1930s are contained in Calkins (1935, 1937a, b and

c); Cockerill et al. (1939); Harper et al. (1943); Leonard (1943); Maes and Fisher (1937); and Oberg (1940). These studies provide valuable perspectives on Hispanic land use patterns, human relationships with the land and its resources, the interrelationships of Anglo and Hispanic land and water uses, and human impacts on a variety of Middle Rio Grande Basin ecosystems. Widdison (1958), in his study of the Rio Puerco valley, has prepared the only historical geography within the Middle Rio Grande Basin. A review of colonial Hispanic water use has been provided by Meyer (1984) in his study of water rights, irrigation, and litigation in the Southwest. R.E. Clark (1958) has provided a study of water law and traditional Hispanic and Puebloan communities.

Anglo-American settlement of the Middle Rio Grande Basin has been addressed in Cordell (1979); Tainter and Gillio (1979); and Tainter and Levine (1987). Studies of the settlement of the public domain in New Mexico in the period after 1848 have been provided by Ganoe (1937), and particularly, Westphall (1965). Simmons (1982) has provided a study of the city of Albuquerque, which is the principal urban area in the Basin. The impacts of urban development in the Middle Rio Grande Valley are addressed by Clark (1987), Linford (1956, 1968), and Simmons (1982). The phenomenon of health seekers in New Mexico is discussed by Jones (1967); however, questions about recreational visitation and tourism, and their impacts, have been addressed only peripherally and for only the most recent years of the 20th century.

In the matter of the diversity of attitudes toward the land and the use of natural resources, we have only limited information in the studies by Eastman et al. (1971) and Harper et al. (1943). Frequent discussions have been carried in the popular media regarding the alleged distinctions among Puebloan, Hispanic, and Anglo-American attitudes toward the land and environment but none of these discussions have any greater time depth than the last three or four decades, and they tend to reflect present and generally non-historical perspectives.

Numerous reports and studies on water control, water supply, and water management in the Middle Rio Grande Basin during the late 19th and 20th centuries have been prepared that address the problems associated with water control and management. These include Burkholder (1928); Clan (1987); Debler (1932); Follansbee and Dean (1915); Gault (1923); Harroun (1898); Lampen (1930); Linford (1956);

Nickerson (1945); van Cleave (1935); and Wortman (1971). The conditions of water control systems for the same period have been reported in detail by Follett (1896) and Yeo (1910 and 1929). The origins and history of the Middle Rio Grande Conservancy District are provided by Clark (1987); Linford (1956); Welsh (1985a, b); and Wozniak (1987). Welsh (1985 a and b) has examined the management of water resources in the basin by the U.S. Army Corps of Engineers.

The lands of the Middle Rio Grande Basin include not only the river valley areas that have been utilized for irrigation agriculture, but also grasslands and forests that have been historically exploited by the communities from the riparian zones. The herding of cattle and sheep on grasslands and forests in the Spanish, Mexican, and American Periods have been explored by Akins (1987); Baxter (1987); Baydo (1970); Carlson (1969); Denevan (1967); Eastman and Gray (1987); Humphrey (1953 and 1987); Jordan (1993); Nickerson (1945); Rowley (1985); Smith (1953); Widdison (1958); and Wooton (1908). The utilization of forest lands in the American Period during the administration by the USDA Forest Service has been specifically addressed by Baker et al. (1988) and Rowley (1985).

Following and associated with the construction of the railroads in the latter part of the 19th century (Greever 1957; Myrick 1989), the commercial exploitation of timber, mineral, and other resources took place in the Middle Rio Grande Basin. Hispanic use of timber has been addressed by Jones (1932). The trapping of fur-bearing animals in the Mexican Period and early American Period has been presented for the whole of New Mexico by Weber (1971). Mining and mining settlement in New Mexico has been studied by Anderson (1957); Christiansen (1974); Long (1964) Northrup (1959); Shannon and Shannon (1975); and Young (1965). A study of mining in a portion of the Jemez Mountains above Cochiti Pueblo has been provided by Wozniak (1981). Utilization of timber resources and their consequences are presented in Baker et al. (1988); Cooper (1960); Cooperrider and Hendricks (1937); Scurlock (1993a) and Tucker (1992).

The results of the utilization of ecosystems throughout the Basin have been reflected in studies by Brown (1974); Bryan (1927 and 1928); Cooke and Reeves (1976); Cooperrider and Hendricks (1937); Dortignac (1963); Headley (1936); Isaacson et al. (1936); and Stewart (1936). These authors have focused on the most visible consequences in the form of arroyo development and soil erosion. The effects

of human uses of the land are also reflected in stream channelization and floods that have been studied by Bryan (1927 and 1928); Bowen and Sacca (1971); Carter (1953); Calkins (1937c); Sergeant (1987); and Scurlock (1993b).

RESEARCH NEEDS, STRATEGIES, AND GOALS

Research in the historical data from the Spanish, Mexican, and Anglo-American Periods would provide the bases for analyzing the human and ethnoecology of the Middle Rio Grande Basin. The result of this research and analysis would be an integrated understanding of the human role in, and human impacts on, the ecosystems of the Basin. Addressing the following problems would create an integrated understanding of the relationships among cultural, political, economic, and environmental factors and processes:

1. Need an improved understanding of the relationship between riparian, grasslands, and mountain ecosystems of the Middle Rio Grande Basin and human activities such as irrigation agriculture, dryland farming, herding of livestock, mining, and lumbering.
2. Need to know the relationship between exploitation of diverse ecosystems by traditional Puebloan and Hispanic communities and the consequences of the late 19th century's introduction of a commercial economy.
3. Need better understanding of the presumably different world views of the Puebloans, Hispanics, and Anglo-Americans regarding land use, land management, and nature itself, and how the differing land-use histories of these distinctive groups have affected relationships among them. This improved understanding would address the question of the cultural sustainability and alternative cultural responses to changes in climate, energy, population, land use, politics, national and global economics, and the environment.

To solve these three problems, the following research topics or goals should be addressed:

a. History of irrigation agriculture and its impacts on riparian ecosystems.
b. History of livestock herding on the upland and riparian grasslands.
c. Comparison of the differing impacts of traditional agriculture practices and "modern" agricultural practices on riparian and upland ecosystems.
d. Comparison of Hispanic and Anglo-American herding practices. Comparison of herding impacts on grassland environments and the differential effects of traditional and commercial livestock raising on the land.
e. History of the impacts of commercial mining and lumbering on upland and mountain ecosystems.
f. Reconstruction of the cycles of arroyo formation, stream channel cutting, deposition and how utilization of the land by Puebloans, Hispanics, and Anglo-American affected soil erosion and arroyo formation regimes.
g. Analysis of the similarities and/or differences in Puebloan agricultural systems along the mainstream of the Rio Grande and along tributary streams.
h. Comparison of differential responses of Puebloans, Hispanics, and Anglo-Americans to changes in ecosystems.
i. Reconstruction of the historic world views of the Puebloan, Hispanic and Anglo-American communities regarding land use, land management, and resource exploitation.
j. Comparison of historic and contemporary Puebloan, Hispanic, and Anglo-American world views regarding land use, land management, and resource exploitation.
k. Understand the role of urbanization in the Albuquerque area on Middle Rio Grande Basin ecosystems.

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Chapter 4
Geology, Climate, Land, and Water Quality

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GEOLOGY

The Middle Rio Grande is part of the chain of structural basins, known as the Rio Grande depression, that extends from the San Luis Valley in Colorado to El Paso, Texas, and through which the Rio Grande flows (Chapin and Seager 1975). Bryan (1938) is credited with designating this reach as the Rio Grande "depression," because of his early research and the level of understanding he provided on the geology of the region. This area is also known as the Rio Grande "rift," a term coined by Kelly (1952), based on his belief in the possibility of significant longitudinal displacement in the "trough" or depression (Baltz 1978). The Rio Grande rift will be the term used in this discussion.

The Middle Rio Grande, as presented in this chapter, includes the area of the Rio Grande rift between Cochiti Dam, southwest of Santa Fe and Elephant Butte dam, south of Socorro, New Mexico (refer to Fig. 2 in Chapter 1). The linear distance between these locations is about 257 km. The Middle Rio Grande includes the four principle basins of Albuquerque, Socorro, La Jencia, and San Marcial (Fig. 1). The Middle Rio Grande is located in the counties of Socorro, Valencia, Bernalillo, and Sandoval, with small extensions into Torrance, Santa Fe, Cibola, Rio Arriba, and Catron counties.

The principal landforms of the Middle Rio Grande include: (1) pediments, (2) dissected slopes, (3) fault scarps, (4) terraces, (5) alluvial slopes, (6) alluvial fans and cones, (7) major stream floodplains or valley bottoms, (8) eolian blankets and dunes, and (9) volcanic fields, ridges, and cones (Kelly 1977; Fitzsimmons 1959).

CHANNEL AND BASIN DESCRIPTIONS

Lagasse (1981) described the channel of the Middle Rio Grande as a shifting sand substratum with low, poorly defined banks. The floodplain contains a mixture of cottonwood, willow, Russian olive, and saltcedar, which together form a dense growth of riparian woodland known as bosque interspersed with pasture and cultivated land. The configuration of the river may be described as one of low sinuosity with some straight reaches. Formation of sediment bars in the channel during low-flow periods and, in particular, during the recession of flood flows, together with rapid growth of vegetation, generally determine the channel configuration within the levees. The slope of the river drops about 0.95 m/km from Cochiti
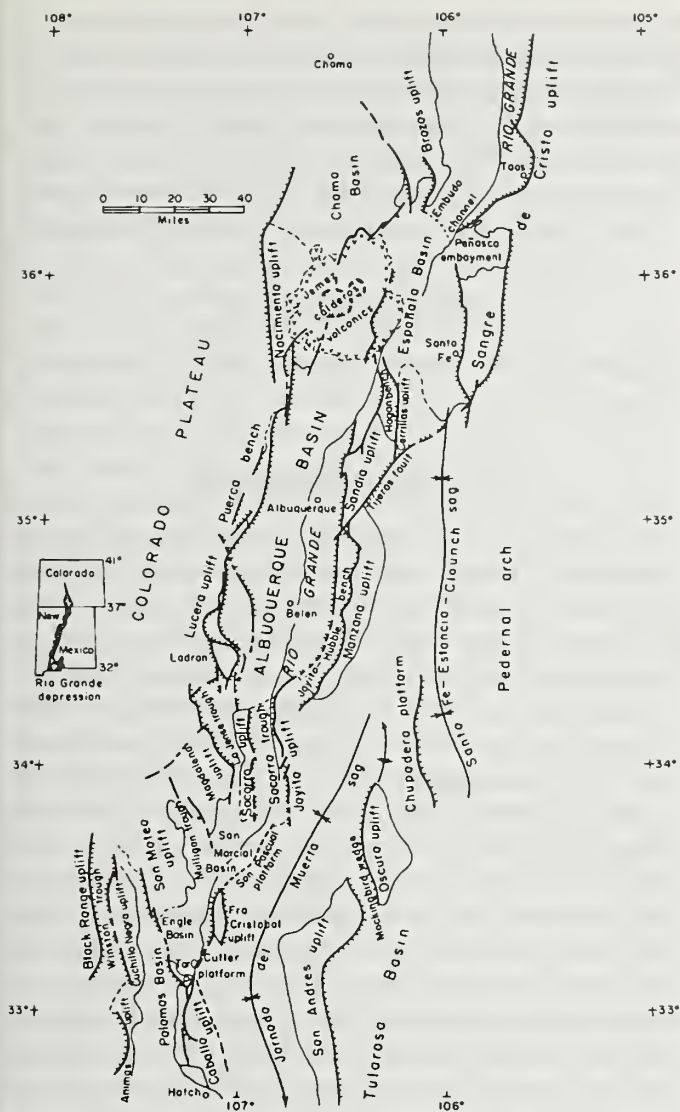
Figure 1.—Tectonic map of Rio Grande rift system (Kelly 1977).

base level and limit upstream and downstream river response of the Rio Grande.

Albuquerque Basin

The Albuquerque Basin is the largest and most important basin in the Middle Rio Grande. The importance of this basin is that it houses the aquifer from which most of the city of Albuquerque draws water. The geology of the Albuquerque Basin has been the subject of numerous studies and publications (Thorn et al. 1993; Kelly 1977). Hawley and Haase (1992) present the status of the geology as it relates to the hydrology of this area in "Hydrogeologic Framework of the Northern Albuquerque Basin." Thorn et al. (1993) summarized much of Hawley and Haase's work in "Geohydrologic Framework and Hydrologic Conditions in the Albuquerque Basin, Central New Mexico." The discussion presented here on the Albuquerque Basin is edited from the work of Thorn et al. (1993), except where noted. Of note is the conclusion from these recent studies of groundwater: that the water supply for the City of Albuquerque and surroundings is considerably more restricted than earlier studies suggested.

The Albuquerque Basin, located in the central part of the Rio Grande rift, is the third largest basin in the rift. The basin extends about 100 miles in length from north to south and about 35 miles in width, with an area of about 7,925 km². The northern boundary of the Albuquerque Basin, and the Middle Rio Grande, are defined by the Nacimiento and Jemez uplifts. The Nacimiento Uplift is characterized by Precambrian plutonic and metamorphic rocks overlain by Paleozoic strata. Cenozoic volcanic rocks form the Jemez uplift (Hawley and Haase 1992). The topographically prominent eastern boundary is the eastward-tilted fault blocks of the Sandia, Manzano, and Los Pinos uplifts; the Sandia uplift is the largest and highest. These three uplifted areas are composed of Precambrian plutonic and metamorphic rocks unconformably overlain by Paleozoic limestone and sandstone (Hawley and Haase 1992). The southern boundary is defined by the Joyita and Socorro Uplifts. This area, often referred to as the "San Acacia constriction," is formed by the convergence of the eastern and western structural boundaries of the Albuquerque Basin. The Ladron and Lucero uplifts define the southwestern boundary. Precambrian granite and metamorphic rocks compose the Ladron Uplift. The westward-tilted Lucero uplift is composed of Paleo-

to just below Albuquerque, and about 0.76 m/km from just below Albuquerque to the confluence of the Rio Puerco. Within the unstabilized floodway, the channel has virtually no banks, and the bed of the river is at or above the level of areas outside the levees due to sediment deposition between the levees.

The Middle Rio Grande is broken by short canyons or narrows at San Felipe, Isleta, and San Acacia, which in turn define the subvalleys or basins of Santo Domingo, Albuquerque, Belen, and Socorro. The diversion dams at Angostura, north of the Jemez River confluence and Isleta, midway between Albuquerque and Belen, act as "geologic" controls of river

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zoic limestone, sandstone, and shale capped by late Cenozoic basalt flows (Hawley and Haase 1992). The topographically subdued northwestern boundary is defined by the Rio Puerco Fault Zone.

The fill material in the Albuquerque Basin is mostly Cenozoic fill deposits of the Santa Fe Group. The Santa Fe Group was deposited during the middle Miocene to early Pleistocene (15 to 1 Ma). During that time the Albuquerque Basin received alluvial sediment from the adjacent highlands and fluvial sediments from Northern New Mexico and southern Colorado. The current sedimentary sequence is intertonguing basin-floor fluvial deposits and piedmont-slope alluvial deposits. Within the Albuquerque area, the source for the piedmont-slope alluvial deposits was the Sandia Mountains east of the City; they provided, for the most part, weathered granitic and limestone material to the basin. The fluvial deposits consist of a variety of material characteristic of the geology north of the Albuquerque Basin, including volcanic rock fragments from volcanic centers north and west of the Albuquerque Basin.

Hawley and Haase (1992) divided the Santa Fe Group and post-Santa Fe Group deposits into four hydrostratigraphic units and 10 lithofacies units. The hydrostratigraphic units consist of major valley and basin-fill units that are grouped on the basis of origin and age of a stratigraphic sequence of deposits. Examples include basin-floor playa, ancestral river valley, alluvial-fan piedmont, and present river valley depositional environments. Time-stratigraphic classes include units deposited during early, middle, and late stages of basin filling (lower, middle, and upper parts of the Santa Fe Group deposits, respectively). Post-Santa Fe Group valley and basin-fill deposits consist of channel and floodplain deposits beneath the modern inner valley or preserved as alluvial terraces (Hawley and Haase 1992). The 10 lithofacies represent different depositional settings, each recognizable by characteristic bedding and compositional properties having distinctive geophysical, geochemical, and hydrologic characteristics (Hawley and Haase 1992). Also dispersed throughout the Santa Fe Group are mafic volcanic flows and ash beds.

Thickness of the Santa Fe Group ranges from less than 2,400 to greater than 3,000 feet along the margins of the basin to 14,000 feet in the central part of the basin. Santa Fe Group deposition ceased about 1 million years ago when the Rio Grande and Rio Puerco started to cut their valleys (Hawley and Haase 1992). Post-Santa Fe units were deposited during a

series of river incision and backfilling episodes; the latest cut and fill episode of the Rio Grande and Rio Puerco systems produced the channel and floodplain deposits of the present inner valley (Hawley and Haase 1992). For the last 10,000 to 15,000 years, the river valleys have been aggrading due to tributary input of more sediment than the regional fluvial system can remove. This young valley fill, as much as 61 m thick, functions as a shallow source of water and as a connection between the surface-water system and the underlying Santa Fe Group (Hawley and Haase 1992).

Socorro Constriction

The Socorro Basin or constriction as defined by Kelly (1952) extends about 64 km from the San Acacia channel on the north to the San Marcial basin on the south. South of the Albuquerque Basin there is, in addition to a pronounced narrowing of the Rio Grande rift, a marked change in the structural alignment of the bordering uplifts. Furthermore, volcanic rocks are prominent especially along the west side of the depression. The Socorro Channel is the main linkage of the Albuquerque Basin with the San Marcial basin through this constriction. The channel lies between the Joyita uplift on the east and the Socorro uplift on the west. The Rio Grande rift along this channel is only 8 to 16 km wide. Pre-Cambrian rocks are at the surface locally in the bordering uplifts (Kelly 1952). Work by Bruning (1973) has shown that the Socorro Basin is actually part of a structure known as the Popotosa Basin which is almost 64 km wide. Extensive late Tertiary to Quaternary erosion surfaces are developed on both sides of the Rio Grande in the area of the Socorro constriction.

The basin fill in this area is part of the Popotosa Formation, which is part of the Santa Fe Group (Chapin and Seager 1975; Baldwin 1963). Denny (1940) and Bruning (1973) provide in-depth descriptions of the Socorro Basin. In addition to fan, playa, and transitional facies (plus interbedded volcanic rocks), the Popotosa Formation contains strikingly different compositional facies. The bulk of the unit consists of reddish, well-indurated volcanic conglomerates composed mainly of clasts of basaltic andesites and ash-flow tuffs derived from the upper part of the Datil volcanic section and from the La Jara Peak Basaltic Andesite (Chapin and Seager 1975).

The Socorro area and the Las Cruces area are anomalous. They are the only areas along the Rio

Grande rift where horsts have been elevated through several thousand feet of late Cenozoic sedimentary fill near the centers of basins. The combination of thin-skinned distension, high heat flow, and other geophysical anomalies suggests the possibility of major intrusions into the rift structure (Chapin and Seager 1975).

San Marcial Basin

South of the Socorro Basin constriction the Rio Grande depression again widens into an irregular basin about 48 km long and 16 to 24 km wide. It is terminated on the south by the Pankey Channel which connects it with the Engle Basin to the southwest. The main axis of the San Marcial Basin trends essentially south-southwest and coincides with the Rio Grande. It is bounded on the east by a low edge of the Jornada del Muerto that lies to the east. This border is here termed the San Pascual Platform, and may be a sort of sub-alluvial bench surmounted by local basalt flows. The sub-alluvial bench of Santa Fe sediments probably does not connect with deep Pliocene basins in the Jornada del Muerto. The western border is more complicated and marked by the in-echelon Socorro, Magdalena, and San Mateo uplifts. The intervening troughs or down-thrown parts of the fault blocks merge with the San Marcial basin and appear to be embayments from the latter. The extensive, although much dissected, erosion surface that exists on both sides of the Rio Grande in the San Marcial Basin is largely cut upon slightly deformed Santa Fe beds (Kelly 1952).

The Rio Puerco Drainage

The Rio Puerco drainage is a major drainage that merges with the Rio Grande south of Albuquerque. The Rio Puerco Basin is more than 200 km long, encompassing approximately 19,036 km^2 straddling the boundaries among the Colorado Plateau, Southern Rocky Mountains, and Basin and Range physiographic provinces. The upper portions of the drainage basin are underlain by bedrock, whereas the middle and lower portions are underlain by thick, semi-consolidated deposits in the Albuquerque structural basin. Although most of the drainage basin is less than 2,000 m above sea level, the headwaters lie in the Nacimiento Mountains (up to 3,176 m), the Zuni Mountains (2,281 m), and Mount Taylor (3,345 m) (Popp et al. 1988). A principal erosional feature

along the Rio Puerco drainage is a series of volcanic plugs that form prominent peaks above the softer Cretaceous sediments (Fitzsimmons 1959). It is assumed that the tops of the plugs represent former positions on the Rio Puerco Valley floor, and that the Mesozoic bedrock (shales and sandstones) and alluvial material through which the basalt was extruded were subsequently stripped away by the river (Slavin 1991).

The Rio Puerco is presently in a phase of incising in its northern reaches. Photographic evidence from the late 1880s indicates that the river has incised up to 15 m (50 ft) in 100 years, an extremely rapid incision rate. Paleochannels within the walls of the river's channel indicate that it has undergone many cycles of cutting and filling. It is possible that the incision of the Mesozoic shales and alluvial material surrounding the Puerco necks was similarly rapid, and that an extraordinarily fast base-level change is recorded in the surfaces of the Rio Puerco valley. It is conceivable that 400 m or more (>1,312 ft.) of bedrock and alluvial material were removed over a very short span of time (e.g., tens of thousands to only thousands of years, based on the above incision rate for the alluvial material eroded over the past 100 years). Even if the erosion of 400 to 500 m (1,312–1,640 ft.) of material has occurred over as much as the last 2.2 million years, these postulated incision rates may force a reconsideration of previously held notions that geologic processes occur slowly over long periods of time (Slavin 1991).

The general features of the landscape as we see them today began to appear in the Cretaceous as a consequence of incipient Laramide deformation. The first deformation may have been by warping, but faulting soon followed. Mountainous areas formed to the north and the Rio Grande depression began to appear on the east in the middle Tertiary. Erosion of the highlands caused filling of the basins and, as the mountains were worn down, erosion surfaces developed arroyos and edges of older and younger beds were beveled. Subsequent uplift has caused streams to cut into these surfaces and to initiate at lower levels new erosional surfaces that have not yet had sufficient time to become large regional features. Faulting and accompanying volcanic eruptions have occurred throughout the Tertiary and Quaternary. Lavas intercalated between basin-filling sediments and faulted lavas, and basin sediments attest to continued and contemporaneous faulting, sedimentation, and volcanic activity (Fitzsimmons 1959).

The major landscape features of the Rio Puerco are sloping valley margins commonly cut into bedrock or in semi-consolidated basin fill. The valley floor is underlain by thick alluvial deposits and the incised axial stream channel. The Rio Puerco and its major tributaries have developed distinct geomorphic features within confined arroyo walls that range from 8 to 13 m high and 145 to 245 m wide (Popp et al. 1988). Love et al. (1983) and Shepherd (1976) described the inner channel as a complex of meanders, straight reaches, and slightly arcuate reaches. The inner channel and floodplain include sandbars and ripple marked surfaces along the floor, slightly finer-grained sandbars along the margins of the inner channel natural levees along the outer margins, and coppice dunes.

The Rio Puerco is an ephemeral stream for most of its length and flows only in direct response to rain or snowmelt. This stream is infamous for large discharges and high sediment loads. It has been estimated that the Rio Puerco contributes more than 50 percent of the sediment load to the Rio Grande in central New Mexico while carrying less than 16 percent of the water (Waite et al. 1972; Popp and Laquer 1980). The Rio Puerco is also highly mobile. Studies of the lower channel (Young 1982) determined that more than 90 percent of the lower channel has shifted laterally since 1954. In this same time, the channel changed from being relatively wide with low banks and unvegetated in the 1930s to relatively narrow with high banks in the 1980s.

The lower Rio Puerco is a losing stream, that is, it loses water to its bed. A flow of as much as $0.14 \text{ m}^3/\text{s}$ at the stream gauge along Highway NM–6, west of Los Lunas, is lost to seepage and evaporation before it reaches the stream gauge at Bernardo (Heath 1983). In this reach west of Belen, the permanent water table is 10–13 m below the base of the modern channel, but there are seasonally fluctuating perched water tables on clay layers within the alluvium above the permanent water table. These perched water lenses tend to be recharged from the Rio Puerco when it is flowing on loose sand and can be depleted by seepage to lower levels and by transpiration by tamarisks and willows.

The channel shape of the lower Rio Puerco reflects repeated attempts at adjustment to extremely variable flows and an extremely high sediment load. Flows much larger than bankfull tend to scour the base of the channel and the floodplain locally. Smaller flows tend to build sand bars attached to both sides of the channel and to aggrade the floor of the chan-nel. The dynamics of the Rio Puerco arroyo system will be discussed in greater detail below.

HUMAN ACTIVITIES, GEOLOGY, AND THE RIO GRANDE

Over 10,000 years of human occupation is preserved in the Rio Grande rift. This occupation was and continues to be intimately related to the geological processes. The rifting that created the Rio Grande trough concentrated the runoff and created a drainage corridor and a perennial water source (Ware 1984).

The rift almost certainly influenced the seasonal movements of early hunters and gatherers in northern New Mexico. The region's first PaleoIndian inhabitants were undoubtedly drawn to the water source, as were the herds of Pleistocene animals they hunted. As water became increasingly scarce during the millennia-long droughts that followed the close of the Pleistocene, the river exerted an important influence on settlement patterns and seasonal population movements.

The rift concentrated important resources other than water. Volcanism associated with rifting produced obsidian for stone tools, altered land forms, and created elevations, ecological diversity, and a greater variety of wild plant and animal resources. The floodplain of the Rio Grande eventually attracted farming settlements. When large areas of the Colorado Plateau were abandoned by prehistoric farmers during the first centuries of the present millennium, many of those who were displaced migrated to the rich bottomlands of the Rio Grande and its tributaries, where there was perennial stream flow and longer growing seasons (Ware 1984).

The Effect of Dam Construction on the Middle Rio Grande

Dams were constructed across the Rio Grande at Elephant Butte, Cochiti, Angostura, and Isleta to control river flow for irrigation, flood control, and sediment detention. Studies near Elephant Butte and Cochiti dams have shown that these dams have had significant effects on the Rio Grande channel above and below the locations of the dams.

Elephant Butte Dam
Elephant Butte Dam, completed in 1916, was built to provide continuous and regulated river flow to the agricultural districts downriver from the dam.

The response of the Rio Grande channel, below the dam, was monitored from 1917 to 1932. After the closure of the dam there were two primary sources of sediment for flows through the Rio Grande below the dam: riverbed scour by the clear water released from the reservoir, and tributary inflow. The material derived from the steep-sloped, ephemeral tributary channels (arroyos) ranged from sand and gravel to boulder size, and was deposited in a fan or delta at the tributary outlet, where it was available for transport by main channel flows. Scour of the river channel itself by clear water released from storage was considered to be the principal sediment source, particularly in the sand size range. It was expected that this would remain the primary source of sands so long as the readjustment of the river channel to the changed conditions of clear regulated flows continued (Lagasse 1981).

Where an arroyo or tributary deposited directly into the main channel in a valley section below Elephant Butte Dam, the coarser material, which was beyond the competence of regulated main channel flows, forced the Rio Grande channel away from the tributary outlet through erosion of the opposite bank. Where the tributary channel entered the Rio Grande in a canyon section, the deposits of heavier debris created obstructions in the river channel, causing backwater above and rapids over the tributary delta. Regulated high flows were not of sufficient magnitude or duration to transport this coarser material downstream. Thus, arroyo and tributary deposits created base-level controls along the mainstream and strongly influenced the processes of degradation and aggradation (Lagasse 1981).

An analysis of the effects of clear-water scour along the Rio Grande below Elephant Butte Dam using successive cross sections indicated that there was a lowering of the river channel near the dam of approximately 0.6 m during the first 15 years of reservoir operation (Lagasse 1981).

The Rio Grande above Elephant Butte Reservoir is aggrading. The cause of this is, in part, the raising of effective local base level by delta building in the lake. This is not the only cause of aggradation, however, and probably not the most important. Arroyo cutting, contributing great qualities of sediment from tributary streams, may be the most significant process of all. Other causes are: windblown silt, increased loss of water because of domestic and irrigation usage, and prevention of flooding by artificial levee building, thus preventing a natural discharge of debris flow over the floodplain and consequently confining all aggradation to the channel. Measurements collected from 1936 to 1941, along the course of the Rio Grande from Cochiti Dam to the head of Elephant Butte Reservoir, indicated that the average annual increment of sediment added to the channel was about 15 cubic hectometers (Happ 1948). About half of that settled in the 23 km stretch immediately above the head of the lake (Fitzsimmons 1955). This will be discussed further in the section on arroyo dynamics.

Cochiti Dam

Cochiti Dam was built in November 1973. Cochiti Dam permits control of the main stem of the Rio Grande above the Middle Valley. This dam was originally intended for flood control and sediment control only. Multipurpose development objectives included arresting damaging flood flows, retaining sediment, and inducing degradation. Concern for recreation led to a modification of the authorization, and a permanent pool has been formed.

The floodway between Cochiti and Bernardo is generally confined by levees and averages 458 m wide through intensively developed rural and urban areas. The Bureau of Reclamation and the Corps of Engineers installed jetties in this reach, varying the density and widths as guided by hydraulic model studies. Design channel widths decrease in a downstream direction from 274 m in the Cochiti reach to 168 m at Bernardo. Operated in conjunction with upstream reservoirs, this channel work was intended to reverse the trend of aggradation and to allow the channel to degrade back to essentially a 1936 condition.

Before construction of Cochiti Dam and upstream tributary dams, the floodway of the Rio Grande was aggrading at rates as high as 0.6 m every 50 years near Albuquerque and as much as 5 m in 50 years near San Marcial. The ultimate result of aggradation is an increase in the height of the river bed or floodway above the adjacent flood plain. By 1960, the river channel near Albuquerque was 1.8 to 2.4 m above the elevation of lands outside the levees. Woodson and Martin (1963) provide an excellent summary of the effects of the Rio Grande Comprehensive Plan on the river regime throughout the middle valley of the Rio Grande. As of 1963 it was apparent that the "Rio Grande within the Middle Valley is still an aggrading stream, and construction of the floodway has not halted aggradation. Aggradation has occurred in amounts varying from practically zero in the Cochiti Division at the upstream end of the valley to a maximum of about 0.01 m per year in the Albuquerque Division" (Woodson and Martin 1963: 359).

Lagasse (1981) reported on a qualitative analysis of the effects of the construction of the Cochiti Dam on the Rio Grande. In the Cochiti to Isleta reach, sediment inflow from arroyos and tributaries has dominated the response of the main-stem Rio Grande to altered conditions of flow and sediment transport following closure of Cochiti Dam. Regulated flows of the post-dam period generally are not capable of transporting the coarser sediment load and volume of material carried to the main stem by arroyos and tributaries. Between Cochiti and the Jemez River, deltaic deposits at the confluence of tributaries and arroyos are sufficiently stable to influence planform, to create reaches of base-level control, and to influence the processes of aggradation, degradation, and armoring on the Rio Grande.

The reach immediately below the dam from Cochiti to Galisteo Creek had essentially completed adjustment to the closure of Cochiti Dam by 1975. Degradation and armoring progressed downstream through the San Felipe reach, and by summer 1979 the upper portion of the study reach had attained a level of stability yet to be achieved in the study area below the Jemez River. The Cochiti to Isleta reach of the Rio Grande will continue to respond to the closure of Cochiti Dam. Even the upstream reach that has adjusted to the altered conditions of flow and sediment transport will experience sequences of aggradation and degradation as sediments move through the system.

Recent evidence indicates that arroyos and tributaries below the Jemez River will play an increasingly important role in main-stem processes as degradation and armoring progress downstream. Response in the lower portion of the study reach will eventually parallel that above the Jemez River. However, the level of stability between the Jemez River and Isleta may never reach that of the Cochiti to Angostura reach, primarily because tributaries and arroyos with a drainage area necessary to influence main-stem processes are less common below Angostura.

The response at the Jemez River confluence supports the conclusion that the base level of the main stem is extremely sensitive not only to coarse material carried in from steeper arroyos, but also to a large volume of finer material contributed by a major tributary. As a result, a decision to establish a permanent pool at an existing dam on a major tributary or to construct sediment-detention dams on smaller arroyos must be supported by a detailed analysis of potential response of the main-stem Rio Grande.

During the extended low-flow period following closure of Cochiti Dam, the well-developed gravel armor above Angostura and stabilization of point bars and closure of chute channels by vegetation "locked" the Rio Grande into the low-flow channel pattern. Flows in excess of 170 m^3/s were required to initiate a transition to a high-flow channel pattern. To prevent the development of a channel pattern "locked in" to low-flow conditions and recurrence of problems associated with the April-July 1979 sustained high flows, releases from Cochiti Dam of about 170 m^3/s should be scheduled annually.

Processes set in motion by the closure of Cochiti Dam will eventually limit the effectiveness of the existing jetty fields. In the post-dam period less frequent inundation of floodplain areas, a reduction in sediment supply from major source areas such as the Jemez River, and degradation and armoring in the upstream channel all dictate against the installation of new jetty fields for channel stabilization. As the Kellner jetties become a less effective device for channel stabilization in the post-dam period, protection of the banks by vegetation will become increasingly important. Control of the beaver community along the banklines may be required, and traditional flood-fighting techniques that involve cutting of trees along the bankline should be reconsidered.

The problem of predicting river response below a dam and the extent to which development of an armor layer will limit degradation is extremely complex. While it is recognized that bank erosion, discharge variability, meandering, and sediment inflow from tributaries affect channel response below dams, analytical techniques currently available in the literature do not address response in the complex environment implied by these variables. Physical process computer modeling offers the most promising approach to solving this complex problem.

GEOLOGY AND ENVIRONMENTAL CONCERNS

The Middle Rio Grande along with the whole of New Mexico faces a special set of environmental problems associated with rich mineral resources, a dry climate, and vast areas of low population. Complex interactions between geology and environmental concerns involve geologic processes that have adverse effects on human activities and our use of mineral, land, and water resources. Geologic processes include moderate-intensity earthquakes, sur-

face subsidence due to rock solution, stream floods, debris flows, and landslides. Geologically related human impacts on the environment include surface and subsurface extraction of economic mineral deposits (primarily energy minerals), groundwater development, construction of dams and power plants, disposal of hazardous wastes, and establishment of large-area reserves for military operations and scientific research (Hawley and Love 1981).

Geologists have a major role in helping to solve environmental problems resulting from effects of geomorphic processes and the development of mineral, water, and land resources. Inventories must be made of these processes and resources in order to put complex process-resource-human interactions in proper space and time perspective. Guidelines can then be formulated for mitigation or prevention of geology-related problems. For example, mined lands need to be reclaimed, cities need to be planned, and sites need to be selected for hazardous waste disposal (Hawley and Love 1981).

CLIMATE

Dorroh (1946) presents data for average annual and seasonal precipitation in New Mexico. His results illustrate that two factors, topography and general atmospheric circulation patterns, exert the major influences on climate of middle Rio Grande region. Thornthwaite et al. (1942) identified five principal source regions of air contributing to the Southwest climate: (1) Cold Dry Continental; (2) Cool, Moist North Pacific; (3) Hot Dry Continental; (4) Warm, Moist Gulf; and (5) Warm, Moist South Pacific. Bryson & Hare (1974) provide monthly mean streamlines of circulation for all of North America. Their January map is illustrative of a rather complex circulation pattern that is the norm in the Rio Grande. Because of this complex circulation, the climate is prone to exhibit swings of substantial variation from mean conditions. These variations are a prominent feature of the climate in the region.

A modern map of annual precipitation for the Middle Rio Grande was published by Ellis et. al in 1993. They make the point that precipitation varies from a high of greater than 50 inches annually in the headwaters in Colorado to less than 6 inches near Albuquerque. A similarly wide variation in temperature is exhibited from the northern headwaters region where mean January temperatures are below 25°F to mean July temperatures above 75°F in cen-
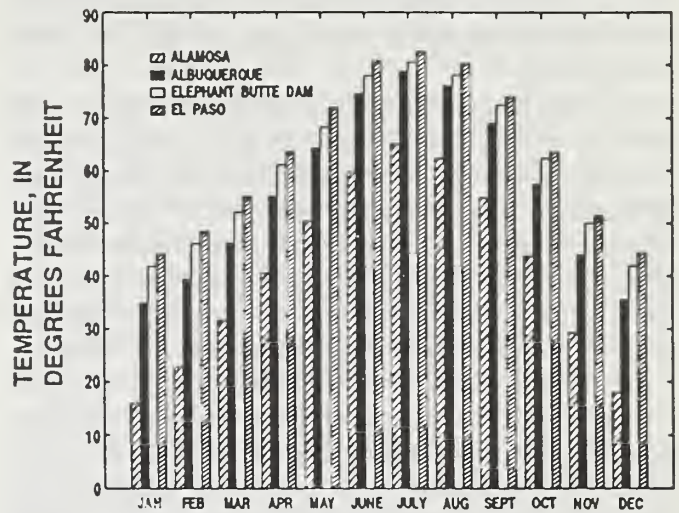
Figure 2a.—Mean monthly temperature for selected sites, 1951-1980 (from Ellis et al. 1993; permission to reprint granted by American Water Resources Association).
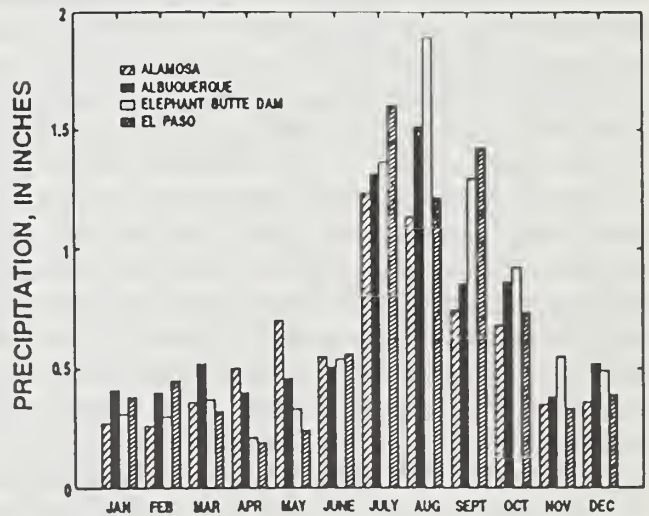
Figure 2b.—Mean monthly precipitation for selected sites, 1951-1980 (from Ellis et al. 1993; permission to reprint granted by American Water Resources Association).

tral New Mexico. Figure 2 illustrates the annual mean monthly temperature and precipitation for the headwaters (Alamosa), north central (Albuquerque), south central (Elephant Butte Dam), and southern (El Paso) region of the Middle Rio Grande. A map presented by Ellis et al. also illustrates that mean

annual evapotranspiration as high as 80 inches occurs near Elephant Butte; that value falls to 75 inches at El Paso, 60 inches at Albuquerque, and 50 inches at Alamosa.

Of perhaps greater interest is the variation of wet and dry years (Diaz 1991; Diaz et al. 1985). In areas such as the middle Rio Grande, dry years and their persistence are particularly important. The relationship between these manifestations of climate and other natural and human disturbances may be among the most significant factors influencing ecological systems in New Mexico (Betancourt et al. 1993).

Of particular interest is the effect of global climate on the Rio Puerco basin as represented by the El Niño-Southern Oscillation (ENSO) meteorological disturbance. Investigators have identified relationships between ENSO events and southwestern United States climate (Ropelowski and Halpert 1986, 1987; Andrade and Sellers 1988; Kiladis and Diaz 1989; Molles and Dahm 1990; Betancourt et al. 1993). D'Arrigo and Jacoby (1991) developed a thousand-year record of winter precipitation for northwestern New Mexico based on dendrochronology and correlated it with ENSO. Dahm and Moore (1994) recently demonstrated a statistically significant correlation between observed precipitation at Socorro, New Mexico, and ENSO events of both polarities. The correlation is strongest in October, significant from November through May, but not significant during the summer (convection) season. Correlation of ENSO or other large-scale climate indicators with regional meteorological conditions is important for model development because weather records are sparse and represent conditions at only a single point, while weather has significant spatial variation. Large-scale indicators are expected to correlate more closely with whole-basin conditions. Furthermore, since ENSO events are predictable phenomena of the global climate (Latif et al. 1994), it is possible that regional effects of global change may be somewhat more predictable when correlated with ENSO events.

A sustained La Niña condition in 1917 may have been a contributor to the high sedimentation rates observed in the Elephant Butte Reservoir during its first decade. A single dry year, however, seems unlikely to degrade vegetation condition to such a degree that a decade or more of enhanced sedimentation would ensue. Thus, multi-annual variations may be a better indicator of vegetation stress and erosion risk factor. The 3-year period that ended in 1919 was one of potential stress on the region (Watts et al. 1994).

ENSO is, however, only one of many signals that determine regional weather; it is certain that uncorrelated weather patterns and events are superimposed on ENSO signals. It is particularly interesting that a dramatic shift from sustained drought to unusually wet climatic conditions occurred between 1895–1904 (strong drought) and 1905–1928 (wet). This was evident in a thousand-year reconstruction of the northern New Mexico paleoclimate (D'Arrigo and Jacoby 1991).

In recent work with the NCAR regional climate model, RegCM, Mearns et al. (1994) have compared simulated current U.S. climate with a simulated double CO_2 climate. For the Southwest, their results show a significant increase in diurnal temperature range, a decrease in cloud cover, and a significant decrease in precipitation frequency for summer conditions. A more uncertain increase in summer precipitation intensity is also suggested. Although these results are too preliminary to draw any conclusions from, they suggest that it is possible for the middle Rio Grande to experience an increase in temperature, a decrease in cloudiness, a reduction in precipitation events, and possibly an increase in storm intensity.

Weather and climate questions can be studied with a "nested" hierarchy of increasingly finer-resolution climate models. The objective of such a model linkage would be to provide a realistic simulation of the spatial and temporal distributions of the middle Rio Grande's climate, in particular of the climate's features that influence sediment production and transport. It is likely that high intensity rainfall events are the most significant climatic feature for land management concerns. Preliminary inspection of the weather records suggest that such precipitation events are infrequent. Hourly (and daily) time series of precipitation can be used to develop a history of significant events. Each of these significant events can be developed as an historical case study. The synoptic patterns in which these events are embedded can be developed from archived analyses (the initial condition field for routinely performed numerical weather predictions). Analysis fields consisting of temperature, pressure, and humidity distributions over a 0.5-degree latitude and longitude grid (approximately 50 km) can be obtained.

These analysis fields can be used to initiate "nested" runs of the RAMS model (Tremback et al. 1986) and/or of the RegCM model (Dickenson et al. 1989; Giorgi et al. 1994; Mearns et al. 1994) at a grid resolution on the order of 10–50 km. Precipitation pre-

dicted by these models can be used to drive other components in a simulation of the land response to this significant event. Even finer-scale spatial resolution in predicted precipitation and temperature fields can be obtained from the higher resolution climate modeling efforts currently underway at Utah State University in collaboration with the USDA-FS Intermountain Research Station (Bowles et al. 1994; Bingham et al. 1995; Luce et al. 1995).

Mesoscale and local-scale (if necessary) models can be "driven" by the larger-scale synoptic analysis (e.g., the larger scale represents both initial and boundary conditions for the higher resolution models), to simulate the most significant precipitation events. Assuming the number of these events is small, it will be possible to "drape" a finely resolved precipitation distribution (order 1 km or less) over the Rio Puerco watershed. The significant events will be simulated from within a time series that simulates the long term climate. The ENSO phenomena would be incorporated in the global scale initialization analyses, thus carrying the global signal to precipitation on the Rio Puerco.

WATER QUALITY

Background

The Middle Rio Grande Basin includes 257 km along the main stem of the Rio Grande between Elephant Butte Reservoir and Cochiti Dam. Tributaries in the Middle Rio Grande Basin are the Jemez River, Rio Salado, and Rio Puerco. Other streams include Abo Arroyo in the Manzano Mountains, Tijeras Creek, Las Huertas Creek, Galisteo Creek, and the Santa Fe River below Cochiti Dam. Secondary tributaries include the Rio San Jose, Bluewater Creek, Rio Paguate, Rio Guadalupe, Vallecito Creek, Rio Moquino, and Seboyeta Creek. Designated uses and corresponding water quality are classified in the state standards and vary from that suitable for a high quality coldwater fishery (e.g., the Jemez River above State Highway 4 near Jemez Springs, and the Guadalupe River and its tributaries) and domestic water supply, to limited warmwater fishery in the main stem above Elephant Butte Reservoir (NMWQCC 1991).

The state authority for water quality is the New Mexico Water Quality Control Commission. The Pueblo of Isleta was the first tribe to adopt water quality standards in New Mexico (in December 1992)

to protect pueblo lands from off-reservation pollution. Standards were subsequently adopted by the Pueblo of Sandia, San Juan Pueblo, and the Jicarilla Apache Nation outside of the Middle Rio Grande Basin. Northern Pueblos that have published a notice of intent to adopt water quality standards include Nambe, Picuris, Pojoaque, Santa Clara, and Tesuque (Blane Sanchez, water resources specialist for Isleta Pueblo, personal communication). The State is primarily concerned about the level of pollution from nonpoint sources (NMWQCC 1992), but Isleta Pueblo is concerned about point source discharges from the City of Albuquerque (Blane Sanchez, personal communication).

Two recent reviews discuss water quality in the Rio Grande Valley, but not throughout the entire Middle Rio Grande Basin (Ellis et al. 1993; Crawford et al. 1993). Water quality throughout the state is reported to Congress every two years in the 305(b) report of the New Mexico Water Quality Control Commission (NMWQCC 1992).

There are four U.S. Geological Survey monitoring stations along the main stem of the Rio Grande between Cochiti Lake and Elephant Butte Reservoir (at San Felipe, Isleta, San Acacia, and San Marcial). Land uses upstream of these sites include various communities, ski areas, summer homes, silviculture, grazing, molybdenum mining, and irrigated agriculture. Water quality from Isleta upstream to Cochiti Reservoir is affected by the City of Albuquerque and other urban areas, wastewater discharges, runoff from dairies, and grazing. The lower portion of the Middle Rio Grande Basin is affected by irrigation return flows, uranium mining in the Rio San Jose watershed, and sediment contributions from three intermittent streams (the Rio Puerco, the Rio San Jose, and the Rio Salado) channeled over unconsolidated sediments. Trends for the following parameters are reported: conductivity, bacteria, alkalinity, sulfate, dissolved solids, dissolved nitrite plus nitrite, and suspended sediment concentrations. For example, suspended sediment concentrations at the mouth of the Rio Puerco are as high as 200,000 mg/L (USGS 1992), with a mean annual suspended sediment load of 2,580,000 tons per year (Ellis et al. 1993; USDI 1994). Others, however, note that sediment concentrations in the Rio Puerco reach 680,000 mg/L during major storm events (USDI 1994).

In addition to the fixed monitoring sites listed above, the USGS is conducting a study of the Rio Grande Valley in the United States as part of the

National Water Quality Assessment Program (NAWQA). Nine sites, including three on the main stem plus floodway and conveyance channel sites, are located on the Rio Grande from just below Cochiti Dam to San Marcial. Additional tributary stations include the Rio Puerco near Bernardo and the Jemez River below Jemez Canyon Dam (Ellis et al. 1993). The state Environment Department (NMED) has sampled tributaries in the Middle Rio Grande Basin as well as the main stem during intensive surveys, e.g., sampling a suite of stations for water chemistry, flow, and biological data at various times throughout a week-long survey. These data are available through the EPA STORET system, are published by survey, and catalogued through the NM State Library (Pierce 1989; Potter 1987a, b; Potter 1986; Potter and Tague 1986; Potter 1985a, b; Potter 1984a-c; Jacobi and Smolka 1984). Reservoir water quality is also monitored by NMED, and data are available for Cochiti and Elephant Butte lakes, as well as upstream reservoirs.

Surface Flows

Surface flows for the main stem are highly modified for flood control, sediment control, irrigation, hydroelectric power, recreation, and reservoir storage for water supply. Reservoirs affecting the Middle Rio Grande Basin hydrology include Heron, El Vado, Abiquiu, Cochiti, Jemez Canyon, Galisteo, and Elephant Butte. These modifications have resulted in intermittent or ephemeral flows in areas that were probably historically perennial flows (Crawford et al. 1993). Recent efforts to mimic natural hydrographs in the main stem include flooding of the bosque habitat. There is also interest in reestablishing the natural surface-water/groundwater exchange (Crawford et al. 1993). Long-term flow data are available for the main stem at Otowi bridge above Cochiti Lake. Flow in the Rio Puerco is not controlled for flooding or water supply and contributes 4 percent of the annual water yield for the Rio Grande at San Marcial (Crawford et al. 1993).

Contaminants

Nutrient enrichment

A number of nutrient loading studies have been conducted in the Middle Rio Grande Basin. A nutrient transport simulation model was developed to define rate constants and transport mechanisms (Wilson and Babcock 1979; Wilson, Tague, Snavely, and Babcock 1984). The state sampled the Rio Grande conveyance channel and Socorro Main Canal to evaluate the effects of irrigation return flow on Rio Grande water quality, and it concluded that irrigated agriculture did not noticeably contribute to the nitrogen and phosphorus loading of the river. Similarly, a New Mexico State University study indicated that less than 20 percent of the nutrients contained in irrigation waters were discharged to the central drain (Wierenega, Duff, Senn, and Gelhar 1981; NMEID 1982).

A study by Tague and Drypolcher (1979) indicated that the annual mass loading rates of both N and P from stormwater was low compared to the loading rate from the Albuquerque wastewater treatment plant, although a single event generated a temporarily high load. In another study, significant correlations and regressions between urban runoff volume and stormwater quality were calculated using data for the Alameda floodway (Diniz 1984).

More recently, high concentrations of un-ionized ammonia, which is toxic to some fish and invertebrate species, have been attributed to water use impairment in the main stem of the Rio Grande from Isleta Diversion Dam to the Jemez River (NMWQCC 1992).

Trace metals

Trace metals occur at detectable levels at various sites throughout the Basin due to a combination of natural and anthropogenic sources. For example, natural arsenic sources (geothermal springs) from the watershed of the Jemez River result in high concentrations of arsenic. Outcrops of organic-rich rocks such as humates and dark shales are a natural source of trace metals in the Rio Puerco Basin (USDI 1994). Popp et al. (1980) collected samples for trace-metal and pesticide analysis at six river sites from Bernalillo to Elephant Butte Reservoir. Water-use impairment in the Middle Rio Grande Basin is attributed to trace metals in the main stem of the Rio Grande from San Marcial to the Rio Puerco, Rio Puerco to Isleta Diversion Dam, from Isleta Diversion Dam to the Jemez River, and from Jemez River to Cochiti Dam (NMWQCC 1992).

Isleta Pueblo will be initiating a joint water quality monitoring program in accordance with an April 1994 settlement agreement regarding the City of Albuquerque's National Pollutant Discharge Elimi-

nation System (NPDES) permit for discharge of municipal waste. Concentrations of four metals—aluminum, arsenic, cyanide and silver—will be monitored from San Felipe to Los Lunas (Blane Sanchez, personal communication).

Several studies have been directed at the bioaccumulation of metals. Mercury, arsenic, and zinc concentrations are higher in fish tissue collected at Middle Rio Grande sites than other sites (Ellis et al. 1993). As a result of statewide sampling for mercury contamination in fish tissue, the state has issued fish consumption guidelines (NMWQCC 1992).

Radionuclides

Uranium-rich rock of the Rio Puerco Basin is a source of radionuclides. The Rio Puerco has elevated levels of uranium, gross alpha, and gross beta, and high concentrations of cesium 137 and lead 210 in Paguate Reservoir on the Paguate Creek tributary of the Rio Puerco (Ellis et al. 1993). Uranium mining and milling activities near Grants, New Mexico, have accelerated the downstream transport of radionuclides and metals. Eroding tailings piles may continue to result in water pollution.

Biocides

Biocide contamination occurs from agriculture, as well as from the cumulative impact of residential and commercial landscaping activities. Potter (1987b) sampled pesticide and herbicide concentrations at three Rio Grande main-stem sites in Socorro County. In general, concentrations were below detection limits. Although chlordane and 2,4-D were detected at the San Antonio station, only the former exceeded the recommended chronic criterion for aquatic life and limits for fish consumption.

Other pesticides found at detectable concentrations in the Rio Grande main stem include diazinon. Also, p-p' DDE was detected in the Middle Rio Grande by the U.S. Fish and Wildlife Service (Ellis et al. 1993). Water-use impairment in the Rio Grande is attributed to pesticides in the main stem from Isleta Diversion Dam to Jemez River and from San Marcial to the Rio Puerco (NMWQCC 1992).

Volatile organic compounds

VOC detectable in the Middle Rio Grande at Isleta include trichlorofluoromethane, chlorpyrifos, and trichlorofluoromethane (Ellis et al. 1993). Organic compounds are not considered to impose a major impact on New Mexico streams (NMWQCC 1992).

Other causes of water use impairment

Other causes of water-use impairment in portions of the Middle Rio Grande Basin include chlorine, pathogens, siltation, reduced riparian vegetation, and streambank destabilization. Sources that contribute to water quality degradation resulting in use-impairment are as follows: agriculture, municipal point sources, urban runoff, storm sewers, spills, hydromodification, and "others" (NMWQCC 1992). The primary in-basin concerns related to water quality are non-point sources of pollution, water quantity and timing, and ecosystem integrity.

Water Quantity and Timing

Stream flow rate is affected by reservoir releases, irrigation withdrawals, irrigation return flows, and precipitation variability. Changes in precipitation can have a disproportionate (e.g., nonlinear) change on streamflow. For example, under global warming scenarios, a 2° C temperature increase is predicted to result in a 10 percent decline in precipitation, but a 75.7 percent decline in annual stream discharge is predicted within the Rio Grande Basin (Revelle and Waggoner 1989). This is the largest predicted percent change per basin in the United States.

In 1990, total water withdrawal (groundwater and surface water) from the Rio Grande Basin in New Mexico was $2,258 \times 10^6$ m^3 (1,830,628 acre feet), significantly exceeding a sustainable rate (Schmandt 1993). Average annual outflow of the Rio Grande from Colorado to New Mexico is 370×10^6 m^3 (300,000 acre-feet) (Schmandt 1993). Significant changes in water supply in the main stem ultimately affect the distribution of water as defined by existing treaties and compacts. The International Boundary and Water Commission has already exercised its authority to protect water quality (e.g., salinity of the Colorado River) delivered to Mexico, and similar requirements could be imposed for the Rio Grande in the future (DuMars 1993). Both streamflow and reservoir storage are affected by terms of the interstate Rio Grande Compact and treaty with Mexico, while the Reclamation Act of 1902 addresses irrigation uses. Such legal implications of changes in water supply extend to various state and federal regulations of water quality and appropriation. For example, "conjunctive management" of surface and groundwater requires that to obtain rights to drill a well in an underground aquifer that recharges a surface stream, an equivalent surface water right must be purchased and retired (Gosz 1992).

The hydrologic effects of floods and droughts in semiarid regions is quite different from mesic regions. In the Rio Salado, for example, loss of streamflow in the summer occurs after wet winter/springs, while summers with high flooding occur after dry winter/springs. Hypothetical reasons for this observation include: less vegetation biomass is available after a dry winter/spring to slow overland flow so runoff therefore increases; wet winter/springs result in reduced hydrophobic tendency of the soils and increased infiltration; and due to the effect of soil temperatures, more intense summer storms may occur after a dry winter/spring and produce high runoff (Molles et al. 1992).

Anthropogenic Effects on Water Quality

Anthropogenic effects on water quality in the Middle Rio Grande Basin are the result of activities associated with irrigation, urbanization, mining, grazing, timber harvest, construction, and recreation (Crawford et al. 1993; NMWQCC 1991, 1992; Ellis et al. 1993; USGS 1992). Additional activities upstream from Cochiti Dam to the San Luis Valley in Colorado also contribute to the cumulative effect on water quality.

Irrigation return flows and runoff affect both water quantity and quality. Irrigated agriculture is the principal water use and a main economic activity in the Basin. Water withdrawals from irrigated agriculture are declining, e.g., from $1,536 \times 10^6$ m^3 to $1,227 \times 10^6$ m^3 (1,244,900 to 995,000 surface water acre-feet) in the New Mexico portion of the Rio Grande Basin (Schmandt 1993). DuMars distinguishes between "commercial agriculture" and "culturally significant marginal agriculture" of rural communities and Indian Pueblos (DuMars 1993).

Urbanization has resulted in commercial and industrial activities that have the potential to affect water quality. It has also resulted in increased levels of treated sewage discharged to streams. Perhaps most importantly, it has increased the demand for water supply, although municipal use relies on groundwater. Urban population growth is predicted to continue in the next century, e.g., when the effects of accelerated climate change may be evident. In contrast, rural populations have remained rather constant in the Basin (Schmandt 1993).

The rate of depletion of Albuquerque's water supply is currently a great concern. The aquifer on which the City of Albuquerque depends for water supply

is less extensive and thinner than was previously estimated, and it has dropped 40 feet from 1989 to 1992 in the eastern, northwestern and south-central areas (Thorn et al. 1993). Over 1.5×10^{11} l (40 billion gallons) of water a year are withdrawn from the aquifer, at a rate exceeding that of recharge (City of Albuquerque 1994). Consumption rate is 947 l (250 gallons) per person per day, and residential use is 71 percent of total. The remainder is consumed by commercial use (17 percent), institutional use (9 percent), and industrial use (3 percent) (City of Albuquerque 1994). Mayor Martin Chavez states that reducing water use is "the most important issue facing the City of Albuquerque, bar none." Groundwater quality is also lower than previously believed, including areas that are unsuitable for drinking.

Human activities may result in regional changes in the water cycle, water quality, and sediment transport systems (Huggett 1993). These changes are modeled at various scales, including the global and continental scales. Predictions can be made for variables such as runoff, stream discharge, soil moisture, and evapotranspiration (Huggett 1993). There is a growing, interdisciplinary interest in water resources issues that relate to sustainable development in the entire Rio Grande Basin (Gosz 1992; Crawford et al. 1993; Schmandt 1994). Those efforts include sharing scientific information and collaborative projects that will improve water and riparian area quality, as well as economic sustainability. Such partnerships, institutional cooperation, and joint decision-making are necessary to address global change issues related to climate, population, economy, the environment, and culture (Gosz 1992). In the Rio Grande Basin, total water consumption is greater than the supply. This water deficit is allowed to continue through diversion systems and groundwater mining (DuMars 1993). It is well recognized that sustainable economic development depends on efficient water use, water conservation, and water pollution control.

ARROYO DYNAMICS OF THE RIO PUERCO BASIN

Background

The Rio Puerco basin is composed of federally managed lands (FS, Bureau of Land Management, National Park Service, and Fish & Wildlife Service: 30 percent,), Indian lands (20 percent), state (10 percent), and private (40 percent) lands. This broad

mosaic of ownerships and management objectives makes the Rio Puerco an excellent candidate for ecosystem management-oriented studies.

The Rio Puerco, a tributary of the Rio Grande, is one of the highest sediment-yielding streams of the United States (Aguilar et al. 1990); as much as 20 percent of the Rio Puerco's historical discharge into the Rio Grande is suspended solids (Laquer 1981). From its 19,036 km^2 drainage basin, it produces an average of 2.4 Mt./y (million metric tons per year) of suspended sediment, or an average of 130 t/km^2/y. Bryan and Post (1927) estimated that 500×10^6 m^3 of sediment was eroded from arroyo walls during the period 1885–1927; this translates to an average rate of 12×10^6 m^3/y or approximately 24 Mt./y based on an estimated pre-erosion sediment density of 2 g/cm^3. These calculations suggest that approximately 90 percent of the sediment mobilized in arroyo incision is redeposited within the basin; the remaining 10 percent is exported as suspended sediment load. Dortignac (1956) estimated that two-thirds of Rio Puerco's sediment was derived from arroyo deepening and widening processes, and one-third from sheet and rill erosion of hill slopes; this estimate reduces the redeposited:exported ratio further, to 93 percent:7 percent, or 13:1. Miller (1985) estimated transport rates of 500 t/km^2/y in regional dune fields, which represents a surface-material mobility:average export ratio of 4:1. The Rio Puerco basin clearly exhibits high mobility of surface and near-surface sediments; the great majority of material is redistributed within the basin, but the fluvial channel system nevertheless receives and exports a significant amount of mobilized material. These have been observed and dated only on an incidental basis.

The current arroyo system developed during the latter part of the 19th century. Kirk Bryan (1925), one of the earliest students of the Rio Puerco, cited 1880 as the approximate time of erosion initiation. Sedimentation rates were particularly high during the 40 years that followed (1880–1920). Elephant Butte dam was closed in 1916. Its reservoir immediately was subjected to high deposition rates—so high that the reservoir would be filled with sediment by 2022 if early deposition rates had been sustained. This scenario is disquieting because Elephant Butte Reservoir is the primary management facility for delivery of water to the lower Rio Grande Basin in New Mexico, Texas, and Mexico. Elephant Butte Reservoir's delivery is governed by interstate compacts and by international treaty; enduring operation of the key storage and management facility is a legal, as well as a practical, necessity. The population of this area is growing rapidly, as much as 20 percent per year in selected locations, as is its dependence on reliable water supplies. While most drinking water needs are currently supplied by groundwater pumping, there is increasing concern about the quality and continuity of this source as well as its relationship to the Rio Grande.

The high sedimentation rates of the early part of this century have, fortunately, moderated. At current sedimentation rates the projected lifetime of Elephant Butte Reservoir is beyond 300 years. The Bureau of Reclamation's Albuquerque Projects Office recently (August 1, 1994) issued a "Draft Preliminary Findings Report—Rio Puerco Sedimentation and Water Quality Study" (USDI Bur. Rec. 1994) that contains an excellent review of the literature and available data. This report recommends against construction of control structures to manage sediment from the Rio Puerco, but rather recommends interagency analysis and model development to improve understanding of the system.

Table 1 summarizes published statistics on the Rio Puerco's sediment production. Some statistics cannot be compared directly because, for example, they represent different time periods. There are, nevertheless, apparent discrepancies and interpretation difficulties. For example, Bryan's estimate of a mean arroyo excavation rate of 12×10^6 m^3/y pales (by a factor of 2.5) in comparison to the Elephant Butte Reservoir's measured rate of sediment influx of 30×10^6 m^3/y during the period 1915–1925. Was Rio Puerco's erosion rate higher during the decade 1915–1925 than for the period 1885–1927? Did other tributaries contribute more than half of the sediment load during the 1915–1925 decade? Are pre-erosion sediments substantially denser than post-deposition sediments? Answers to these questions lie in field observations of the Rio Puerco Basin and of Elephant Butte Reservoir.

In-Basin Concerns

The foregoing discussion focused narrowly on sedimentary processes and on the out-of-basin effects on the Rio Grande surface water supply. There are also concerns regarding in-basin land and water resources.

While the Rio Grande channel system and Elephant Butte Reservoir accumulated large quantities of sediment, the Rio Puerco landscape lost it. The

Table 1.—Values taken from the literature indicate magnitudes of various types of mass redistributions in the Rio Puerco watershed.

	Period start	Period end	Basin total	Units	Amount/ area	Units
Area[a]			1.9E+04	km^2		
Area			1.9E+10	m^2		
Area			1.9E+16	mm^2		
Mean water outflow	1941	1993	3.0E+07	m^3/y	1.6E-03	m^3/y
Mean water outflow	1941	1993	3.0E+16	mm^3/y	1.6	mm/y
Mean sediment outflow	1941	1993	2.3E+06	t/y	1.21E+02	t/km^2/y
Mean sediment outflow[b]	1941	1993	1.2E+06	m^3/y	6.1E-05	m/y
Mean sediment outflow[b]	1941	1993	1.2E+15	mm^3/y	0.061	mm/y
Arroyo excavation	1885	1927	5.0E+08	m^3	0.026	m
Arroyo excavation	1885	1927	1.2E+07	m^3/y	6.1E-04	m/y
Arroyo excavation	1885	1927	1.2E+16	mm^3/y	0.61	mm/y
Eolian movement	?	1985			500	t/km^2/y
Eolian movement	?	1985			250	m^3/km^2/y
Eolian movement	?	1985			0	mm/y
EBR sediment[b]	1915	1926	3.0E+07	m^3/y		

[a]includes area of closed inferior drainages
[b]assumed density = 2,000 kg/m^3

arroyos, as suggested earlier, may have lost sediment volume 10 times greater than was exported to the Rio Grande. Natural excavation of such deep grooves in the valley floors drained valley-fill aquifers and defeated extant agricultural surface-water diversions; in an apparent repetition of the demise of the settlement at Chaco Canyon, several agrarian communities abandoned the Rio Puerco basin. Sediment that remained in the basin (>90 percent of the excavated amount) has been redeposited in the lower reaches of the arroyos; vegetation has become established there and retards peak flows in the channel and further increases aggradation. Water tables rise as arroyos continue to refill with sediment. Conditions may be ripe for reinitiation of a basin-wide arroyo cycle (Gellis 1991).

What factures or combinations of factors will initiate the next cycle of erosion? What measures might be taken to ameliorate negative impact? Of measures that might be identified, which ones provide optimum benefits? What observations or monitoring would provide early warning of pending erosion? These are practical questions of concern to landowners and to land and water resource managers of the Rio Puerco and downstream areas.

Mining is a substantial activity in the Rio Puerco Basin, particularly in its southwestern quadrant. Both radioactive and toxic minerals are present in mine tailings that are exposed on the land surface. Tailings materials have episodically entered the drainage network and certainly do so on a continuous basis in a setting where surficial materials are highly mobile (Miller 1985). The presence of these materials poses both in-basin and downstream threats to water and environmental quality. In its recent study, the Bureau of Reclamation (1994) concluded: "Evidence exists that heavy metal and radionuclide contaminants are carried into the Rio Grande by the Rio Puerco. The majority of these contaminants are attached to sediment particles. It is not known whether the Rio Puerco contributes trace metals or radionuclides to the Rio Grande in quantities sufficient to cause health risks to humans or adverse ecological effects."

Research Problems

More than 1,200 technical references have been cited in a recent review of Rio Puerco literature; yet, in spite of such extensive scientific scrutiny, the cause, character, and future of erosion in the basin remain subjects of debate. Various authors have attributed arroyo incision to climatic variations or changes; to grazing; to roads and stock trails; to combinations of these factors; or to cyclic behavior of arroyo systems (coupled or uncoupled with climate variations). The ambiguity

of interpretation of the prehistoric and historic record encourages study of the Rio Puerco arroyo processes through the use of numerical simulation models.

Arroyo-inducing conditions and high sediment yields are not synchronous with climate conditions owing to the critical role of vegetation as landscape armor. It takes several years for plants to succumb to stress and more for their physical soil-stabilizing structures to decompose. Other factors, such as grazing, accelerate the removal of sediment-fixing plant structures, but these also have their characteristic rates of progress. Thus, there are unknown delays between climatic causative conditions and high erosion; there are further delays (transmission times) in the channel system itself.

Conceptual Model

A simple model of influences over sediment-generating processes can be conceptualized. Hillslope conditions are interposed between major causative factors—weather and human activities—introducing characteristic time responses that delay, mask, and mix the driving signals. One could develop a model that incorporates the essentials of these dynamics in a way that allows for substantial duplication of historical observations. Such a model will be used to investigate effects that would follow different driving conditions—primarily changes in climate and human-influenced conditions such as grazing.

A structured sequence of hypotheses and tests for this project could be:

1. *Hypothesis*: A linear arroyo characterized by typical but static Rio Puerco soil, slope, and vegetation conditions exhibits repeated episodes of incision and high sediment discharge when driven with historical regional weather.
   Implications: If the hypothesis is true, then the factors of dynamic vegetation, soil disturbance, and drainage network geometry may be contributory but are not essential to the gross behavior of the arroyo system. Gross behavior of the system can be used, at least qualitatively, to investigate frequency and intensity of sediment production of the basin, including production of entrained toxic materials. If the hypothesis is false, then the effect of each of the named factors must be considered.
2. *Hypothesis*: A simple, branched arroyo characterized by typical but static Rio Puerco soil,

slope, and vegetation conditions exhibits repeated episodes of incision and high sediment discharge when driven with historical regional weather.
   Implications: If hypothesis 1 was false but this hypothesis is true, then interaction among tributaries, or between tributaries and main channel, is an essential driver of arroyo instability. If the hypothesis is true, then the factors of dynamic vegetation and soil disturbance may be contributory but are not essential to the gross behavior of the arroyo system. If false, then the effect of each of these additional factors must be considered.

Development of an object-oriented arroyo dynamics process simulation model is currently underway at the TERRA laboratory (Watts et al. 1994). This model is based on geographic coverage of the Rio Puerco. The hydrologic system of the Rio Puerco is mapped from digital elevation models at 30 m resolution of the entire Basin. The resulting stream system can be analyzed automatically using geographic statistics. This allows the watershed to be analytically reduced into a combination of channel reach segments. The model being developed at TERRA treats each channnel reach as a separate object having a headwater, a right, and a left input. The system can be simulated with whatever degree of complexity is necessary by linking these objects into a simulated map of the channel system. Since the dynamics of arroyos depend on a number of features beyond simply the hydrology, each object contains geomorphic, vegetation, and other characteristics.

NUTRIENT RETENTION, STREAM METABOLISM, AND ARROYO FORMATION

The perception of streams as inanimate pipes that drain watersheds has been rejected by both hydrologists and ecologists. Streams are no longer viewed as receptacles for hillslope water; instead, groundwater and surface water fluxes are now considered interactive and hydrologically integrate hillslope and channel systems (Bencala 1993; Harvey and Bencala 1993). Solute transport in all ecosystems is tied to the movement of water. Given the advective, unidirectional transport characteristic of lotic systems, the retention of nutrients and organic matter is an insightful measure of ecosystem functioning. A suite of physical, chemical, and biological processes de-

lays the downstream flux of nutrients, and the interplay of these factors influences the structure and functioning of stream systems. Geomorphic differences among streams can have a large impact on the retention and cycling of nutrients (Lamberti et al. 1988; Coleman and Dahm 1990; Gregory et al. 1991). In the Rio Puerco drainage, arroyo formation is an agent of geomorphic change that is of great importance to downstream environments and terrestrial systems within the catchment. In this study plan, we describe a research program to assess the influence of arroyo formation on the retention of nutrients by headwater streams of the Rio Puerco, New Mexico.

Hydrologic Retention

Stream channel complexity, as well as surface water-groundwater interactions, entrain nutrients in flowpaths that move at slower velocities than those predicted by the average advective velocity of surface flow. The resulting delay in transport is known as hydrologic retention and has been quantified using conservative hydrologic tracers (Bencala and Walters 1983; Stream Solute Workshop 1990). Analysis of tracer response in wells provides point measurements of hydrologic retention in interstitial water. Individual wells reveal the extent of penetration of surface water into the groundwater at specific locations. Average travel time to a sampling well expresses the rate of exchange between surface water and groundwater. In this manner, distribution of conservative tracers in well networks can provide a qualitative measure of hydrologic retention along a reach of stream (Triska et al. 1989, 1993).

Downstream transport of water and tracer can be simulated using numerical models to provide a quantitative measure of hydrologic retention (Bencala and Walters 1983; Stream Solute Workshop 1990; Runkel and Broshears 1991). One such approach is the One-dimensional Transport with Inflow and Storage model (OTIS) developed by Runkel and Broshears (1991). This model treats the stream as a two compartment system—a main stream channel and a transient storage zone. Transient storage reflects the temporary delay of downstream transport and includes hydrological and geomorphic features of surface and subsurface systems. The size of the storage zone can be determined by OTIS to provide a quantitative, comparative, reach-scale measurement of hydrologic retention.

Recent studies have sought to identify features of stream ecosystems that influence and organize transient storage. Surface complexities such as debris dams have been shown to increase hydrologic residence time and enhanced retention of particulate organic material (Speaker et al. 1984; Trotter 1990; Ehrman and Lamberti 1992). D'Angelo et al. (1993) examined the relationship between stream order and transient storage. They found an overall decrease in storage zone size with increasing stream order.

The interaction of surface water with groundwater also contributes to transient storage in lotic ecosystems (Bencala and Walters 1983). Surface and subsurface systems of streams are linked by vertical gradients causing groundwater discharge (upwelling) and recharge (downwelling) that result from stream bottom geometry (Vaux 1968; White et al. 1987) and hillslope-channel water interaction (Harvey and Bencala 1993). The term "hyporheic zone" refers to the subsurface component of transient storage and is defined as the region of groundwater that receives water from the above-ground channel (Triska et al. 1989). Hyporheic flowpaths have been identified as a significant source of hydrologic retention in gravel-bottom streams (Castro and Hornberger 1991; Bencala 1993).

The magnitude of subsurface storage changes with space and time. Constrained stream reaches occur when the valley floor is less than two times the active channel, reflecting geomorphic limits on the lateral extent of the fluvial system (Gregory et al. 1991). Using the above definition, D'Angelo et al. (1993) showed that transient storage was higher in unconstrained segments of a stream in the Pacific Northwest than in constrained reaches of the same stream. For a single stream reach, transient storage changes with time. For headwater streams of Appalachian (D'Angelo et al. 1991) and New Mexican (Morrice et al., in review) mountains, there is a negative correlation between discharge and hyporheic zone size.

Morrice et al. (in review) identified hydraulic conductivity as a parameter that influences hydrologic retention through its affect on surface water-groundwater exchange. Using hydrologic tracers, we compared the transient storage of three headwater streams located in catchments of contrasting geologic material and differing alluvial properties (Morrice et al. [in review], Valett et al. [in review]). The rate and spatial extent of hydrologic interaction between the streams and their alluvial aquifers decreased with decreasing alluvial hydraulic conductivity and decreasing channel complexity.

Hydrologic interaction between streams and their alluvial aquifers is heavily influenced by

hydrogeologic parameters (e.g., hydraulic conductivity) and surface channel features, as well as fluvial geomorphology, including channel gradient, sinuosity, and width-to-depth ratio (Larkin and Sharp 1992). Ecological consequences of arroyo formation on headwater streams probably reflect geomorphological responses of the fluvial system. We suggest that because of its close relationship to reach complexity, hydrologic retention will be sensitive to the potential impacts of stream incision and arroyo formation.

Biological Retention

Nutrient transport in streams can also be attenuated by pathways involving biological retention. In lotic ecosystems, the competing processes of hydrologic export and biological retention are expressed in the nutrient spiralling concept (Webster and Patten 1979; Elwood et al. 1982; Newbold et al. 1983). Downstream transport adds longitudinal displacement to nutrient cycles such that they act as nutrient spirals. Comparisons of solute loads (mass transported per unit time) at successive points along a reach provides a measure of nutrient uptake or release. Ecosystem retention is then calculated as the net difference between inputs and outputs from an established reach (Grimm 1987; Stream Solute Workshop 1990; Triska et al. 1990).

Biological retention in streams can be measured in reach-scale experiments that involve the concomitant release of conservative (non-active) and non-conservative (biologically active) solutes. Uptake lengths represent the average distance traveled by a solute (*sensu* Newbold et al. 1983) and are determined from analysis of plateau concentrations of conservative and non-conservative solutes at successive points along a reach.

Hyporheic zones are historically known as habitat for unique and diverse invertebrate assemblages (for review see Williams 1984), but these groundwater/surface water mixing zones also affect stream metabolism (Grimm and Fisher 1984; Metzler and Smock 1989) and nutrient dynamics (Triska et al. 1989; Duff and Triska 1990; Hill 1990; Hendricks and White 1991). Because subsurface sediments are metabolically active, hyporheic zones may act as sources or sinks of nutrients depending on the relative magnitude of processes generating or immobilizing biologically important solutes (Triska et al. 1989; McDowell et al. 1992).

Morrice et al. (in review) and Valett et al. (in review), found that nitrate uptake length was correlated with storage zone size. Increased hydrologic exchange between surface water and groundwater promoted tighter cycling of nitrogen between surface and interstitial systems. Mixing between surface water and groundwater integrates the biogeochemistry of these regions and generates nutrient fluxes that may influence processes in both subsystems (Gibert et al. 1990; Valett et al. 1994).

Metabolism and Nutrient Cycling in Stream Hyporheic Zones

The size of the hyporheic zone and the direction and magnitude of groundwater-surface water interaction varies greatly among and within catchments, and has important implications for ecosystem metabolism and nutrient cycling. For example, Valett et al. (in review) found that interstitial dissolved oxygen concentrations were significantly correlated to the rate of exchange between surface and subsurface. This suggests that residence time in aquifer sediments governs oxygen availability and strongly influences redox potential along subsurface flow paths. Microbial respiration in groundwater proceeds through a predictable series of electron acceptors (O_2, NO_3^{-1}, Mn^{+4}, Fe_3^+, SO_4^{-2}, CO_2) reflecting the nature of their hydrologic supply (Chapelle and Lovely 1990). Additionally, respiration rates in stream systems (surface and subsurface) are linked to the supply of dissolved organic carbon (Dahm 1981; Kaplan and Bott 1982, 1989; Findlay et al. 1993; Vervier et al. 1993; Jones et al. [in review]) and availability of terminal electron acceptors. Since residence time affects dissolved oxygen distribution, we predict that hyporheic zones in basins with low rates of surface water-groundwater exchange will be dominated by anaerobic metabolism. In contrast, interstitial regions with high rates of surface water-groundwater exchange should be well oxygenated and dominated by aerobic processes.

Arroyo Formation and Lotic Ecosystem Functioning

Across stream systems, basin lithology influences the availability of biologically important solutes (Hynes 1975; Kruger and Waters 1983; Munn and Meyer 1990; Pringle and Triska 1991), properties of alluvial materials, sediment bed loads (Kelson and

Wells 1989), and groundwater/surface water interaction (Morrice et al. [in review]). Within catchments, nutrient retention has been shown to vary among pools, riffles, and debris dams (Munn and Meyer 1990) and is influenced by varying geomorphology within similar reach types (Coleman and Dahm 1990) and frequency of woody debris (Trotter 1990; Ehrman and Lamberti 1992). Within streams, variation in channel geomorphology influences ecosystem functioning. Just as D'Angelo et al. (1993) found lower transient storage in constrained reaches, Lamberti et al. (1988) concluded that constrained reaches were far less retentive of dissolved and particulate matter than were unconstrained reaches where channel complexity is higher.

In the semiarid southwest, stream-bed sediments of sandy-bottom streams are metabolically active (Grimm and Fisher 1984; Coleman and Dahm 1990; Valett et al. 1990) and highly mobile (Wertz 1963; Graf 1988), reflecting variable precipitation (Molles and Dahm 1990) and the influence of flash floods (Graf 1988). Under these conditions, movement of sediments may represent a significant disturbance to instream aquatic communities of the surface (Gray 1980; Boulton et al. 1992a) and hyporheic zone (Boulton et al. 1992b) and to ecosystem processes (Fisher et al. 1978; Grimm and Fisher 1989; Valett et al. 1994).

Mobilization of vast quantities of sediments due to arroyo formation has been a focus of concern for managing agencies in the southwestern United States (Hereford 1987; Lagasse et al. 1987; Watts et al. 1994). In New Mexico, the Rio Puerco contributes an enormous amount of sediment to the Rio Grande (and ultimately to Elephant Butte Reservoir), but Watts et al. (1994) emphasized that over 90 percent of the mobilized sediment is redeposited within the basin. Associated with convective thunderstorms, summer floods in the headwater streams of the Puerco restructure channel geomorphology, decimate benthic stream biota, and initiate stream incision and arroyo formation. In other sandy-bottom streams disturbed by flash floods, rates of ecosystem recovery are influenced by nutrient fluxes between groundwater and benthic environments (Valett et al. 1994). While arroyo formation is recognized as a critical issue for terrestrial and fluvial systems in terms of sediment erosion and transport, little is known about its local implications on biological aspects of headwater streams. Via its impacts on small-scale (e. g., 100–1000 m) stream geomorphology and its potential to disturb aquatic communities, arroyo formation may affect the rates of groundwater-surface water exchange, ecosystem metabolism, and nutrient retention in perennial headwater streams of the Rio Puerco drainage.

Research

Objectives

The structure and functioning of stream ecosystems are intimately linked to processes occurring at the watershed scale (Hynes 1975). For this reason, the biogeochemistry of streams has been used as an indicator of disturbance and successional state in adjacent terrestrial ecosystems (Likens et al. 1970; Vitousek and Reiners 1975). Cyclical arroyo formation impacts the structure and functioning of downstream reaches (e.g., Rio Grande, Elephant Butte Reservoir) and alters upland terrestrial systems, but nothing is known about its impact on the perennial aquatic habitats of headwater streams.

The general objective of this research is to determine the effect of arroyo formation on nutrient retention in headwater streams of the Rio Puerco Basin. To do this, we will interact with researchers from the Bureau of Land Management who have established study sites on a number of perennial streams near the San Pedro Wilderness in the Jemez Mountains of the Santa Fe National Forest. We will describe ecosystem structure in areas variably impacted by arroyo formation and compare nutrient dynamics in incised and unconstrained reaches. Finally, we will compare retention in these sites to a similar stream (Rio Calaveras) in the Jemez Mountains where we have studied hydrologic and biological retention and stream/groundwater interactions for the past three years (see Wroblicky et al. 1992; Morrice et al. [in review]; Valett et al. [in review]). Our current study plan includes studies of arroyo influences within single streams and comparisons of retention between an arroyo-impacted catchment and a reference catchment not impacted by arroyo formation.

Specifically, we will: (1) describe the hydrogeologic and chemical conditions of surface water and groundwater environments in headwater catchments of the Rio Puerco that are impacted by arroyo formation, (2) determine the influence of arroyo formation on the retention of water and nutrients, and (3) investigate the metabolic activity of sediments deposited in perennial reaches and imported from ephemeral tributaries (e.g., arroyos). We will pursue these objectives with three research elements: (1) structure

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of the groundwater/surface water interface, (2) hydrologic and biological aspects of nutrient retention, and (3) metabolism and carbon cycling in stream sediments.

Study sites

The initial phase of our research will focus on establishing study sites in perennial reaches of headwater streams that drain into the Rio Puerco near Cuba, New Mexico, on the western slopes of the Jemez Mountains in the Santa Fe National Forest. We will coordinate our efforts with ongoing research projects organized by the Bureau of Land Management focusing on headwater restoration in the Rio Puerco basin. Perennial reaches of headwater streams near the San Pedro Wilderness Area will be assessed. Potential study sites now include San Pablo Creek, the Rito Leche, and Nacimiento Creek near Señorito Canyon.

Structure of the groundwater/surface water interface

Initial field sampling will be aimed at characterizing the hydrogeologic and biogeochemical conditions of surface and groundwater environments in our study streams. Using standard methods modified for use in sandy-bottom streams, we will analyze hydrogeologic properties (e.g., vertical hydraulic gradients, alluvial hydraulic conductivity) and the distribution and concentration of biologically important (e.g., redox-sensitive) solutes at the benthic/hyporheic interface. We will compare biogeochemical structure of incised and unconstrained reaches and the physical-chemical conditions of saturated sands entering the main channel from ephemeral tributaries (e.g., arroyos). Results from these surveys will be used to identify characteristic reach types and locate sites for experimentation (see below).

Hydrologic and biological aspects of nutrient retention

Rivers and streams are "open" ecosystems, dominated by physical transport of nutrients across upstream and downstream boundaries. The downstream flow of water accounts for the vast majority of the input and output of materials for a reach of stream or river (Cummins et al. 1983; Grimm 1987). Retention integrates the processes that retard the movement of nutrients out of an ecosystem and is defined as the difference between inputs and outputs over a designated time period (e.g., retention = [nutrients in—nutrients out]/time). Biological activity entrains nutrients in plant and animal biomass, reducing the movement across the downstream boundary. This is a significant component of nutrient retention in streams. Similarly, nutrients may enter volumes of water moving much slower than the main current. Pools, eddies, backwaters, and flowpaths routing surface water through the near-stream groundwater system are features of streams that result in hydrologic retention. We will investigate the influence of arroyo formation on the hydrologic and biological retention of NO_3-N. We focus on NO_3-N because it is the predominant form of plant-available nitrogen in streams and because nitrogen is the nutrient commonly limiting biological processes in southwestern streams and rivers (Grimm and Fisher 1986).

This research element addresses the impacts of arroyo formation on hydrologic and biological mechanisms of nutrient retention. We will compare transient storage and nutrient uptake lengths within individual streams and compare results to those already analyzed for a nearby reference stream (Rio Calaveras, Jemez Mountains, New Mexico) to investigate the influence of arroyo formation on nutrient retention.

Question 1: How does arroyo formation influence hydrologic retention in headwater streams of the Rio Puerco Basin?

Hypothesis 1: Decreased channel complexity and deposition of silt in the beds of arroyo-cut streams results in decreased hydrologic retention.

Predictions: (1) Transient hydraulic storage will be lower in reaches where arroyo formation has impacted the stream channel through incision and/or deposition of fine-grained sediments. (2) Average values for transient storage in Rio Puerco headwaters will be less than in the reference stream (Rio Calaveras).

Alternatively, sediment deposition may provide extensive sand bars and channel storage that promotes subsurface flow and hydrologic retention.

Tests: After identifying geomorphic reaches associated with arroyo formation, we will compare the transient storage of incised (or constricted) reaches with intact reaches of greater channel complexity. Bromide will be used as a biologically and chemically conservative solute to be injected into the surface waters of all study reaches. Bromide transport will be simulated by a one-dimensional transport with inflow and storage computer model (OTIS, Runkel, and

Broshears 1991). Transient storage size (As) is a parameter of the OTIS model that is widely accepted as a measure of hydrologic retention, and will be determined and compared among reaches and streams. Comparison of As among reach types will assess the extent and variation in transient storage with the Rio Puerco headwaters. Comparisons with past injections in the reference stream will be used to test the prediction that arroyo-impacted streams have less transient storage.

Increased hydrologic retention results in longer contact time between water and microbial communities of benthic and hyporheic habitats. Our past research has shown that uptake lengths (the average downstream distance a molecule of nitrate travels in solution before being entrained by biological processing) and transient storage are closely related (Valett et al. [in review]).

Question 2: How does arroyo formation affect the retention of NO_3-N in headwater streams of the Rio Puerco Basin?

Hypothesis 2: Disturbance in the form of scouring during elevated flow and instability of sediments at base flow maintains lower biological activity in the stream channel resulting in reduced nitrate retention in streams affected by arroyo formation.

Predictions: (1) Uptake lengths for NO_3-N will be greater in streams heavily impacted by arroyo formation (e.g., longer uptake lengths will occur in the Rio Puerco headwaters compared to the reference stream). (2) Uptake lengths will be longer in constrained (incised) reaches compared to unconstrained reaches.

Tests: Uptake length for NO_3-N will be determined from experiments in which nitrate is injected with a conservative tracer (Tests for Hypothesis 1, above). Calculated uptake lengths will be compared among study streams (Rio Puerco streams vs. Rio Calaveras) and designated reaches (constrained vs. unconstrained) to assess differences in biological nutrient retention.

Metabolism and carbon cycling in stream sediments

This research element focuses on carbon cycling and the rates and nature of metabolic processes in the sediments of arroyo-impacted streams and associated shallow groundwater systems. Convective thunderstorms and intermittent flows in arroyo tributaries are expected to result in the importation of fine-grained sediments that are low in organic matter content. This research element addresses the intensity of biological activity and the implications of hydro-

logic exchange between surface and interstitial zones on the metabolism of saturated sediments in headwater streams of the Rio Puerco.

Question 3: What is the influence of arroyo formation on aquatic microbial processes that cycle carbon?

Hypothesis 3a: Because of low organic matter content and frequent disturbance, metabolic demand of stream sediments will be low compared to the hydrologic supply of oxygen, promoting aerobic metabolism in the hyporheic zone.

Prediction: (1) Stream sediments will be low in organic matter (e.g., < 1 percent by weight). (2) Porewater will be well oxygenated. (3) Metabolic activity in sediment will occur aerobically.

Hypothesis 3b: Grain size and other alluvial properties of imported sediments will result in low rates of exchange between oxygenated surface water and metabolically active subsurface regions resulting in anaerobic metabolism and nutrient transformations in stream bed sediments.

Prediction: (1) Alluvial hydraulic conductivity will be low (e.g., less than 1×10^{-5} cm/s) in reaches containing imported sediments. (2) Interstitial water will be anoxic. (3) Metabolic activity in sediments will be anaerobic.

Tests: Sediment cores will be used for measures of respiration, after which sediments will be analyzed for organic matter content. Evolution of CO_2 and O_2 consumption will be used to differentiate between aerobic and anaerobic metabolism in sediment cores. Oxygen concentration in interstitial spaces and alluvial properties will be measured in accordance with Research Element I.

Climatic factors that will be investigated include intense, sustained, or repeated La Niña (dry-winter) conditions and Gulf moisture (intense summer precipitation) conditions. Models will be used to simulate conditions and effects of climate, land use, and vegetation condition on sheet and rill erosion and on arroyo sediment dynamics. The studies have practical application for evaluating water quantity risks imposed on the Elephant Butte Reservoir, located downstream on the Rio Grande from the confluence of the Rio Puerco, and other reservoirs in similar geoclimatic settings. Elephant Butte Reservoir has historically suffered high rates of sedimentation; if these were to recur, then the utility of the dam as the major controlling structure for release of water to the lower Rio Grande (Texas and Mexico) would be impaired. These studies also have practical application to evaluation of water quality risks because toxic and

radioactive mine tailings are copious in parts of the basin; their entrainment in sediments may adversely affect water and riparian habitat downstream. Although these studies focus principally on sedimentary processes, they will provide information that benefit the integrated management of the Rio Puerco and Rio Grande ecosystems. Issues as broad as the health of the bosque or wetland forests, the water supplies of El Paso and Albuquerque, and the general economy of the Rio Grande border region may eventually be related to these analyses.

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Chapter 5
Desert Grassland and Shrubland Ecosystems

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INTRODUCTION

The productivity, stability, and health of the Middle Rio Grande Basin, arid and semiarid grassland and shrubland ecosystems depend upon complex interactions. These relationships occur between factors such as climate, domestic livestock, and wildlife use, and human activities such as urban development, agriculture, and recreation. These grassland/shrubland ecosystems are particularly sensitive to change because they depend highly upon water availability.

Southwestern rangelands experienced heavy livestock grazing and human activities over the past century, which substantially reduced total plant cover and density (Dortignac and Hickey 1963). The greatly reduced fuel loads resulting from livestock overgrazing may have altered the frequency of wildfires in nearby forested environments (Baisan and Swetnam 1995) and probably rangelands. The disruption of natural fire frequency has allowed fire intolerant species to increase, which adversely affects the sustainability of these ecosystems. Soil erosion from Southwestern desert grasslands and shrublands has contributed to nonpoint source pollution, which is reported to be the most serious threat to surface water quality in the Rio Grande Basin (Ellis et al. 1993). It is this alteration of surface water quantity and quality that is largely responsible for the increasing public concern about the health of our nation's rangelands (Joyce 1995).

GEOGRAPHIC DISTRIBUTION

Historical

The following summary of the historical geographic distribution of vegetation in New Mexico is taken from a review by Dick-Peddie (1993). The extensive grasslands and shrublands of North America developed in response to climate change and the uplifting of the western mountain ranges, including the Rocky, Cascade, and Sierra Nevada Mountains, which began in the early to mid-Tertiary period (65–26 million years ago). The vegetation of North America early in the Tertiary period has been grouped into three major gefloras. The Artco-Tertiary Geflora occupied cool, moist, upper latitudes, the Neotropical-Tertiary Geflora occupied the warm, moist, lower latitudes, and the Madro-Tertiary Geflora occupied intermediate, drier regions. Rain shadows created by rising mountain ranges created new habitats for xeric-adapted plant species. The pre-adapted Madro-Tertiary Geflora quickly expanded its range into this new habitat, while the Arcto- and Neotropical-Tertiary Gefloras were forced north and south, respectively. Interestingly, the major grass species of the present grasslands are actually xeric-adapted remnants of the Arcto- and Neotropical-Tertiary Gefloras. The Madro-Tertiary Geflora today is represented primarily by desert scrub and pinyon pine.

Analysis of fossil pollen suggests that there were no extensive grasslands in New Mexico until approximately 12,000 years ago when coniferous woodland was replaced by grassland as the climate became warmer and drier. Although New Mexico's climate experienced several cooling and warming changes in the past several thousand years, it has remained fairly stable for the past 800–600 years.

Current

The Rio Grande Basin begins in southern Colorado and extends through New Mexico, between western

Texas and Chihuahua, Mexico, to the Gulf of Mexico. The basin itself is a major rift valley produced by a series of grabens (elongated depressions between parallel faults) that have subsided along the crests of the surrounding plateaus and mountains. The central and southern portion of the rift are included in the Basin and Range Section of the Chihuahuan Semi-Desert Province (Bailey et al. 1994). However, the central and northern portions of the rift, bounded by the Colorado Plateau and southern Rocky Mountains, are distinct morphotectonic basins (Baldridge et al. 1983). The Middle Rio Grande Basin (Cochiti Lake to Elephant Butte Reservoir) is bounded on the west by the San Juan Basin of the Colorado Plateau and on the east by the linear mountain chain including the Sandia, Manzano, and Los Pinos Mountains. This geographic area encompasses part of the Central Rio Grande Intermontane Ecosubregion (Bailey et al. 1994).

GEOLOGY/GEOMORPHOLOGY

The desert grassland and shrubland ecosystems within the Rio Grande Basin are largely established on Quaternary alluvium along streams and alluvial fan deposits near the mountain fronts. However, these vegetation assemblages are also commonly found on Miocene volcanic rocks and volcaniclastic deposits in the northern portions of the Rio Grande Basin and on Oligocene and older sedimentary rocks associated with the Great Basin grassland type along the margins of the Rio Grande Basin and with the Colorado Plateau to the west. Detailed discussions on the geomorphological distribution of the various alluvial deposits, volcanic parent materials, and sedimentary parent materials are available in Bulletin 137, New Mexico Bureau of Mines and Mineral Resources (1991), Baldridge et al. (1983), and Gile et al. (1981).

CLIMATE

Climate in Rio Grande Basin grassland ecosystems is one of extremes. Plant growth and production are predominantly controlled by soil water content which is highly variable within and between years, depending upon precipitation patterns. Grasslands, including those of the middle Rio Grande Basin, are not merely controlled by total annual precipitation, but by complex relationships such as the precipitation-evaporation ratio and the seasonality of precipitation in relation to the temperature regime and growing season (Risser et al. 1981).

Mean annual precipitation in the Middle Rio Grande Basin grassland and shrubland ecosystems ranges from a low of 200 mm to over 400 mm at the higher elevations to the north (Dick-Peddie et al. 1993). A large portion of this rainfall occurs as high intensity, short-lived thunderstorms. Snow is common during the winter months (December through March) but the contribution of these storms to the total annual precipitation is less than that of the summer thunderstorms.

The distribution and availability of water are the major factors determining the composition and structure of arid ecosystems, but plant growth and productivity in these ecosystems are greatly modified by soil parent material and topography. For example, Aguilar and Heil (1988) found that organic matter and associated C, N, and P in Plains-Mesa Grassland varied with microclimate, which was strongly correlated to landscape position and parent material. Organic matter in soils characterized along toposequences in sandstone, siltstone, and shale parent materials in southwestern North Dakota rangeland generally increased downslope. Greater quantities of organic matter on lower landscape segments were attributed to greater vegetation productivity due to higher effective precipitation and to accretion of soil organic matter from runon and organic matter-enriched sediment deposition.

SOILS

Detailed information on general soil characteristics for specific sites within the Basin can be obtained from soil surveys published by the USDA Soil Conservation Service's (USDA-SCS, now USDA-NRCS) National Cooperative Soil Survey and Forest Service (USDA-FS). Published soil surveys encompassing the Middle Rio Grande Basin include: Soil Survey of Santa Fe Area (Santa Fe County and Part of the Rio Arriba County) August 1975; Soil Survey of Sandoval County (in press); Soil Survey of Bernalillo County and Parts of Sandoval and Valencia Counties, June 1977; Soil Survey of Valencia County - Eastern Part, April 1975; Soil Survey of Socorro County Area, December 1988; Soil Survey of Sierra County Area, June 1984, General Ecosystem Survey USDA-FS and Terrestrial Ecosystem Survey of the Santa Fe National Forest.

Soils associated with the grassland and shrubland ecosystems of the Middle Rio Grande Basin are classified within the orders of Aridisols, Entisols, and

Mollisols. Suborders of the Aridisols common in the Basin include Argids, Calcids, Cambids, and Gypsids. These calcareous and alkaline soils are characterized by relatively low organic matter and have soluble secondary salts, including calcium carbonate and in some cases gypsum, at varying depths within the soil profile. The Argids are older soils generally found on the older and more stable landscapes and have well-developed secondary clay enriched subsurface horizons and in many cases have a petrocalcic (calcium carbonate and/or silica cemented) horizon at depth.

The Entisols, soils with little pedogenic development, are represented in the Basin by the suborders Orthents, Psamments, and Fluvents. Orthents are widely distributed on some of the more active landscapes including recently active alluvial fans and arroyos and in shallow sediments over slowly weatherable parent materials such as volcanic basalts and sedimentary bedrock. Psamments, high sand content soils, are common in eolian deposits such as active or stabilized dunes. Fluvents, characterized by stratification and irregular decreases in organic matter with depth, are common on floodplains along perennial stream channels and ephemeral drainages.

Mollisols, soils with much higher organic matter contents than Aridisols and Entisols, are less extensive in the Middle Rio Grande Basin, but do occur in the more moist environments of steppe and montane meadows at higher elevations of the Basin.

Perhaps the most important property of soils in any arid or semiarids ecosystem is organic matter (Stott and Martin 1989; Aronson et al. 1993). Soil organic matter content reflects the balance of surface litter and belowground root production inputs and loss through microbial decomposition. Although soil organic matter in Middle Rio Grande Basin grassland and shrubland soils is relatively low, ranging from about 3 percent to less than 1 percent, the importance of soil organic matter to site stability and productivity far outweighs that of other soil properties. Soil organic matter influences virtually all aspects of soil fertility and plays a key role in nutrient cycling, thus inhibiting the process of desertification by increasing soil aggregate stability and resistance to erosion (Tate 1987).

HYDROLOGY

The availability of clean water for residential, commercial, agricultural, and wildlife use is the most critical resource problem within the Middle Rio Grande Basin. Vegetation in the grasslands and shrublands of the Basin depends on surficial hydrologic processes, such as runoff (surface water lost from a site), runon (surface water deposited on a site), infiltration, and evapotranspiration. High intensity thunderstorms common during the summer and early fall months (July through September) often generate large volumes of runoff. With the exception of the Rio Grande and its major tributaries (including the Jemez River, the Chama River, and the Rio Puerco), perennial surface water is relatively scarce in the Middle Rio Grande Basin. Many ephemeral channels carry water only after localized, high intensity rainstorms. Runoff water generally carries large quantities of suspended solids. The Rio Puerco, in particular, has been included among the highest sediment yielding drainage areas in the United States. As suggested by the stream's Spanish name, implying "muddy river," high sediment loads are a natural characteristic of the Rio Puerco. The Rio Puerco Watershed has a deeply incised streambank and an exceptionally high rate of gully erosion and bank erosion and collapse contributing to the stream's high sediment load (Love 1986; Love and Young 1983; Wells et al. 1983; Wells et al. 1982).

Runoff and sediment yields from grasslands and shrublands can be highly variable in the Middle Rio Grande Basin, dependent upon plant community composition, ground cover, and specific soil properties (e.g., infiltration rates). Aguilar and Aldon (1991) reported that two distinct soil/vegetation assemblages a few hundred meters apart within the Rio Puerco Watershed Resource Area had differences in runoff rates of 6 to 8 times, with differences in sediment yield of 10 to 15 times. Sediment-laden runoff from degraded sites within the Middle Rio Grande Basin has had a significant impact on the water quality of the region's perennial streams and rivers (NM Water Quality Control Commission 1995).

VEGETATION ASSEMBLAGES

For the purposes of this review we are using a broad classification of grassland and shrubland ecosystems in the Middle Rio Grande Valley. Our ecosystem designations combine a previous classification (Dick-Peddie 1993) of Chihuahuan Desert Scrub, and Plains-Mesa Sand Scrub into shrubland and Desert Grassland and Plains-Mesa Grassland into desert grassland (Fig. 1). Detailed discussions of veg-
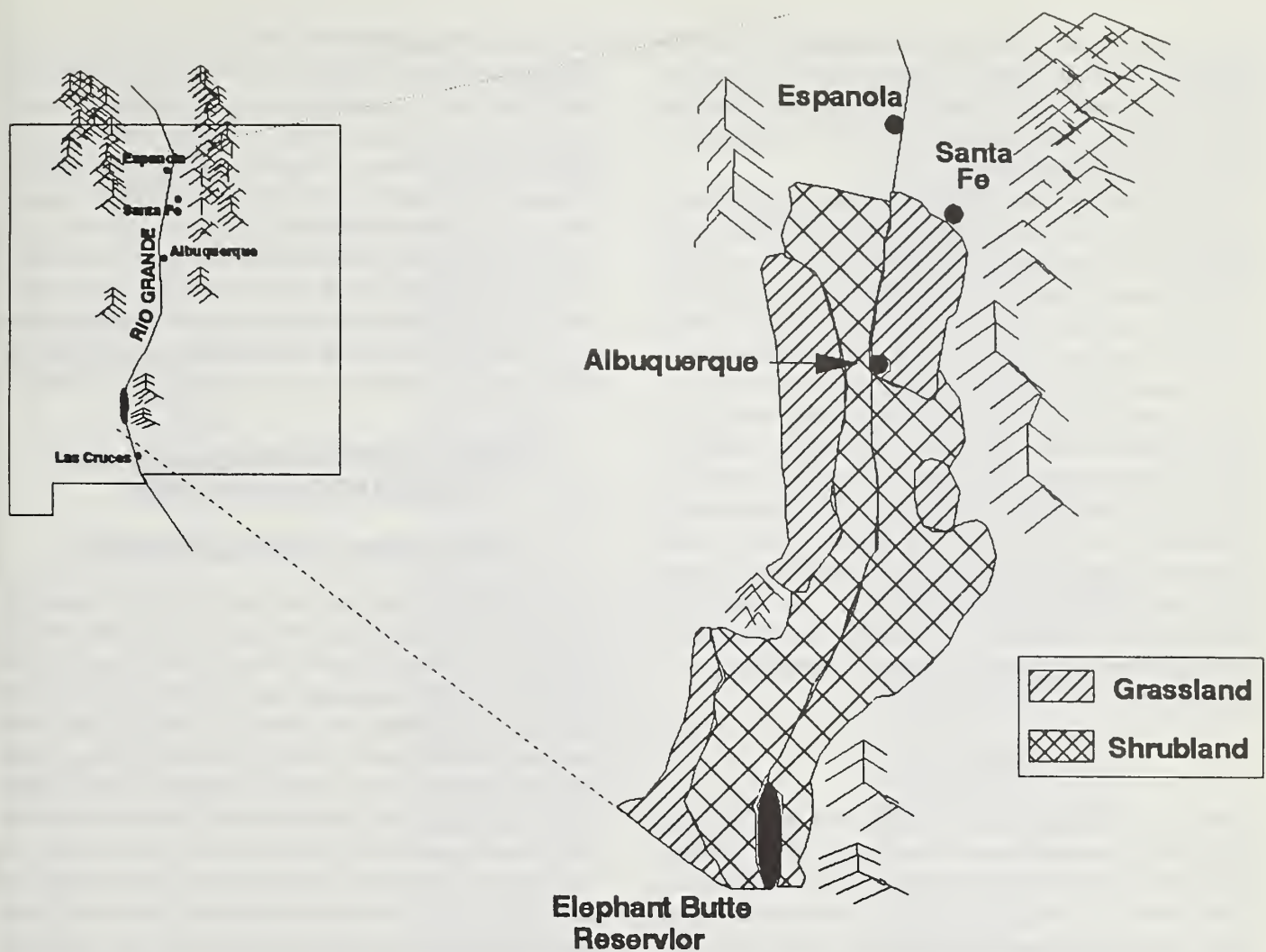
Figure 1.—Distribution of the major grassland and desertshrubland ecosystems in the Middle Rio Grande Valley, New Mexico.

etation types found in the Southwestern United States and New Mexico can be found in Brown (1982) and Dick-Peddie (1993), respectively.

Chihuahuan Desert Scrub is confined to alluvial terrace sites in the southern portion of the Middle Rio Grande Valley. The northernmost extent of this plant community is near Isleta Pueblo, Bernalillo County, NM. Chihuahuan Desert Scrub occupies regions that receive 200 to 300 mm of rainfall annually, most of which comes from highly variable summer thunderstorms (Brown 1982). The dominant indicator species in this northern region of the Chihuahuan Desert Scrub is creosotebush (*Larrea tridentata*).

Plains-Mesa Sand Scrub is a shrub dominated community that occupies deep, sandy soils throughout the basin. Dominant shrubs include sand sage (*Arte-*

misia filifolia), broom pea (*Dalea scoparia*), and honey mesquite (*Prosopis glandulosa*).

Chihuahuan Desert Scrub grades into Desert Grassland or Semidesert Grassland which occupies an elevational range of approximately 1,100 to 1,600 m (Brown 1982). Desert Grassland receives an average of 250 to 450 mm of rainfall annually, again mostly in summer and fall. Both Brown (1982) and Dick-Peddie (1993) describe Desert Grassland as a plant community between Chihuahuan Desert Scrub and Plains-Mesa Grassland, but with a distinct vegetation assemblage. Desert Grassland generally has a greater shrub component than Plains-Mesa Grassland. Dominant shrub species in this region include the small soapweed (*Yucca glauca*), soaptree yucca (*Yucca elata*), tree cholla (*Opuntia imbricata*), and

broom snakeweed (*Gutierrezia sarothrae*), and the dominant grasses include black grama (*Bouteloua eriopoda*), galleta (*Hilaria jamesii*), three awn (*Aristida spp.*), burrograss (*Scleropogon brevifolius*), and sacaton/dropseed (*Sporobolus spp.*).

At higher elevations and to the north, Desert Grassland mixes with Plains-Mesa Grassland (Plains and Great Plains Grassland). The Plains-Mesa Grassland occupies an elevational range of approximately 1,200 to 2,300 m and receives an average of 300 to 450 mm of rainfall per year. Rainfall in the Plains-Mesa Grassland community is more evenly distributed throughout the year than in the other two vegetation types. The dominant shrub species in this region include Bigelow sagebrush (*Artemisia bigelovii*), winterfat (*Ceratoides lanata*), rabbitbrush (*Chysothamnus nauseosus*), and broom snakeweed (*Gutierrezia sarothrae*), while the grass species include blue grama (*Bouteloua gracilis*), sideoats grama (*B. curtipendula*), galleta (*Hilaria jamesii*), ring muhly (*Muhlenbergia torreyi*), indian ricegrass (*Oryzopsis hymenoides*), and sacaton/dropseed (*Sporobolus spp.*).

WILDLIFE

Many mammals, birds, reptiles, and amphibians utilize the grassland and shrubland habitat of the Middle Rio Grande Basin. Although the number and distribution of larger mammals (carnivores and hoofed mammals) are not great nor unique to the desert grassland/shrubland habitat, a rich community of small mammals (Table 1) unique to these habitats is supported (Grant et al. 1982). Due to the periodic but explosive production of seeds by arid-adapted plants in the Southwest, granivorous, pocket mice and kangaroo rats (family Heteromyidae) represent a large component of the small mammal fauna (Findley 1987). Other rodents utilizing seeds, grasses, and other vegetative, animal, or insect matter in grasslands and shrublands are antelope squirrels, spotted ground squirrel, pocket gophers, harvest mice, several species of *Peromyscus*, grasshopper mice, cotton rats, and woodrats. Current populations of black-tailed prairie dog are drastically lower than historic levels as a result of pest control measures of the past. Also common are the black-tailed jackrabbit and the desert cottontail.

In addition to foraging habitat, desert grasslands provide breeding or year-round habitat for many bird species (table 2) The geographical break of several bird species distributions and the northern end of

year-round range all occur in the vicinity of the Middle Rio Grande Basin for several bird species. Reptiles and amphibians in grasslands and shrublands are represented by one species of salamander, two species of turtles, and several species of frogs, toads, lizards, and snakes (Table 3) (J. Stuart, [personal communication]). Of these species, the western box turtle, the lesser earless lizard, the desert-grassland whiptail lizard, the western hognose snake, and the western hooknose snake are all endemic species centered on Desert Grassland (as opposed to Plains-Mesa Grassland) ecosystems (Brown 1982).

CURRENT ISSUES IN GRASSLAND AND SHRUBLAND MANAGEMENT

Degradation and Desertification

Livestock production has been a major means of economic survival for the many cultures in the Middle Rio Grande Basin. Most authorities believe the Basin's grasslands have been greatly depleted and deteriorated because of livestock overgrazing over the past 100–150 years (Dortignac and Hickey 1963; Sheridan 1981; Grover and Musick 1990; Dick-Peddie 1993). Leopold (1951) documented that there had already been great local reductions in grass forage in the vicinity of Spanish communities within the Rio Grande Basin by the time the second wave of European immigrants moved into New Mexico from the eastern plains during the latter part of the 19th century. Dick-Peddie (1993) reported that New Mexico grassland must still have been very productive even after the turn of the century, considering the amount of livestock present in the state (over one million cattle and almost six million sheep). According to Dick-Peddie, these large numbers of livestock indicated "native forage potentials far in excess of those found today."

Although grassland desertification is often attributed to anthropogenic disturbance, the influence of short-term climatic fluctuation should not be overlooked. A review of rangeland vegetation changes by Branson (1985) reported that during the drought of 1932–1936, basal cover of vegetation in the Mixed Grass or Shortgrass Prairie (Plains-Mesa Grassland) decreased from around 80 percent to often less than 10 percent. Apparently, this kind of response to periodic drought in grasslands is not uncommon and Branson concluded that forage production displayed far greater variation in response to changes in an-

Table 1.—Mammals of grasslands/shrublands in the Middle Rio Grande Basin, NM.

Order	Common name	Scientific name
Artiodactyla	mule deer	*Odocoileus hemionus*
	pronghorn antelope	*Antilocapra americana*
Carnivora	coyote	*Canis latrans*
	kit fox	*Vulpes macrotis*
	long-tailed weasel	*Mustela frenata*
	badger	*Taxidea taxus*
	spotted skunk	*Spilogale putorius*
	striped skunk	*Mephitis mephitis*
	bobcat	*Lynx rufus*
Chiroptera	pallid bat	*Antrozous pallidus*
	California myotis	*Myotis californicus*
Insectivora	desert shrew	*Notiosorex crawfordi*
Lagomorpha	black-tailed jackrabbit	*Lepus californicus*
	desert cottontail	*Sylvilagus auduboni*
Rodentia	silky pocket mouse	*Perognathus flavus*
	Plains pocket mouse	*Perognathus flavescens*
	banner-tailed kangaroo rat	*Dipodomys spectabilis*
	Ord's kangaroo rat	*Dipodomys ordii*
	Merriam's kangaroo rat	*Dipodomys merriami*
	white-tailed antelope squirrel	*Ammospermophilus leucurus*
	Texas antelope squirrel	*Ammospermophilus interpres*
	spotted ground squirrel	*Spermophilus spilosoma*
	black-tailed prairie dog	*Cynomys ludovicianus*
	Gunnison's prairie dog	*Cynomys gunnisoni*
	Botta's pocket gopher	*Thomomys bottae*
	yellow-faced pocket gopher[a]	*Pappogeomys castanops*
	desert pocket gopher[a]	*Geomys arenarius*
	western harvest mouse	*Reithrodontomys megalotis*
	Plains harvest mouse	*Reithrodontomys montanus*
	white-footed mouse	*Peromyscus leucopus*
	deer mouse	*Peromyscus maniculatus*
	cactus mouse[a]	*Peromyscus eremicus*
	pinon mouse[a]	*Peromyscus truei*
	brush mouse[a]	*Peromyscus boylii*
	rock mouse[a]	*Peromyscus difficilis*
	northern grasshopper mouse	*Onychomys leucogaster*
	southern grasshopper mouse	*Onychomys arenicola*
	southern plains woodrat	*Neotoma micropus*
	white-throated woodrat	*Neotoma albigula*
	porcupine[a]	*Erethizon dorsatum*

[a]Indicates occasional presence or presence at periphery of grasslands and shrublands.

nual precipitation than to differences in livestock grazing intensities.

Most sources agree that a combination of long and short term climate change, historic overgrazing, and direct and indirect fire suppression were probably responsible for the degradation and/or desertification of many southwestern grasslands (Westoby et al. 1989; Grover and Musick 1990; Schlesinger et al. 1990; George et al. 1992; Tausch et al. 1993; Milton et al. 1994). The process of degradation and conversion of productive grassland to less productive shrubland, sometimes included as desertification, is especially common in arid and semiarid regions. In the United States alone, over 225 million acres are estimated to

have experienced severe or very severe desertification (Sheridan 1981).

Grasslands are generally considered fire dependent ecosystems because they require periodic disturbance by fire in order to maintain the composition and function of grassland plant species (Desert Grassland is perhaps one exception). Stable grasslands consisted of a mosaic of vegetation and bare interspaces (George et al. 1992; Montana 1992). The dynamics of these stable grassland communities may have been similar to systems described by Watt (1947), where the spatial arrangement of vegetation and interspaces changed through time but the overall amount of space occupied by each component

Table 2.—Birds of grasslands/shrublands in the Middle Rio Grande Basin, New Mexico.

Fomily	Common nome	Scientific nome	Occurrence
Accipitridoe	ferruginous howk	*Buteo regalis*	spr/sum or yeor-round
	Swoinson's howk	*Buteo swainsoni*	spr/sum
	Americon kestrel	*Falco sparverius sparverius*	spr/sum or yeor-round
	proirie folcon	*Falco mexicanus*	spr/sum or yeor-round
Loniidoe	loggerheod shrike	*Lanius ludovicianus*	yeor-round
Strigidoe	burrowing owl	*Speotyto cunicularia hypugaea*	yeor-round
Cuculidoe	roodrunner	*Geococcyx californianus*	yeor-round
Coprimulgidoe	common nighthowk	*Chordeiles minor*	spr/sum
	common poor-will	*Phalaenophtilus nutallii*	spr/sum or yeor-round
Corvidoe	common roven	*Corvus corax*	yeor-round
	Chihuohuon roven	*Corvus cryptoleucus*	spr/sum or yeor-round
	Americon crow	*Corvus brachyrhynchos*	yeor-round
Columbidoe	mourning dove	*Zenaida macroura*	yeor-round
Phosionidoe	scoled quoil	*Callipepla squamata pallida*	yeor-round
Chorodriidoe	mountoin plover	*Charadrius montanus*	spr/sum
Aloudidoe	horned lork	*Eremophila alpestris*	yeor-round
Hirundinidoe	born swollow	*Hirundo rustica erythrogaster*	spr/sum
Remizidoe	verdin	*Auriparus flaviceps ornatus*	yeor-round in south
Troglodytidoe	coctus wren	*Campylorhynchus brunneicapillus couesi*	yeor-round in south
Mimidoe	mockingbird	*Mimus polyglottos leucopterus*	spr/sum or yeor-round
Fringillidoe	house finch	*Carpodacus mexicanus frontalis*	yeor-round
Tyronnidoe	western kingbird	*Tyrannus verticalis*	spr/sum
	osh-throoted flycotcher	*Myriarchus cinerascens cinerascens*	spr/sum
	Soy's phoebe	*Sayornis saya*	spr/sum or yeor-round
Emberizidoe	meodowlork	*Sturnella neglecta*	yeor-round
	brown-heoded cowbird	*Molothrus ater*	yeor-round
	lork sporrow	*Chondestes grammacus strigatus*	spr/sum
	Cossin's sporrow	*Aimophila cassinii*	spr/sum or yeor-round
	lork bunting	*Calamospiza melanocorys*	spr/sum

remained the same. Soil erosion from these systems may have been minimal because of the connectivity of the vegetation and the relative stability of interspace soils, which were probably stabilized by desert pavements and/or cryptogamic (microphytic) crusts (West 1990).

Fire suppression in semiarid grasslands would eliminate the dominant stabilizing force in these fire dependent ecosystems and would allow ecological succession to proceed to shrubland at lower elevations or juniper savanna or Pinyon-Juniper (P-J) woodland at higher elevations (Fig. 2). Extensive livestock grazing exacerbates the situation by decreasing herbaceous plant cover which formerly carried the fire, and disturbing the structure and stability of surface soils, particularly interspace soils. Loose interspace soils can then be blown under the canopy of vegetation (phase I). It is this process of intrasite soil and nutrient redistribution that results in the formation of islands of fertility (Garcia-Moya and McKell 1970; Schlesinger et al. 1990). Often these processes result in the conversion of grassland to shrubland, dominated by non-palatable species, or to P-J Woodland. If this scenario truly results in a redistribution of resources as hypothesized by Schlesinger et al. (1990), and not a net loss of resources, then this process may be reversible.

Continued disturbance of grasslands, shrublands, or P-J Woodlands would result in the expansion and coalescence of bare interspaces. Soil erosion, particularly in areas with moderately steep to steep slopes, would increase because connected interspaces would serve as paths of least resistance to water flow (erosion corridors). Soil erosion via these corridors represents nutrient and water export and loss from the system. At this point (phase II) the system is losing the very constituents it most requires for stabilization and recovery. The ultimate fate of this ecosystem is now under the control of hydrologic and geomorphic processes rather than biological processes. Without intervention, the system can become locked into a cycle of increasing degradation that may eventually stabilize at a state of drastically reduced site productivity (Naveh 1988; El-Tayeb and Skujins 1989; Klein 1989).

Table 3.—Herpetofauna of grasslands/shrublands in the Middle Rio Grande Basin, New Mexico.

Order	Common name	Scientific name
Caudata (salamanders)	tiger salamander	*Ambystoma tigrinum*
Salientia (frogs/toads)	Plains spadefoot toad	*Scaphiopus bombifrons*
	Couch's spadefoot toad	*Scaphiopus couchi*
	New Mexico spadefoot toad	*Scaphiopus multiplicatus*
	Great Plains toad	*Bufo cognatus*
	Plains leopard frog	*Rana blairi*
	bullfrog	*Rana catesbeiana*
Testudines (turtles)	yellow mud turtle	*Kinosternon flavescens*
	western box turtle	*Terrapene ornata*
Squamata- Suborder Lacertilia (lizards)	greater earless lizard	*Cophosaurus texanus*
	collared lizard	*Crotaphytus collaris*
	leopard lizard	*Gambelia wislizenii*
	lesser earless lizard	*Holbrookia maculata*
	Texas horned lizard	*Phrynosoma cornutum*
	round-tailed horned lizard	*Phrynosoma modestum*
	desert spiny lizard	*Sceloporus magister*
	eastern fence lizard	*Sceloporus undulatus*
	side-blotched lizard	*Uta stansburiana*
	Chihuahua whiptail lizard	*Cnemidophorus exsanguis*
	little striped whiptail lizard	*Cnemidophorus inornatus*
	New Mexico whiptail lizard	*Cnemidophorus neomexicanus*
	western whiptail lizard	*Cnemidophorus tigris*
	desert-grassland whiptail lizard	*Cnemidophorus uniparens*
	Plateau striped whiptail lizard	*Cnemidophorus velox*
	Great Plains skink	*Eumeces obsoletus*
Squamata- Suborder Serpentes (snakes)	Texas blind snake	*Leptotyphlops dulcis*
	glossy snake	*Arizona elegans*
	ringneck snake	*Diadophis punctatu*
	western hooknose snake	*Gyalopion canum*
	western hognose snake	*Heterodon nasicus*
	night snake	*Hypsiglena torquata*
	common kingsnake	*Lampropeltis getulus*
	coachwhip	*Masticophis flagellum*
	striped whipsnake	*Masticophis taeniatus*
	gopher snake or bullsnake	*Pituophis melanoleucus*
	long-nosed snake	*Rhinocheilus lecontei*
	patch-nosed snake	*Salvadora deserticola*
	ground snake	*Sonor semiannulata*
	Plains black-headed snake	*Tantilla nigriceps*
	checkered garter snake	*Thamnophis marcianus*
	western diamondback rattlesnake	*Crotalus atrox*
	western or prairie rattlesnake	*Crotalus viridis*
	Massasauga	*Sistrurus catenatus*

Threatened, Endangered, and Candidate Species

Recent changes in Middle Rio Grande Basin vegetation are also attributed to direct human activities such as farming, off-road vehicle recreation, road construction, and urbanization. Not only do these land-use practices affect grasslands and shrublands directly, but these practices also exert indirect effects, through fragmentation and loss of contiguous, larger expanses of habitat.

Protection of biological diversity (flora, fauna) is necessary to maintain ecosystem integrity (Grumbine 1994). Simberloff (1993) stated that fragmentation of habitat is the major global environmental change occurring today and the one most likely to sacrifice the sustainability of biodiversity and ecological processes in the near future. Within the United States, loss of habitat due to human land use was the most common underlying factor in the endangerment of 667 threatened and endangered plant and animal species. Seven of the 10 regions of high species en-
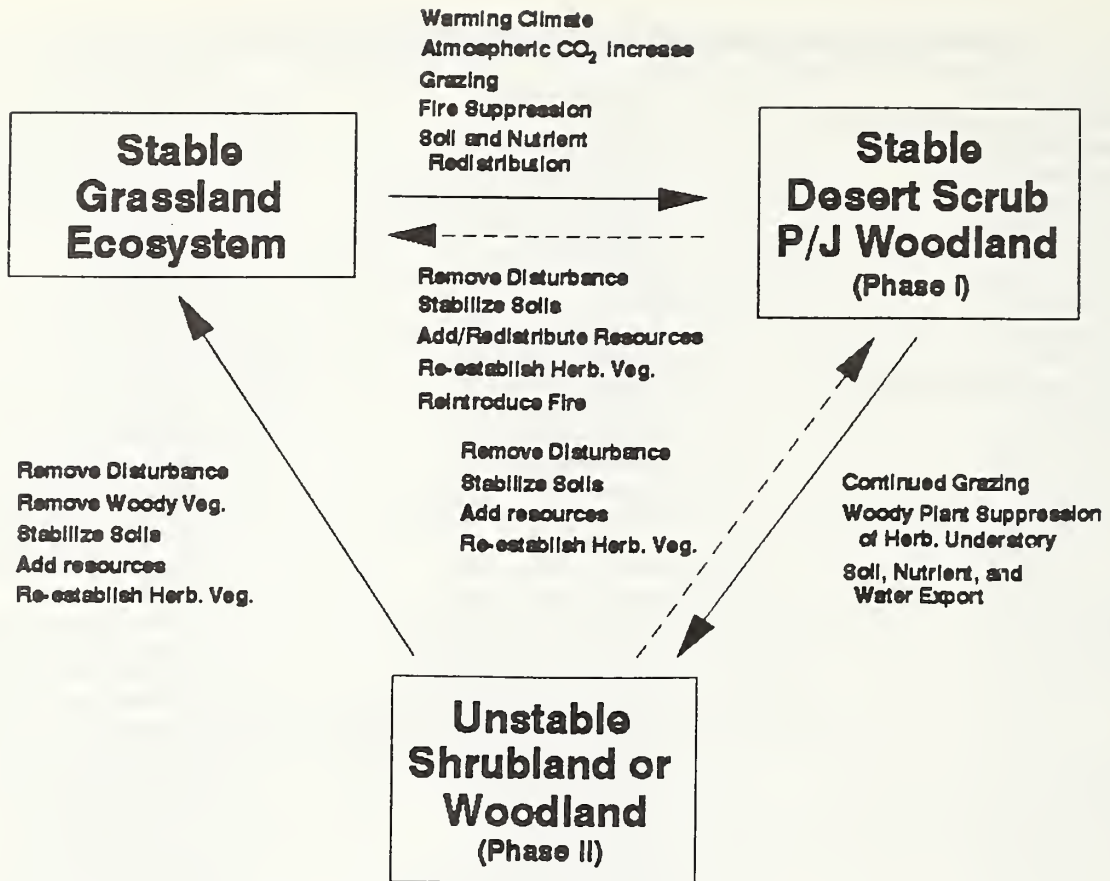
Figure 2.—A conceptual model of desertification/degradation in a semiarid grassland ecosystem. Periodic disturbance by fire is necessary to maintain a grass-dominated ground cover. Climate warming and increased atmospheric CO_2 levels may have promoted the growth of woody perennial plants but these processes are beyond the control of the local land manager. Certain land management practices can initiate desertification.

dangerment in the United States were located in the Southwest. In these Southwestern regions, endangerments were predominantly associated with rangeland ecosystems and regions of rapid human population growth and development (Flather and Joyce 1994).

Current federally listed or candidate animal species that may utilize Middle Rio Grande Basin grasslands include: Arizona black-tailed prairie dog (*Cynomys ludovicianus arizonensis*), ferruginous hawk, loggerhead shrike, mountain plover, and the Texas horned lizard (50 CFR 17.11 & 17.12). Although the number of federally listed or candidate animal species utilizing Plains-Mesa and Desert Grassland habitat is not as great as those using other habitats (such as riparian), the Middle Rio Grande Basin, with its growing population and current land use practices,

certainly has the characteristics of a high endangerment region and thus, the potential for future problems with other sensitive grassland and shrubland species.

Grazing and Fire Effects on Wildlife

The major human impacts in these habitats, grazing and fire suppression, have both direct and indirect effects on wildlife populations. Direct impacts include competition and physical disturbance of habitat. Cattle compete with wildlife for vegetation biomass that would typically be shared between insects and other herbivorous animals. Thus, energy and water in vegetation eaten by cattle ultimately leave the grassland system instead of supporting a network of wildlife species along the food chain. Cattle also may physically disturb ground-nesting

birds and cause degradation of arroyo banks in which small rodents may burrow and nest.

Changes in vegetation composition and structure caused by soil erosion and loss of plant cover are the means by which grazing and fire suppression may cause indirect, yet severe, impacts on wildlife. These changes affect two main requirements for wildlife: food and cover. When grasslands convert to alternative habitats, plant species composition, food quality, and food quantity are altered. Diet requirements for many species may no longer be met. More time may be spent searching out appropriate foods in sufficient quantities, thus altering time and energy budgets, water balance, and eventually the survival and success of the individual and the population.

The loss of ground cover associated with the conversion of grassland to shrubland or P-J Woodland reduces protection of ground-nesting and foraging wildlife from predators and the elements. Scrubland encroachment and formation of islands of woody vegetation due to fire suppression resulted in increased predation of ground-nesting birds in prairie habitat (Burger et al. 1994).

Support for the hypothesis that small mammal community composition in grasslands is primarily determined by vegetation structure was provided by a study of small mammals and grazing-induced changes in vegetation cover (Grant et al. 1982). Lizard abundance and species diversity decreased in heavily grazed desert grasslands, most likely due to the changes in vegetation structure (loss of low-height vegetation) (Jones 1981). Populations of the Plains-Mesa Grassland-inhabiting little striped whiptail lizard may be declining due to encroachment of P-J Woodland and the associated plateau striped whiptail lizard at higher elevations and with the encroachment of Desert Grassland/Chihuahuan Desert Scrub and the associated New Mexico and desert-grassland whiptail lizards at lower elevations (Behler and King 1988; (J. Stuart, personal communication, National Biological Survey, 1994). The loss of habitat by one species is the gain of habitat to another. Thus, studies have not always found negative impacts on wildlife from grazing. Mentioned previously, the conversion of Plains-Mesa Grassland to alternate habitat types allows three species other than the little striped whiptail lizard to utilize the habitat. For songbirds, grazing in Plains-Mesa Grassland had a positive influence on horned lark and lark sparrows, but a negative influence on Cassin's sparrows and western meadowlarks (Saab et al. 1995). De-

graded grasslands with many open spaces may not provide suitable habitat for small rodents that prefer dense, grassy cover such as silky pocket mice, harvest mice, and cotton rats (Hall and Willig 1994; Findley 1987). If maintenance of grassland ecosystem integrity is the objective, then wildlife species associated with grasslands must be protected by maintaining current grassland habitat, restoring degraded grassland habitats, and preventing the encroachment of woodland and shrubland.

RESEARCH NEEDS

The ultimate application of research results is to guide the development and implementation of management objectives. The current trend in management within the USDA-FS and many other Federal and State land management agencies is a holistic approach termed "ecosystem management." The USDA-FS Rocky Mountain Forest and Range Experiment Station has published a document that outlines the guiding principles of Forest Service ecosystem management (Kaufmann et al. 1994). In brief, the principles are (1) ecosystem sustainability for human and nonhuman use, (2) conservation of abiotic and biotic components of ecosystems, (3) conservation of natural ecosystem processes, and (4) protection of ecosystems from adverse human impact. Research that addresses all aspects of ecosystem management in the grassland and shrubland ecosystems of the Middle Rio Grande Basin is needed. Information is needed on the impacts of different land use practices on the abiotic and biotic ecosystem components (soils, vegetation, wildlife, livestock, and humans) and effects on ecosystem processes such as surface and ground water hydrology, soil erosion and sediment yields, nutrient cycling, and plant community productivity and stability. The following discussion describes current and future research objectives of the Rocky Mountain Forest and Range Experiment Station for the grasslands and shrublands of the Middle Rio Grande Basin.

Restoration of a Pinyon-Juniper/Grassland Ecosystem in Central New Mexico

Pinyon-juniper woodlands occupy about seven million acres in the Southwest, of which approximately 3.5 million acres are considered to be in unsatisfactory soil and watershed condition (USDA Forest Service 1993). The encroachment of P-J Wood-

land into grasslands, coupled with the loss of herbaceous understory vegetation, can decrease productivity, increase soil erosion, and decrease watershed condition in many grassland ecosystems (Fig. 2). At some sites, converting P-J woodland to P-J grassland Savanna with a productive herbaceous understory would improve the watershed condition while retaining the older and larger trees. Researchers with the USDA-FS Rocky Mountain Station, the National Park Service, and the National Biological Survey have initiated a project within Bandelier National Monument and the Santa Fe National Forest that is designed to test the effects of different management techniques on restoration of a P-J Grassland Savanna. Previous research on the Monument suggests that tree thinning and/or seeding with native herbaceous vegetation may increase herbaceous ground cover and decrease soil erosion (Chong 1994). Management officials with the Santa Fe National Forest are supportive of this research because it represents a practical approach to the solution of ecosystem degradation. One of the major concerns for Bandelier National Monument is that soil erosion is destroying valuable Anasazi archeological sites. The specific objectives of the proposed research are to:

- experimentally test restoration techniques designed to stop ecosystem degradation (soil erosion);
- accelerate the recovery of herbaceous understory biomass; and
- protect threatened historical sites within threatened grassland ecosystems.

Response of Southern Plains-Mesa Grassland to Fire

The importance of frequent fire to the stability of grasslands was previously discussed. Unfortunately, some of our statements concerning the role of fire in grasslands of the Middle Rio Grande Valley are necessarily conjectural because there have been very few grassland fire studies conducted in this region. We are initiating a project that would evaluate the short- and long-term response of grassland and shrubland ecosystems to prescribed fire.

The Rocky Mountain Station is collaborating with researchers from the University of New Mexico, Department of Biology, as well as with management officials with the City of Albuquerque Open Space Division, the Cibola National Forest, and the National Park Service. Two sites have been chosen for the proposed fire study. The Bernalillo Watershed site is in the western foothills of the Sandia Mountains on the Cibola National Forest and adjacent to the Bernalillo Watershed Research Natural Area. The vegetation at the Bernalillo Watershed is a blue grama/galleta grassland which contains a high proportion of broom snakeweed even though the area has received only intermittent grazing since the mid 1950s. The second site is west of Albuquerque on property owned by Albuquerque's Open Space Division. This area has been free from livestock grazing for at least 20 years. The vegetation at this site is dominated by Indian ricegrass, galleta, and dropseed with scattered broom snakeweed, fourwing saltbush, and winterfat (*Ceratoides lanata*) shrubs. The importance of fire in this grassland can be observed by comparing undisturbed areas with areas recently burned by wildfires. The undisturbed vegetation contains a substantial shrub component and plant mortality appears to be high, while within the adjacent area burned by wildfire, shrubs are less abundant and individual plants appear to be much more healthy and robust. The specific objectives of this research project are to:

- experimentally test the effects of prescribed fire on soils and vegetation in a semiarid grassland ecosystem; and
- experimentally test the effects of prescribed fire on the surface hydrology of a semiarid grassland ecosystem.

Recovery From Livestock Grazing

As discussed earlier, one of the most significant changes to grassland ecosystems resulting from heavy livestock grazing has been a decrease in vegetation cover and a depletion in soil organic matter. Removal of livestock grazing pressure may ultimately increase vegetation cover and plant litter additions, which in turn would slowly replenish diminished soil organic matter. However, this "passive approach" to rangeland restoration would be slow and the recovery may take decades. Additional research is needed to determine the rate of vegetation and soil fertility recovery in the absence of livestock grazing. Is recovery going to occur without additional manipulations aside from livestock exclusion?

Restoration With Soil Amendments

Research in Middle Rio Grande Basin grasslands and shrublands is needed to support ongoing research at the Rocky Mountain Forest and Range Experiment Station which has shown that degraded semiarid rangeland sites respond favorably to surface applications of organic amendments such as municipal sewage sludge biosolids. Responses include significant increases in soil fertility accompanied by increased biomass production and ground cover (Fresquez et al. 1990a & b; Fresquez et al. 1991; Loftin and Aguilar 1995; Loftin et al. 1995). More recent research has shown that organic amendments on degraded rangeland significantly increase rainfall infiltration, thereby reducing runoff and sediment yields (Aguilar et al. 1994).

Additional information is needed on the effects and feasibility of active restoration practices, such as increasing soil fertility and site productivity using soil amendments with different types of soils and degrees of ecosystem degradation.

Research Needs for Wildlife

As discussed earlier, the Middle Rio Grande Basin has the characteristics of a high endangerment region for wildlife species because of its rapidly growing human population. The following is a list of important research issues to be addressed for the region:

- Assess the detrimental effects of grassland habitat fragmentation on vertebrate species, composition and abundance.
- Identify species sensitive to loss of continuous grassland habitat and encroachment of desert scrub or pinyon-juniper habitat (i.e., little striped whiptail lizard).
- Determine critical components and minimum habitat requirements (food, cover, etc.) for sensitive and potentially sensitive species.
- Investigate differences in plant productivity and wildlife composition and abundance (mammals, birds, reptile/amphibians, arthropods) between grazed and ungrazed, or burned and unburned grasslands. Research is needed to determine if alternate grazing practices may retard, halt, or reverse the process of desertification and the associated changes in wildlife composition. Also the effects of prescribed burns at different times of the year and different fire intervals must be investigated.

- Compare the quality, quantity, and use versus availability of different plant foods by wildlife in degraded and nondegraded grasslands. Does grazing increase production of secondary plant chemical defenses by plants or does grazing and fire suppression cause increases in the prevalence of plants containing defensive plant chemicals or armed with physical anti-herbivore defenses?
- Investigate the interactions among species assemblages at interfaces between grasslands and pinyon-juniper or desert scrub habitat (i.e., nest predation of grassland nesting birds by cowbirds, predation by forest carnivores on grassland species).

SUMMARY

Human populations and development in the Middle Rio Grande Basin will increase and continue to impact the health and stability of grassland and shrubland ecosystems. Increasing demands for the region's already limited water supplies will undoubtedly bring about greater pubic awareness of the importance of ecosystem health for sustaining water quality and quantities.

Maintaining or improving the existing grassland and shrubland ecosystems in the Middle Rio Grande Basin will require a better understanding of their current state and their future directional shift upon the application of various management practices. Some of the more important management concerns for the basin will undoubtedly include the restoration of those highly degraded areas that are currently characterized by extremely high erosion and sediment problems. However, we also need to gain a better understanding on how these ecosystems should function and what degree of restoration they require. Other priority research should be directed towards increasing our knowledge of the relationships between wildlife species within these grassland and shrubland ecosystems and gaining a comprehensive understanding of the effects of development and land use on all wildlife species. Current and anticipated future land use practices such as livestock grazing, protected wildlife habitat, (i.e., refuges), and urban development must be re-evaluated with a broader focus on the effects of these practices on the stability and future health of the grassland and shrubland ecosystems of the Middle Rio Grande Basin.

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Chapter 6
Pinyon-Juniper Woodlands

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INTRODUCTION

Pinyon-juniper woodlands are one of the largest ecosystems in the Southwest and in the Middle Rio Grande Basin (Fig. 1). The woodlands have been important to the region's inhabitants since prehistoric times for a variety of natural resources and amenities. The ecosystems have not been static; their distributions, stand characteristics, and site conditions have been altered by changes in climatic patterns and human use and, often, abuse. Management of these lands since European settlement has varied from light exploitation and benign neglect, to attempts to remove the trees in favor of forage for livestock, and then to a realization that these lands contain useful resources and should be managed accordingly.

Land management agencies are committed to ecosystem management. While there are several definitions of ecosystem management, the goal is to use ecological approaches to create and maintain diverse, productive, and healthy ecosystems (Kaufmann et al. 1994). Ecosystem management recognizes that people are an integral part of the system and that their needs must be considered. Ecological approaches are central to the concept, but our understanding of basic woodland ecology is incomplete, and there are different opinions and interpretations of existing information (Gottfried and Severson 1993). There are many questions concerning proper ecosystem management of the pinyon-juniper woodlands and how managers can achieve these goals (Gottfried and Severson 1993). While the broad concept of ecosystem management generally is accepted, the USDA Forest Service, other public land management agencies, American Indian tribes, and private landowners may have differing definitions of what constitutes desired conditions.

Key questions about the pinyon-juniper ecosystems remain unanswered. Some concern the basic dynamics of biological and physical components of the pinyon-juniper ecosystems. Others concern the distribution of woodlands prior to European settlement and changes since the introduction of livestock and fire control. This relates to whether tree densities have been increasing or whether trees are invading grasslands and, to a lesser extent, drier ponderosa pine (*Pinus ponderosa*) forests. In areas where woodlands were heavily used by American Indians for fuelwood prior to European contact, the advance of pinyon and juniper could represent the slow recovery from intensive use (Samuels and Betancourt 1982). There are numerous questions regarding declines in watershed condition related to changes in pinyon-juniper tree stand densities and to the density and composition of understory vegetation.

There are different opinions about proper management of woodland ecosystems. Should these lands be managed for a single resource, such as forage for livestock production, or managed for sustained production of multiple resource products and amenities? Depending on site and stand conditions, the woodlands can produce variable quantities of fuelwood, pinyon nuts, wildlife habitat, forage for livestock, and cover for watershed protection. Management must
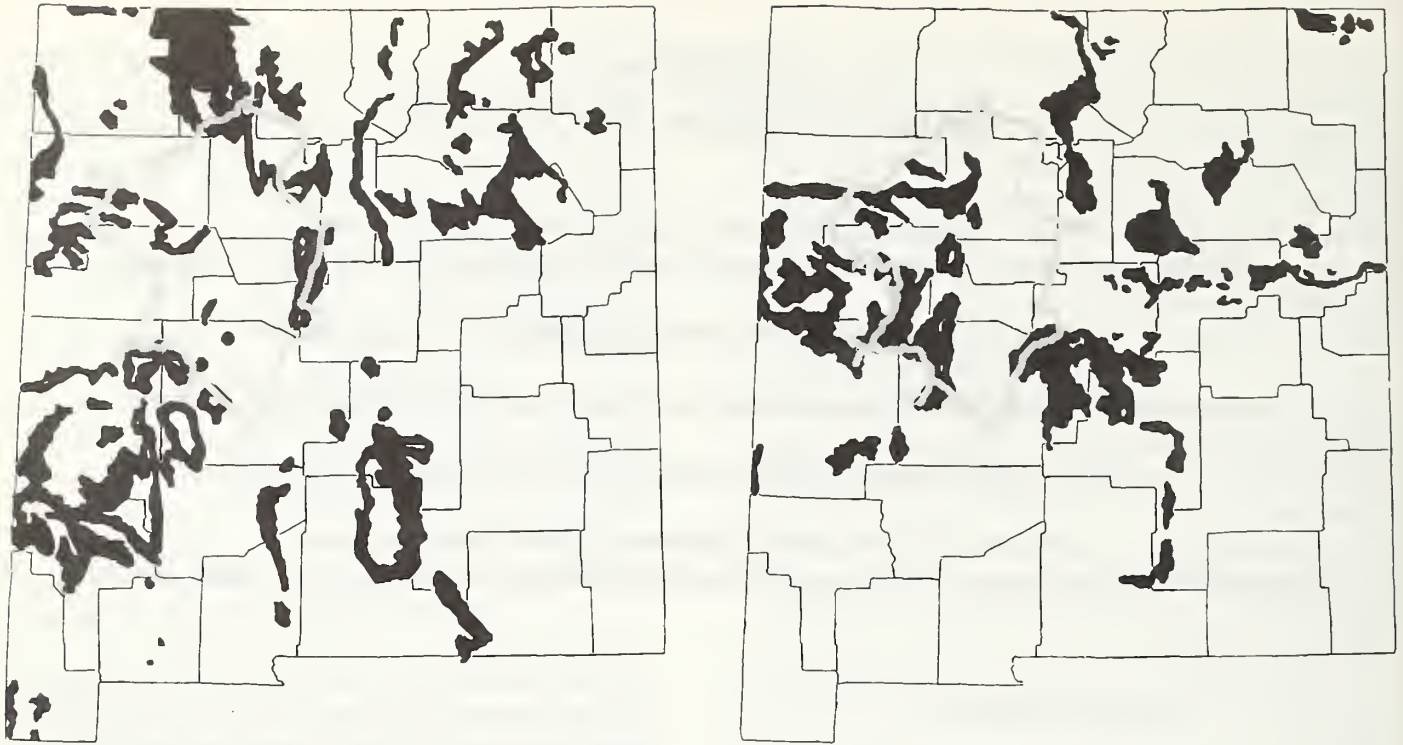
Figure 1.—The distribution of pinyon-juniper woodlands (left) and juniper savannas (right) in New Mexico based on Dick-Peddie (1992). The Middle Rio Grande River Basin is outlined in gray.

also consider increasing recreational demands, threatened and endangered species, and protection of archeological sites. Many pinyon-juniper woodland watersheds in New Mexico have unsatisfactory soil and watershed conditions (USDA Forest Service 1993); managers must develop restoration procedures that recognize the value of woodland ecosystems.

The concerns, questions, and conflicts surrounding management of pinyon-juniper lands, as well as the ecological foundations of ecosystem management, require that all interested parties reevaluate attitudes toward the woodlands. Ecosystem management goals and concepts recognize diversity. Pinyon-juniper woodlands are diverse, and stand characteristics and site productivities vary. Management objectives and prescriptions must evaluate the potential of each site, and decisions must be based on sound scientific information. This information is often unavailable. Therefore, this paper describes what we do know about the characteristics, distribution, and ecology of pinyon-juniper woodlands, including the effects of natural and human factors, within the southwestern United States and particularly the Middle Rio Grande Basin. It also reviews some past and present management options in this widespread

and important vegetation type. The review draws on research and management information from the Rio Grande Basin and from similar areas in the Southwest and adjacent regions. It does not attempt to review all of the relevant literature; additional sources can be found within the articles cited in the References.

CHARACTERISTICS

What are pinyon-juniper woodlands? Woodlands are generally characterized by trees that are of small stature but often more than 5 m in height; have relatively open canopies; and have greater than 40 percent crown closure (USDA Forest Service 1993). In the Southwest, relatively open stands where tree crown cover is between 10 and 40 percent are also classified as woodlands. The pinyon-juniper woodlands are variable in species composition, density, and physiographic site characteristics. Some sites contain dense stands of relatively large trees and meet many of the criteria of old growth (USDA Forest Service 1990), while other sites contain open stands of mainly younger trees that appear to be of a more recent origin. Pinyon-juniper and pure juniper woodlands are generally considered together in this review.

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The two-needle Colorado pinyon (*Pinus edulis*) is the common species in most pinyon-juniper stands in the Southwest and eastern Utah and Colorado. A one-needle pinyon, *P. californiarum* var. *fallax*, hybridizes with *P. edulis* in low elevations of central Arizona and southwestern New Mexico. Pinyons with a mix of one and two-needle fascicles are found in the low elevations of the Middle Rio Grande Basin, and probably represent Holocene long-distance seed or pollen dispersal from *P. californiarum* var. *fallax* stands in southwestern New Mexico. Pinyons are typically between 3 and 11 m tall and 13 to 46 cm in diameter, although larger individuals can be found on moister sites. The pinyons are slow growing but relatively long-lived trees (Ronco 1990). Trees 300 to 400 years old are common in old-growth stands in both Arizona and New Mexico, but trees over 500 years in age are rare (Swetnam and Brown 1992).

Juniper (*Juniperus* spp.) is the other major tree genus occurring in these woodlands. Junipers are generally small, multi-stemmed trees less than 12 m tall. There are four major juniper species in the Southwest: one-seed juniper (*J. monosperma*); Utah juniper (*J. osteosperma*); alligator juniper (*J. deppeana*); and Rocky Mountain juniper (*J. scopulorum*). Stands can contain one of the juniper species or a combination of species. Junipers can attain great ages, but unfortunately, it is difficult to determine precise ages using tree rings because of the prevalence of false and missing rings, particularly in alligator and one-seed junipers. Rocky Mountain juniper is an exception, and several trees over 1,000 years in age recently have been accurately dated in west-central New Mexico (Grissino-Mayer et al., in press). Less than 50 percent of the Utah juniper stems can be dendrochronologically dated; however, on relatively wetter sites, there is a better chance of cross-dating ring-width patterns within and across populations. Dendrochronology has allowed precise dating of archeological sites that incorporate ancient timber (Bannister and Robinson 1975); dendroclimatic reconstructions spanning a thousand years or more (D'Arrigo and Jacoby 1991; Grissino-Mayer et al., in press); and reconstruction of tree demographies at interannual resolution (Betancourt et al. 1993).

Understory biomass within southwestern pinyon-juniper stands is generally small. However, because of the broad distribution of this vegetation type, the total number of plant species associated with the woodlands is great (Medina 1987; Ronco 1990). Some important representative herbaceous species include

blue grama (*Bouteloua gracilis*), sideoats grama (*B. curtipendula*), sand bluestem (*Andropogon hallii*), Arizona fescue (*Festuca arizonica*), and goosefoot (*Chenopodium graveolens*). Representative trees and shrubs include gray oak (*Quercus grisea*), true mountain-mahogany (*Cercocarpus montanus*), sagebrush (*Artemisia* spp.), and Mexican cliffrose (*Cowania mexicana*). More details on understory vegetation are found in Medina (1987), Ronco (1990), and USDA Forest Service (1987).

ECOLOGY

Distribution

Approximately 19 million ha of pinyon-juniper woodland occur in the United States; it is an important vegetation type in seven of the western states (Evans 1988). Pinyon-juniper woodlands constitute the most common vegetation type in Arizona and New Mexico. The literature contains several estimates of the area occupied by woodlands; many of the differences may be attributed to the way marginal juniper savanna lands are defined. West et al. (1975) indicated that conifer woodlands cover approximately 26 percent or about 8.2 million ha of New Mexico, but this value probably included grasslands that have a tree component. A recent survey of New Mexico's forest resources (Van Hooser et al. 1993) reports that approximately 3.4 million ha of pinyon-juniper and pure juniper woodlands have the potential for producing wood products. Fowler et al. (1985) indicated a relatively similar area of about 4 million ha or 14 percent of New Mexico that contain stands that could be considered manageable for tree products because of their site and stand characteristics.

Pinyon-juniper woodlands are an important type within the 64,150 km² Middle Rio Grande Valley (Fig. 1), which includes parts of ten counties (Crawford et al. 1993). A major part of the Middle Rio Grande Basin is in Bernalillo, Cibola, McKinley, Sandoval, Socorro, and Valencia counties, and a minor part occurs in Catron, Torrance, Rio Arriba, and Santa Fe counties. Although statistics for the area of pinyon-juniper woodlands within the Basin are not readily available, calculations based on data reported by Van Hooser et al. (1993) indicate that the six counties contain about 1 million ha of woodland or 18 percent of the total county areas. The proportion of area occupied by woodlands ranges from 27 percent for Cibola to 5 percent for Valencia County. Woodlands occur on private, USDA Forest Service, USDI

Bureau of Land Management, American Indian, and State of New Mexico lands.

Available soil moisture and season of precipitation are the most critical factors controlling woodland distribution, composition, density, and stand condition in undisturbed sites. The high variability of woodland habitat types is associated with the variability of climatic and site conditions. Moir and Carleton (1987) recognized at least 70 habitat types and 280 ecological site types in Arizona and New Mexico. Woodlands occur on relatively moist sites that support dense stands of relatively tall trees and on dry sites where trees are scattered and of low stature. Junipers are more drought tolerant than pinyon and tend to dominate drier sites. The proportion of pinyon increases with increased elevation and available moisture. In general, pinyon is dominant above 2,200 m. Competition with ponderosa pine for moisture, or fire regimes associated with ponderosa pine, may determine the upper limit as suggested by the fact that pinyon achieves its greatest abundance or density near its upper limit. Generally species density would taper off near its upper and lower environmental limits.

Topographic and edaphic influences are apparent in southern New Mexico where pure one-seed juniper stands have higher densities on northeastern exposures than on drier southwestern slopes (Pieper and Lymbery 1987). Distribution of Utah juniper in Arizona and northern New Mexico is related to the predominance of winter moisture relative to summer moisture (Springfield 1976). One-seed juniper is most common where winters are cool and dry and where summer precipitation is more important. Alligator juniper is also identified with summer moisture regimes. Rocky Mountain juniper is considered the least drought-tolerant of the common juniper species and generally occurs above 2,100 m in the Middle Rio Grande Basin.

Climate

Southwestern pinyon-juniper woodlands occupy the warmest tree-dominated zone in the region. The climate is usually classified as arid, semiarid, or occasionally, dry subhumid (Ronco 1990). The woodlands grade into juniper savannas, grasslands, oak woodlands, and brush-dominated vegetation zones on drier sites and into ponderosa pine forests at higher, moister elevations. Average annual precipitation ranges from 305 to 560 mm and is influenced by geography, elevation, and topography. Temperature ranges are also variable and may control the upper elevational distribution of the type (Evans 1988).

The seasonal distribution of precipitation in the Middle Rio Grande Basin, like most of the Southwest, varies depending on sea surface temperature regimes in the eastern Pacific Ocean and the seasonal position of the polar and subtropical jet streams, the Pacific anticyclone, and the Bermuda High. The climatic regime is characterized by highly variable frontal precipitation in winter, an arid pre-summer, and summer rains that are predictable in timing and amount at a given station but highly variable from site to site. The importance of monsoonal rains diminishes to the northwest, and the April to June period becomes wetter to the northeast. Summer precipitation is greatest on the east flank of the southern Rocky Mountains, i.e., the Sangre de Cristo, Sandia, Manzano, and Sacramento Mountains.

Interannual and interdecadal variability in cool season precipitation apparently is driven by the sea surface temperatures (SST) and sea surface pressure anomalies in the tropical Pacific and the latitudinal position and sinuosity (meridionality) of the polar jet stream, reflecting expansion and contraction of the circumpolar vortex. Two climatic indices that define these conditions are the Southern Oscillation Index (SOI) and Pacific North American Index (PNA). A negative SOI reflects El Niño (warm conditions) in the tropical Pacific; a positive SOI reflects La Nina (cold conditions). A positive PNA value reflects an intensified Aleutian Low, causing winter storm tracks to shift southward; a negative PNA value indicates more northerly storm tracks. In the Middle Rio Grande Basin, wet winters and springs are associated with positive PNA and La Niña conditions.

Decadal-scale variability in rainfall records from the Line Islands (tropical Pacific islands near the Date Line) indicate precipitation surges during El Niño events. In the 20th century, there has been a general (decadal) association between periods of frequent El Niños and an expanded circumpolar vortex (positive PNA) prior to 1930 and after 1960. The period between 1930 and 1960 was characterized by few El Niño events and a contracted circumpolar vortex (negative PNA). There has been an almost permanent shift to El Niño-like conditions that began in 1976 and continued to 1995 (with the exception of the 1988–89 La Niña) (Fig. 2). Teleconnections (cor-
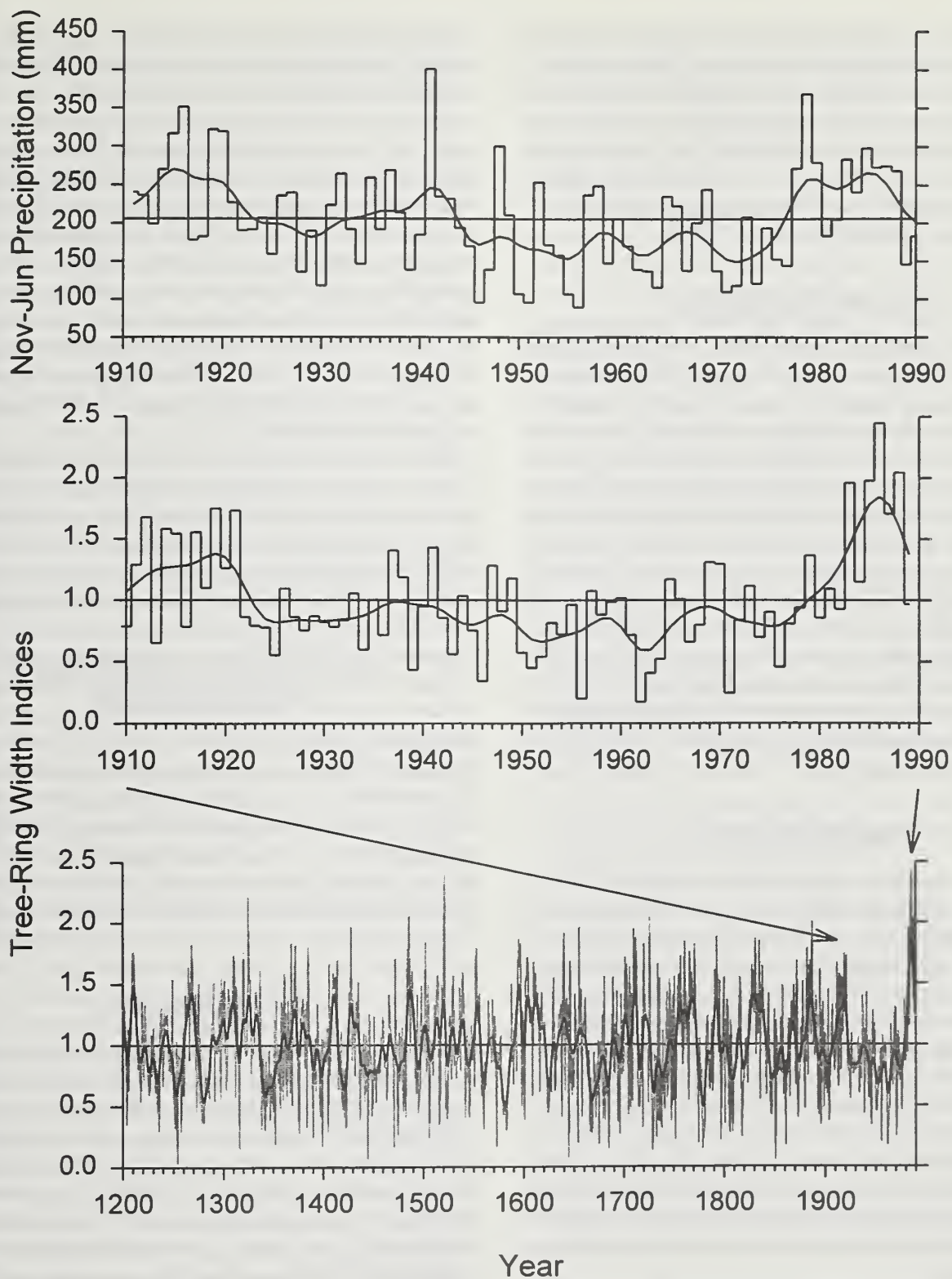
Figure 2.—Winter to spring precipitation variations in northern New Mexico since AD 1200. The upper plot shows total November through June precipitation, 1910-1990, averaged across three recording stations at Chama, Jemez Springs, and Socorro. The middle plot shows annual ring-width variations during the same period from a limber pine (*Pinus flexilis*) tree-ring site near Red River. The Pearson correlation between the precipitation and tree-ring time series is 0.61 (p < 0.001). The bottom plot shows the past 700 years of tree-ring variation at this site, suggesting that the late 20th century climatic variation has been very unusual, perhaps unprecedented during the past 8 centuries.

relations between the climate at two distant locations) have shown relationships between the tropical Pacific indices such as SOI, tropical SSTs, Line Island rainfall and southwestern precipitation (Douglas and Engelhardt 1984; Cayan and Webb 1992), streamflow (Molles and Dahm 1990; Cayan and Webb 1992; Webb and Betancourt 1992), and even area burned by wildfires (Swetnam and Betancourt 1990).

Soils and Topography

The woodlands generally occur at elevations of 1,370 to 2,290 m and on all topographic positions. Old-growth stands occur on a variety of physiographic sites. In New Mexico, old stands are often associated with rocky hillslopes where the sparse understory will not carry fire (Swetnam and Brown 1992; Wood and Javed 1992). Woodlands occur on soils that have developed from a variety of parent materials and belong to one of six soil orders (Aridisols, Alfisols, Entisols, Mollisols, Vertisols, and Inceptisols) (Evans 1988). Soils are generally classified as being shallow and well-drained. Woodlands are associated with soils having low fertility (Pieper 1977; Evans 1988), but recent data (USDA Forest Service 1993) indicate that they also can occur on relatively productive soils.

Seed Production

Pinyon is generally monoecious, although dioecious trees are found when the trees are under insect attack or growing under stressed conditions (Gottfried 1987). Seed crops occur every 4 to 7 years depending upon the weather, site conditions, and insect herbivory. Crops are more frequent on the better sites. Trees can start bearing cones at 25 years, but production peaks when trees are between 75 and 100 years old. Cones require three growing seasons to mature (Little 1938) and will contain about 20 relatively large, wingless seeds. A productive tree can produce about 9 kg of seed, and a hectare can yield about 336 kg of seed (Ronco 1990). Mature seed release starts in mid-September and can continue for a 50-day period.

Reproductive success of pinyon is largely a measure of the abundance of episodic bumper seed crops, which are probably linked to favorable climatic events initiating cone primordia and enhancing cone and seed development over a period of several years. Pinyon, during mast years, typically produces large crops simultaneously across large geographic areas. In the 1940s, seed crops in Arizona and New Mexico were monitored annually (Little 1940). The specific influence of climatic variability on flowering, fruiting, and seed germination over a three-year reproductive cycle remains unexplored. Equally unknown is the effect of mast years on long-term fluctuations in stand structure. The climatic trigger must inhibit vegetative growth and induce formation of ovulate cone primordia in late summer, must recur irregularly once every few years, and must be synoptic in scale. By definition, the trigger must be embedded in interannual climatic variability over the region, and ultimately, in the global-scale climatologies that affect the Southwest.

Some of the southwestern junipers are monoecious, such as Utah and alligator junipers, and some are predominately dioecious, such as one-seed and Rocky Mountain junipers (Johnsen and Alexander 1974). Seed-bearing age varies by species and also can be affected by moisture conditions and competition (Gottfried 1989; McPherson and Wright 1987). One-seed and Rocky Mountain junipers begin bearing seed at between 10 and 20 years, while Utah juniper begins at about 33 years (Johnsen and Alexander 1974). Juniper berries, which can contain one to four seeds depending on the species, can be dry and leathery, as in Utah juniper, or thin and resinous, as in one-seed juniper. The main southwestern junipers flower in the spring with berries ripening in the fall; however, some species require two years for the berries to mature. Mature berries can stay on the tree for several years before dispersal.

Seed Dispersal

Wind and gravity are not important dispersal agents for the heavy seeds or berries. Most pinyon seed will fall directly below the canopy and very few seeds will land in adjacent interspace areas (Gottfried 1992a). Birds are considered to be the most important dispersal agents. Balda (1987) found that four species of corvid birds—scrub jay (*Aphelocoma coerulescens*), pinyon jay (*Gymnorhinus cyanocephalus*), Clark's nutcracker (*Nucifraga columbiana*), and Steller's jay (*Cyanocitta stelleri*)—are responsible for caching hundreds of thousands of pinyon seeds during years with large cone crops. Some of these species have special anatomical adaptations which allow them to transport large quantities of seed over considerable distances. Scrub jays are the only one

of the four species that spends most of its time in the woodlands and contributes more to pinyon regeneration in the woodlands than Steller's jay and Clark's nutcracker, which spend much of their time in higher elevation forests.

Hall and Balda (1988) studied caching behavior of scrub jays, and found that they prefer to cache seeds in the soil under pinyon trees even when other locations were available. The birds, as well as mice, will recover 92 percent of the caches by the following spring. The surviving caches are the source of future pinyon regeneration.

Birds also are important for juniper dispersal. Townsend's solitaires (*Myadestes townsendi*) are important dispersal agents for one-seed juniper (Salomonson 1978) and Bohemian waxwings (*Bombycilla garrula*) are important for Rocky Mountain juniper (Noble 1990). In addition to birds, other animals such as coyotes (*Canis latrans*), mice, rabbits, and livestock are considered major dispersal agents for junipers (Johnsen 1962; Noble 1990).

Germination, Establishment, and Early Growth

The environmental and physiological requirements for successful pinyon germination have not been evaluated fully. Preliminary data from an ongoing study have shown that pinyon seeds will germinate in the spring, but if conditions are not satisfactory, they may not germinate until the summer monsoon rain season (Gottfried [unpublished data]). Pinyon germination is between 83 and 96 percent (Gottfried and Heidmann 1986; Ronco 1990). Most juniper seeds will also germinate in the spring; however, germination can be delayed for up to two years because of embryo dormancy, the impermeable seed coat, or chemical inhibitors (Gottfried 1989; Johnsen and Alexander 1974). In general, successful germination is low, ranging from 8 to 49 percent in Utah juniper and from 20 to 75 percent in one-seed juniper.

Although pinyon and juniper are considered shade-intolerant, most new seedlings are often found in the shade of mature trees, shrubs, and slash; overstory foliage generally is not dense enough to reduce light intensities below tolerance levels for survival (Meeuwig and Bassett 1983). Seeds do germinate in the open, but establishment and survival are less certain. Shade moderates the microclimate and, therefore, enhances survival. Seedlings growing under shrubs, which eventually can be overtopped, have

the best chance of survival (Meeuwig and Bassett 1983); seedlings growing under mature trees must be released in order to accelerate growth. Seedlings that survive the first year in the open are larger than those that are growing in shaded micro-sites (Harrington 1987).

Although several climatic factors influence germination and establishment, moisture is probably the most critical factor. Meagher (1943) found that supplemental watering did not influence percent germination, but it did improve the speed of germination and survival of pinyon seedlings over a 2-year period. Rapid germination would favor a seedling by allowing it to become established prior to the summer or fall drought periods (Gottfried 1987). Meagher (1943) also determined that shade and/or watering had a similar effect on Utah and one-seed juniper germination and initial survival. Johnsen (1962) reported that one-seed juniper seedling survival under drought is directly related to age. Competition from grasses will limit regeneration but the impact will decline once the tree roots have grown below the zone of highest grass root concentration.

Vegetative regeneration commonly has been found in alligator juniper which sprouts from stems, roots, or the root crown after the removal or death of the main trunk. Jameson and Johnsen (1964) indicated that the ability to sprout declined as stump diameter increased. Some sprouting has been reported for one-seed juniper (Gottfried 1989).

Both pinyon and junipers exhibit slow early growth under natural conditions. Colorado pinyon seedlings can put on between 2.5 and 5.0 cm of top growth annually (Ronco 1990), while taproot growth is about 18 to 28 cm during the first year (Harrington 1987). One-seed juniper can grow approximately 3 cm in the first 20 months in the field (Meagher 1943) while roots can be 23 cm long after 3 months (Johnsen 1962). Top growth of 4 cm in the first year has been reported for Utah juniper (Meagher 1943) and 30 cm in 8 years has been reported for Rocky Mountain juniper (Noble 1990). Actual growth rates will depend largely upon site conditions with the best growth occurring on the moister sites (Gottfried 1987).

Growth of Older Trees

Growth of older pinyon and the junipers also is relatively slow, with best growth occurring on the more moist sites. Pinyon saplings will grow about 10 to 15 cm in height annually and mature trees will

grow 5 to 10 cm annually (Ronco 1990). Little (1987) followed the growth of pinyon trees near Santa Fe over a 47-year period beginning in 1938, when the trees were between 5 and 6 m tall. He reported average annual height growth of 3 cm and average annual growth at b.h. of 0.15 cm or 2.5 cm every 16.8 years. On better sites, pinyon can grow to 30 cm in diameter within 150 years (Ronco 1990).

Junipers generally grow slower than pinyon (Conner et al. 1990). Junipers have the ability to grow when conditions are favorable and to stop growing when conditions are unsatisfactory (Johnsen 1962). This is probably the reason that numerous false and missing rings are characteristic of these species. Growth rates for the main juniper species vary by species and generally decline with age.

Root growth varies by species. Pinyon has both lateral and vertical root systems. Lateral roots usually are found at depths of 15 to 41 cm and can extend away from the bole by a factor of two times the crown radius (Ronco 1990). Junipers have both tap and lateral roots; tap roots can be from 0.5 to 3.7 m in depth, while laterals usually are concentrated in the top 90 cm of soil. One-seed juniper lateral roots are about 2.5 to 3 times as long as the tree is tall (Gottfried 1989). Roots can occupy most of the interspace areas where they mine soil nutrients and moisture.

Stand Characteristics and Productivity

Most pinyon-juniper stands in the Southwest are uneven-aged (Barger and Ffolliott 1972). Woodland stand productivity is variable. In New Mexico, conifer woodlands contain approximately 2.3 billion trees; 62 percent are pinyon (Van Hooser et al. 1993). About 28 percent of the trees are less than 8 cm in diameter at root collar (d.r.c.) and 86 percent are less than 28 cm at d.r.c. Net volume in New Mexico is 144,000,000 m^3, of which 53 percent is pinyon (Van Hooser et al. 1993). Pinyon and juniper volumes can be calculated using tables and equations developed by Chojnacky (1985). Schuler and Smith (1988) suggested that the higher size/density, leaf area, and growth relations in mixed woodland stands than in pure stands can be related to differences in rooting habits and water relations between pinyon and junipers. High growth rates are found on better sites; for example, an Arizona alligator juniper stand had a net annual growth of 1.4 m^3/ha (Gottfried and Ffolliott 1995), and a pinyon-juniper stand at Zuni, New Mexico, had an annual growth of 1.0 m^3/ha

(B. Schwab, personal communication, USDI Bureau of Indian Affairs, 1994).

Damaging Agents

A number of insects attack pinyon (Ronco 1990), including the pinyon sawfly (*Neodiprion edulicolus*), pinyon tip moth (*Dioryctria albovittella*), and the pinyon needle scale (*Matsucoccus acalyptus*). The cone moth (*Eucosma bobana*) is particularly damaging to pinyon. A number of bark beetles attack pinyon; for example, severe mortality associated with the pinyon Ips (*Ips confusus*) recently has been observed in areas of the Apache-Sitgreaves National Forests (Wilson and Tkacz 1992). The mortality may have been associated with an extended drought period that weakened the trees' defenses. Pinyon dwarf mistletoe (*Arceuthobium divaricatum*) is an important parasite that can cause locally severe damage and mortality.

The junipers have their own suite of insect problems and diseases (Gottfried 1989). Some examples are twig beetles (*Phloeosinus* sp.) and twig girdlers (*Stylox* sp.). Rusts (*Gymnosporangium* sp.) attack most junipers, causing witches' brooms, galls, leaf damage, and branch excrescences. True mistletoes (*Phorandendron* sp.), which are spread by birds, also are common parasites but generally do not cause heavy damage.

Additional information about the ecology of pinyon-juniper woodland ecosystems can be found in a number of sources. The autecology of pinyon has been reviewed by Gottfried (1987) and Ronco (1990) and juniper by Gottfried (1989), Johnsen (1962), Johnsen and Alexander (1974), and Noble (1990). Papers included in the proceedings of the 1986 pinyon-juniper conference at Reno (Everett 1987), the 1993 pinyon-juniper symposium at Santa Fe (Aldon and Shaw 1993), and the 1994 pinyon-juniper symposium in Flagstaff (Shaw et al. 1995). Evans (1988) and Gottfried (1992a) also are informative.

Biodiversity

Significant biological variability (biodiversity), as indicated by stand types, relative abundance of species, and species richness, exists in pinyon-juniper woodlands. Many of the pinyon-juniper habitat types that have been described (Moir and Carleton 1987) are present across a diverse range of landscape conditions in the Middle Rio Grande Basin. Biodiversity at any location is a result of many factors, including:

site characteristics like topography, geology, soils, climate; specific site history (Hamburg and Sanford 1986; Ricklefs 1987); successional state; and disturbance processes, which are central in determining the structure and function of ecosystems. Disturbances affect ecosystems at multiple spatial and temporal scales, creating variable conditions (niches), which allow multiple species to co-exist in the same area. Any brief review of pinyon-juniper biodiversity will contain generalizations across the range of existing conditions.

Biodiversity is often considered a function of species richness (number of species) within or between habitats. By this criterion, pinyon-juniper woodlands might be thought of as relatively unimpressive reservoirs of biodiversity, since the visual impression of many woodlands is of uniform conditions, with overstories dominated by only a few species of conifers. These woodlands also harbor relatively few endemic vertebrate species (Brown 1982). However, a broad and detailed examination of the woodlands reveals significant levels of biodiversity in less prominent ecosystem components, particularly herbaceous vegetation and soil organisms.

In pinyon-juniper woodlands, floristic diversity primarily reflects the herbaceous components of the system rather than the several species of pinyon and juniper that dominate many sites. About 450 species of vascular plants, out of a total of 722 species documented at the Bandelier National Monument, New Mexico, occur in pinyon-juniper and juniper woodland zones (Jacobs 1989). Barnes (1983), also working at Bandelier, found 7 shrub taxa, 25 forbs, 21 grasses, and 7 cacti in one survey, while another inventory found 12 shrub species, 47 forbs, 27 graminoids, and 6 cacti (C. D. Allen [unpublished data]). Two other examples are Mesita de los Ladrones, a 405 ha research natural area (RNA) in an open woodland on the Santa Fe National Forest near Pecos, that has at least 100 forb and 36 grass species, and Comanche Canyon, a proposed RNA on 210 ha near El Rito on the Carson National Forest, that has at least 6 tree taxa, 12 shrubs, 31 forbs, and 15 grasses (E. Muldavin, personal communication, The Nature Conservancy, 1994). All of these sites have been little-grazed by domestic livestock in recent decades, although Bandelier was heavily affected by feral burros. Vascular plant richness may generally be lower than these values suggest for most woodlands in the Middle Rio Grande Basin due to historic changes in these ecosystems associated with domestic livestock grazing. Biodiversity has been modified through direct and indirect introduction of alien species and genotypes; at least 20 percent of 722 species at Bandelier are aliens. Some species may have been introduced during aerial seeding, which included non-native genotypes and weed seeds, after the 1977 La Mesa Fire.

Emphasis is placed on soil biota in pinyon-juniper woodlands because of their species richness and critical functional role in ecosystems (Whitford 1991), as well as our relative ignorance of subsurface patterns and processes. A great diversity of microhabitats exists within soils, with a resultant diversity of organisms (Dindal 1990). Whitford (1991) provides an overview of pinyon-juniper soil biota, while the diversity and ecological role of the similar communities of soil-associated invertebrates from arid deserts that adjoin pinyon-juniper woodlands are reviewed by Crawford (1986, 1990). Surface dwelling arthropods recently were sampled in woodlands at Pecos National Historical Park (Parmenter and Lightfoot 1994) and Bandelier National Monument (Lightfoot and Parmenter 1994), with 189 and 115 species reported, respectively.

Soil organisms affect numerous ecosystem processes (Hole 1981; Crawford 1986), including: recycling of plant litter by detritivores (notably springtails in pinyon-juniper woodlands); controlling the rate of nutrient cycling, especially through eating fungi, which are the predominant decomposers (Parker et al. 1984); plant productivity; site hydrology through effects on vegetation and by altered soil porosity through burrowing actions; soil-forming processes through mixing and mounding soil; and consumption of live and dead organisms, especially underground plant parts (like roots). For example, 1990 was a big year for the emergence of cicadas in the Jemez Mountains, with emerging densities of over 25,000 per hectare in much of Bandelier's pinyon-juniper woodlands. This single species has significant effects on local woodland ecosystems, ranging from years of feeding on the roots of perennial plants (including the trees) and the alteration of nutrient cycling and soil physical conditions by their subsurface activities. The effects of harvester ants (*Pogonomyrmex occidentalis*) on the vegetation and soils of local pinyon-juniper woodlands also have been documented (Carlson 1988).

Microbiotic, or cryptogamic, crusts are important features of pinyon-juniper woodlands. These crusts are composed of varying species of cyanobacteria

with lichens, mosses, green algae, fungi, and bacteria (West 1990; Belnap 1990). The cyanobacteria, which have bundles of filaments with sticky, hydrophilic, polysaccharide sheaths (Belnap and Gardner 1993), serve to bind soil, hold nutrients and water, fix atmospheric nitrogen (Loftin and White, in review), and colonize disturbed sites (i.e., initiate primary succession). These crusts are readily damaged by mechanical disturbance, like hoof action or off-road vehicles. More data on the ecological role played by microphytic crusts are needed, given the widespread, but unsubstantiated, belief among many range managers that breaking up such crusts by livestock hoof action can be beneficial (Brown 1994).

Pinyon-Juniper Associated Wildlife

The wide variety of habitats within the pinyon-juniper ecosystem supports at least 70 species of birds and 48 species of mammals (Findley et al. 1975; Balda 1987). Although a few of these species are obligate to pinyon-juniper, most can be found to some degree in adjacent ecosystems. Whether an animal is present or absent or a permanent, summer, or winter resident depends on the species, geographic location, and the type of pinyon-juniper habitat.

Birds that have been found to breed only within pinyon-juniper habitats, in spite of other available habitats, include the screech owl (*Otus asio*), gray flycatcher (*Empidonax wrightii*), scrub jay (*Aphelocoma coerulescens*), and the plain titmouse (*Parus inornatus*). Semi-obligatory species, birds that breed in pinyon-juniper and only one other habitat type, include the pinyon jay, ash-throated flycatcher (*Myiarchus cinerascens cinerascens*), bushtit (*Psaltriparis minimus*), mockingbird (*Mimus polyglottis leucopterus*), black-throated gray warbler (*Dendroica nigrescens*), house finch (*Carpodacus mexicanus frontalis*), rufous-sided towhee (*Pipilo erythrophthlamus*), and lark sparrow (*Chondestes grammacus strigatus*) (Balda and Masters 1980). The gray flycatcher and black-throated gray warbler are inhabitants of mature pinyon-juniper woodlands and are 5th and 15th, respectively, on New Mexico Partners in Flight's prioritized list of neotropical migratory species. Many other species of birds, including raptors, songbirds, corvids, and hummingbirds, breed within pinyon-juniper woodlands but not exclusively.

Although the pinyon jay will forage and nest in ponderosa pine and pinyon and juniper trees (Balda and Bateman 1971), this species, with its physiologi-

cal and behavioral adaptations for harvesting pinyon nuts, has a life history that is more strongly interwoven with pinyon than is any other avian species. The species' strong, sharply tapered bill and lack of feathers around the nostrils are adaptations for chiseling into unopened cones and reaching between cone scales for nuts without pitch soiling the facial feathers (Balda 1987). For the pinyon jay, the nuts, which are cached singly in many locations, provide a high energy food source for the birds during the winter, and seeds that escape consumption may germinate to produce a new generation of trees.

Water availability, juniper berries, and pinyon nut crops are major factors determining which nonresident species will overwinter in pinyon-juniper woodlands. Good pinyon nut crops in winter may attract red crossbills (*Loxia curvirostra*) and Cassin's finches (*Carpodacus cassinii*), in addition to the resident pinyon jays, scrub jays, Steller's jays and Clark's nutcrackers (Balda 1987). Juniper berry crops may also determine densities of overwintering birds that consume berries and/or seeds, such as Townsend's solitaires, western and mountain bluebirds (*Sialia mexicana bairdi* and *S. currucoides*), and robins (*Turdus migratorius*) (Balda 1987). Merriam's turkeys (*Meleagris gallapavo merriami*) occupy many pinyon-juniper sites where ponderosa pine is available for roost sites (Scott and Boeker 1977). They prefer pinyon seeds but juniper seeds are used during drought periods and when pine and oak seed production is low.

Many species of bats are associated with pinyon-juniper habitats and have been identified by mistnetting over watering tanks, ponds, streams, and other permanent sources of water. Bats that have been commonly captured in pinyon-juniper habitats include eight species of *Myotis*, big brown bats (*Eptesicus fuscus*), spotted bats (*Euderma maculatum*), western pipistrelles (*Pipistrellus hesperus*), and pallid bats (*Antrozous pallidus*) (Findley et al. 1975). Other occasional captures have included big-eared bats (*Plecotus townsendii*) and brazilian free-tailed bats (*Tadarida brasiliensis*). Female hoary bats (*Lasiurus cinereus*) have been seen migrating through New Mexico in the spring and fall, whereas males are commonly found in pinyon-juniper woodlands in the summer. Silver-haired bats (*Lasionycteris noctivagans*) are found in pinyon-juniper woodlands as well as in other habitat types; however, these bats may move to more northern states in midsummer (Findley et al. 1975). Because the mentioned bat species have been captured in pinyon-juniper woodlands by

mistnetting at night, they must use the woodlands for foraging and/or water. Little else is known about the species' use of pinyon-juniper woodlands, i.e., whether they roost in pinyon and juniper trees and, if so, in what structures, whether they feed exclusively in the woodlands, and whether they overwinter/hibernate in the woodland habitats. Although it is likely that rock cliffs, tree branches and bark, and hollows of mature pinyon and juniper trees provide roost sites for many of these species, few studies have been undertaken to prove such hypotheses or investigate other habitat requirements and associations of these bat species.

Many species of small mammals may be found in pinyon-juniper habitats; species composition depends on the mix of vegetation, cover, elevation, soil, and other factors. Many of these species are present in pinyon-juniper stands only at the periphery of their ranges (primarily ponderosa pine or grassland distributions) or have broad distributional ranges that merely include pinyon-juniper woodlands. Species that have distributions centered in pinyon-juniper woodlands include cliff chipmunk (*Tamisas dorsalis*), rock squirrels (*Spermophilus variegatus*), brush mice (*Peromyscus boylii*), pinyon mice (*P. truei*), rock mice (*P. difficilis*), and white-throated (*Neotoma albigula*) and Mexican (*N. mexicana*) woodrats (Findley et al. 1975). Pinyon mice are more or less restricted to pinyon-juniper woodlands and are often the most common small mammal in open stands of this vegetation type (Findley et al. 1975; Short and McCulloch 1977). Abundances of pinyon mice were shown to decline in pinyon-juniper habitats where the overstory was completely removed (Severson 1986a). Populations of pinyon mice, as well as other seed predators, probably explode during mast years. How these fluctuations cascade through the ecosystem remains largely undetermined. Brush mice, essentially oak specialists, can become the predominant species in lower elevational habitats lacking pinyon or in pinyon-juniper habitats with an evergreen oak and shrub understory (Findley et al. 1975). Rock mice and rock squirrels are more common amongst rocks, boulders, and broken terrain within the pinyon-juniper woodlands.

Species that may be found at the periphery of their grassland/desert distributions in the more open pinyon-juniper habitats include white-tailed antelope squirrel (*Ammospermophilus leucurus*), Texas antelope squirrel (*A. interpres*), silky pocket mice (*Perognathus flavus*), Plains pocket mice (*P. flavescens*), Ord's kangaroo rat (*Dipodomys ordii*), and desert cottontail

(*Sylvilagus audubonii*). More mesic sites where pinyon-juniper grades into and intermingles with ponderosa pine and mixed conifer species may support eastern cottontails (*Sylvilagus floridanus*), Colorado chipmunks (*Tamias quadrivitattus*), deer mice (*Peromyscus maniculatus*), and Mexican woodrats (*N. mexicana*) (Findley et al. 1975).

The invertebrate and small mammal communities sustain a number of avian and mammalian predators. Mammalian predators may include coyote, gray fox (*Urocyon cinereargenteus*), ringtail (*Bassariscus astutus*), long-tailed weasel (*Mustela frenata*), western spotted skunk (*Spilogale gracilis*), striped skunk (*Mephitis mephitis*), hog-nosed skunk (*Conepatus mesoleucus*), mountain lion (*Felis concolor*), and bobcat (*Felis rufus*) (Findley et al. 1975). Skunks, ringtails, coyotes, and gray foxes may also include fruits and other vegetative matter in their diets, depending on availability and season. Avian predators that hunt small mammals and/or birds within pinyon-juniper woodlands may include golden eagle (*Aquila chrysaetos canadensis*), Swainson's hawk (*Buteo swainsoni*), Cooper's hawk (*Accipiter cooperii*), kestrel (*Falco sparverius sparverius*), red-tailed hawk (*B. jamaicensis*), and great-horned owl (*Bubo virginianus*) (Frischknecht 1975). Although individual predators might forage, breed, and maintain territories in pinyon-juniper habitats alone, all of these predatory species have distributions that extend beyond the pinyon-juniper ecosystem into grasslands, deserts, and/or forests (Findley et al. 1975).

Other year-round residents in pinyon-juniper stands are mule deer (*Odocoileus hemionus*), white-tailed deer (*O. virginianus*), and elk (*Cervus elaphus*), all of which consume leaves and fruits of pinyons and junipers (Martin et al. 1961). Deep snows in the higher elevation forest zones may force additional deer and elk down from these higher elevations into pinyon-juniper habitats during the winter. Although forbs and grasses are utilized by deer during the spring and summer, browse from dwarf trees and shrubs are more important year-round. Elk also utilize forbs in the summer, grass in the summer and winter, and shrubs to some extent throughout the year. Some shrubs and dwarf trees found in the mid- and understory that are important to these cervids are mountain mahogany (*Cercocarpus breviflorus*), desert ceanothus (*Ceanothus greggii*), shrub live oak (*Quercus turbinella*), wavyleafed oak (*Q. undulata*), Gambel oak (*Q. gambelii*), and cliffrose (Short and McCulloch 1977). Bighorn sheep (*Ovis canadensis*

canadensis) may also utilize pinyon-juniper habitat where there is rough terrain suitable to their habitat needs (Short and McCulloch 1977).

Although only a few species of wildlife rely solely on pinyon-juniper habitats for suitable habitat, many species utilize the wide array of habitat types found in this ecosystem. Pinyon and juniper trees provide nesting material and sites for birds and mammals, hiding cover, and valuable year-round food resources in the form of leaves, nuts, and berries. During temperature extremes of the summer and winter, pinyon-juniper habitats also provide thermal protection, the degree of which is determined by canopy closure. On the other hand, birds and mammals are important to pinyon and juniper trees as agents of seed dispersal. Mid- and understory trees, shrubs, and grasses, the quantity of which is inversely related to canopy closure, provide additional food resources, hiding cover, and nesting cover for other wildlife species.

IMPACTS ON PINYON-JUNIPER ECOSYSTEMS

Climatic Variability

Climatic fluctuations throughout time have influenced changes in the distribution and density of pinyon-juniper woodlands. Fluctuations during prehistoric periods have been greater than during historic times. During the Late Pleistocene (40,000–11,000 years ago), for example, pinyon-juniper woodlands occupied lower elevation sites, which currently support deserts, grasslands, or scrublands (Betancourt 1987; Betancourt et al. 1990, 1993). Drier and warmer conditions during the Holocene caused the woodlands to retreat northward and upward in elevation until the woodlands occupied their present locations during the late Holocene (the last 4,000 years). Changes during the late Holocene are presumably due to climate variability at an interdecadal scale, which is currently receiving more attention by climatologists (Karl 1988; Guetter and Georgakakos 1993; Kushnir 1993; Xu 1993; Graham 1994; Miller et al. 1994a).

Interdecadal climate variability, which produces prolonged episodes of wet and dry conditions in the central Rio Grande Basin, has left a strong imprint on the demography of pinyon-juniper woodlands. For example, a less sinuous and more northerly polar jet stream, a weakened subtropical jet stream, and a decrease in the frequency of El Niño events contributed to a subcontinental-scale drought in the middle of the century. The 1950s drought, an event

with a 200 to 500-year return period (Stahle and Cleaveland 1988), caused massive die-off of pinyons and junipers throughout the Middle Rio Grande Basin (Betancourt et al. 1993). The drought probably reset demographic clocks, created disequilibria in carbon and nutrient cycling, accelerated shrub invasions into grasslands, and shifted ecotonal boundaries that had been stable for several millennia. Data indicate that the pinyon mortality associated with this outbreak caused the ecotones between pinyon-juniper and juniper woodlands and between the pinyon-juniper and ponderosa pine forests to shift sporadically about 100 m horizontally upslope in the Frijoles watershed of the Jemez Mountains. A similar impact on pinyon populations has been documented at the Sevilleta Long-Term Ecological Research Site, near Socorro, New Mexico (Betancourt et al. 1993). The intense drought may have further reduced the herbaceous ground cover enough to initiate and exacerbate desertification and erosion processes. The return of wet conditions beginning in the late 1970s is likely responsible for the recent recovery of range conditions and may have produced a surge of recruitment of pinyon and junipers throughout the region.

During the last 50 years, the Middle Rio Grande Basin has experienced one of the driest (late 1940s to early 1960s) and one of the wettest (1976 to present) episodes of the last few hundred years, according to the tree-ring record (Fig. 2). The latter period is now gaining a lot of notoriety in the global change arena. There appears to have been a step change in global climate since about 1976, including record warmth that is related, in part, to an almost permanent shift to El Niño-like conditions (Ebbesmeyer et al. 1991; Miller et al. 1994b). This shift suggests that the tropical Pacific may be the pacemaker for the global system at interdecadal scales; climatologists are now entertaining the possibility that an enhanced greenhouse effect accelerates the tropical heat machine (Latif and Barnett 1994; Kumar et al. 1994). Thus pinyon-juniper woodlands in the Middle Rio Grande basin may already be responding to climatic effects from greenhouse warming, in the form of increased cool season precipitation with persistent El Niño conditions in the 1980s and 1990s.

Fire

Fire was the most important natural disturbance in the pinyon-juniper woodlands before the introduction of large herds of livestock in the 19th century.

Although ecologists and managers have long recognized that fire was an important factor in presettlement dynamics of the pinyon-juniper type (Leopold 1924), there is little specific data documenting the range and variability of past fire regimes. There are only a few studies located in the upper border of the pinyon-juniper zone, where it occurs with ponderosa pine, that clearly document the frequency, extent, seasonality, or other presettlement or long-term fire regime patterns (Allen 1989; Despain and Mosley 1990; Swetnam and Baisan 1995).

The evidence of past fire occurrence is visible in many stands as the presence of charcoal in the soil; charred, remnant juniper snags or stumps; and fire scars on living junipers and pinyons. Fire scars on living pinyons are generally rare, especially in comparison with scar abundance in higher elevation ponderosa pine and mixed conifer stands (Swetnam 1990; Swetnam and Baisan 1995). The rarity of pinyon fire scars may be due to high susceptibility of pinyon boles and crowns to damage by surface fires; trees are either killed outright, or do not live long after being scarred. Heart-rotting fungi may enter the fire-scar wounds to hasten mortality. In spite of the poor preservation of the record from fire-scarred pinyon, several specimens from New Mexico have been dendrochronologically dated; one tree located in a stand that contained ponderosa pine had 11 fire scars over a period of 200 years (Swetnam [unpublished data]). In contrast to pinyon, fire-scarred and fire-charred junipers have often been noted but rarely systematically sampled or quantitatively analyzed. Unfortunately, as previously mentioned, junipers in the Southwest cannot be accurately dated because of numerous false and missing rings.

One of the most detailed and informative fire-scar-based studies in southwestern pinyon-juniper woodlands was conducted at Walnut Canyon National Monument near Flagstaff, Arizona (Despain and Mosley 1990). Dead, fire-charred junipers were sampled within a 300 ha stand and a fire chronology was also constructed from fire-scarred ponderosa pine trees in an adjacent stand. Results from the analyses indicated a surface fire interval of approximately 20 to 30 years. Three other fire history studies in New Mexico, based on fire-scarred ponderosa pine trees scattered within the pinyon-juniper woodlands, indicate that stand-wide fires, those burning more than 10 ha, occurred about every 15 to 20 years on the average. These studies were conducted in the Jemez Mountains (Allen 1989), Organ Mountains

(Morino and Swetnam [unpublished data]; Swetnam and Baisan 1995), and El Malpais National Monument (Grissino Mayer and Swetham, in press).

Dense pinyon-juniper stands (approximately 1,110 trees per hectare) can burn as crown fires under extreme weather conditions. Wright and Bailey (1982) reported that such stands will burn when relative humidities are lower than 30 percent and winds exceed 55 km per hour. The key conditions for such burns are sufficient canopy closure to promote fire spread between trees, abundance of dead woody fuels on the surface and as standing snags, and extreme weather conditions. Hence, it appears that presettlement pinyon-juniper fire regimes were a mixture of surface and crown fires and of variable intensity and frequency and depended largely on site productivity. Productive sites, such as at Walnut Canyon, probably sustained patchy surface fires at intervals of 10 to 50 years. Some of these stands attained densities sufficient to carry crown fires at intervals of 200 to 300 years or longer.

On less productive sites with discontinuous grass cover, fires were probably very infrequent, and burns were small or patchy when they did occur. In sites with relatively continuous grass cover, frequent widespread fires (10-year intervals or less) probably maintained grasslands or savannas, with pinyons and junipers restricted to rocky outcrops and microsites where grasses were discontinuous. Savannas were maintained because fires tended to kill trees less than about 1 m tall (Johnsen 1962).

The Sevilleta National Wildlife Refuge and adjacent mountains in the central Rio Grande may be an area where the full range of possible fire regimes in pinyon-juniper existed in the past. This area encompasses the National Science Foundation's Sevilleta Long Term Ecological Research site. The Manzano and Los Pinos Mountains border the east and northeast sides of the area. These ranges extend along a north-south axis on the east of the Rio Grande. Today, grasslands and creosote stands occur from the lowest elevations at about 1,450 m at the Rio Grande up to the foothills of the mountains at about 1,800 m. Livestock grazing has been excluded within the Refuge since the late 1970s. As a result, grass cover has expanded and increasingly large grass fires ignited by lightning have burned during the summer months. Most of the larger burns (e.g., greater than 1,000 ha) were extinguished by managers. Some of these fires would have burned substantially greater areas if they had been allowed to, and in some cases,

they would have burned up into the extant pinyon-juniper (or pure juniper) savannas and woodlands. At the lower elevations, grasslands currently extend up to the steep rocky escarpments on the west sides of the Manzano and Los Pinos Mountains, while in other areas, the grasslands ascend bajadas, gentle ridges, and canyon bottoms up onto the mountains where scattered junipers and pinyons form savannas that transition into woodlands. Confirmation of lower densities in the past, however, awaits demographic studies of the kind now being conducted at the Sevilleta Long Term Ecological Research site.

Before the advent of intensive livestock grazing, we suspect that, during certain years, very large areas burned in the grasslands, adjacent savannas, and woodlands. These years of extensive burning were probably dry, and they may have followed wet years when substantial grass and herbaceous growth was enhanced (Rogers and Vint 1987; Swetnam and Baisan 1995). Eyewitness accounts of burning in this area have not been found, but in other parts of the Southwest—such as in southern Arizona and southeastern New Mexico—newspapers reported "millions of acres" burning in grasslands and woodlands during the 1870s and 1880s (Bahre 1985).

Above the grasslands and savannas, many areas are very rocky with thin soils. Grass cover is sparse or nonexistent within most of the woodlands on the slopes and ridges, and it is unclear if these areas ever sustained adequate soil or moisture resources necessary for production of a more-or-less continuous understory cover that is needed to support spreading surface fires. Nevertheless, charred, ancient-looking juniper stumps are commonly seen within these stands. In the Los Pinos Mountains, at an elevation of 1,900 to 2,100 m, a number of fire scars have been discovered that are completely grown over within the stems of living and dead pinyons (Swetnam and Betancourt [unpublished data]). Many of these scars date to the year 1748. Other dendrochronological studies indicate that this was one of the driest years in the Southwest in the past 300 years, and it followed one of the wettest years (1747). Moreover, this was probably the largest regional fire year to occur in the Southwest in several centuries; it is recorded by fire scars in 41 of 63 sites where fire chronologies have been reconstructed (Swetnam and Betancourt 1990, Swetnam and Baisan 1995). Thus, it seems that fire-free intervals in these less productive pinyon-juniper sites were very long (i.e., greater than 100 years), but in unusual climatic conditions, spreading surface or canopy fires did occur.

The other extreme of pinyon-juniper productivity can be observed on the east side of the Manzano Mountains. On this side of the mountains, where summer rainfall is apparently greater than on the west side, dense, closed-canopy pinyon-juniper stands cover large areas. Mixed within these stands are numerous homes that will probably be consumed by future catastrophic crown fires. Such burns have already occurred in some locales on the mountain, prompting the Cibola National Forest, and the Department of Defense, which has jurisdiction over a "military withdrawal area" within the Manzanos, to expend considerable resources in preparing fuel breaks. It is unknown if these more productive pinyon-juniper stands sustained surface fires in the past, but fire-scar studies in adjacent ponderosa pine stands suggest that they did. Despite uncertainty about the frequency or extent of fires, it is very likely that the densities of these productive stands have increased in the late 20th century compared to the 19th and earlier centuries when surface fires, and extensive fuelwood cutting for Albuquerque, probably maintained more open stand conditions.

Succession

Soil development is slow under semi-arid climates with accumulations of many soil properties taking from 1,000 to 100,000 years. Thus, most soils in the pinyon-juniper woodlands are not necessarily in equilibrium with modern climate and vegetation. Many of the soils that may have developed under mixed conifer forests during the last glacial period were later affected by Holocene erosion, approximately 8,500–6,000 years ago; these same areas are now occupied by pinyon-juniper woodlands (S. Reneau, personal communication, Los Alamos National Laboratory, 1994).

There have been numerous studies of succession in old pinyon-juniper burns and tree control areas (Arnold et al.; 1964, Clary et al. 1974; Rippel et al. 1983; Severson 1986b). In woodlands, successive stages usually contain the same species but in different amounts and dominance (Evans 1988). Habitat type also will affect the successional process. Arnold et al. (1964) proposed one successional sere for the Southwest, which started with the establishment of annuals after a fire and progressed to the renewed dominance of the arboreal vegetation; other pathways have also been suggested for the woodlands of southwestern Colorado and western Utah (Evans

1988). Junipers can be the first tree species to invade an area, but they are often followed and replaced by pinyon. In Utah, tree dominance does not occur until 70 to 80 years following fire. Herbage yields decline as tree crown cover increases (Arnold et al. 1964). Succession has been more rapid in some cleared areas because of the presence of tree advance regeneration that survived the initial control treatment.

The invasion of native grasslands by woodland species has been a topic of concern and controversy. As noted above, fire was the dominant factor limiting the spread of trees and maintaining open stands where trees always dominated. However, most of the new tree establishment occurred in juniper savannas, as indicated by the presence of old trees, or in grassland inclusions within the woodlands, and little occurred in true grasslands (Johnsen 1962). The expansion of pinyon in some areas of New Mexico may actually be its reestablishment on previous woodland sites (Samuels and Betancourt 1982; Dick-Peddie 1993). The successful establishment of tree species indicates that they are adapted to existing site conditions, and while competition and fire may have limited their numbers, the invaded areas are climatically woodlands. Trees may also indicate that the initial habitat, especially as it affects species germination and establishment, has been modified and may no longer be optimum for the original mix of species (Dick-Peddie 1993). Some of the tree control operations of the 1950s and 1960s may have failed because woodland soil and microclimatic conditions no longer favored the establishment of seeded grasses.

The distribution and composition of plant communities are dynamic, varying in both time and space (Tausch et al. 1993). Climatic variability, as indicated above, has affected the distribution of pinyon-juniper woodlands within the Middle Rio Grande Basin. Natural changes may be subtle, occurring over a long period, or dramatic, as are the effects of the 1950s drought. Human management can alter site conditions in such a way that certain species can no longer maintain or reestablish themselves once a perturbation has been eliminated. Changes in environmental conditions can change dominance patterns and species compositions; there are several structurally and functionally similar plant communities that could become established on a site (Tausch et al. 1993). More information about ecological thresholds, multiple steady states, and multiple successional pathways is presented by Tausch et al. (1993).

Land Use History and Ecosystem Changes

Land use of pinyon-juniper woodlands by prehistoric and historic human societies has affected these ecosystems. The land use history of the Pajarito Plateau on the eastern flank of the Jemez Mountains, northwest of Santa Fe, is broadly similar to other portions of the Middle Rio Grande Basin. A review of this history is presented as an illustrative case study that probably reflects changes over a larger area. Extensive research has been conducted on the archeology (Head 1992; Mathien et al. 1993; Orcutt [unpublished manuscript]), general land use histories (Allen 1989; Rothman 1989; Scurlock and Johnson 1994), ecology (Barnes 1986; Padien and Lajtha 1992; Breshears 1993; Chong 1993), and hydrology (Wilcox et al., in press) of Pajarito Plateau woodlands. Synthesizing this information with research results from other areas (e.g., Rogers 1982; West and Van Pelt 1987; Cartledge and Propper 1993; Betancourt et al. 1993; Miller and Wigand 1994) leads to the general scenario noted in figure 3 of changes in local pinyon-juniper woodlands.

American Indian effects on local woodlands are thought to have been insignificant or highly localized until the late 12th century, when the Anasazi population began to build markedly (Orcutt [unpublished manuscript]). Recent archeological survey and excavation work at Bandelier shows evidence of extensive Anasazi impacts on woodland resources during the peak occupation period of A.D. 1200–1500. Cutting and burning of pinyon and juniper trees for cooking, heating, building, and agricultural activities likely led to significant deforestation of upland mesas during this time, and local ungulate (primarily mule deer) and rabbit populations may have been reduced by hunting pressure (Kohler 1992).

The overall ecological effect of several centuries of Anasazi occupation of the Pajarito Plateau may have been to favor herbaceous vegetation at the expense of the woodland trees. Intensive soil disturbance certainly occurred in farmed areas and around habitations. But there probably was little net change in landscape-wide erosion rates due to the small size and dispersed location of farm "fields" and habitations and the effectiveness of herbaceous vegetation at protecting soils from erosion. Perhaps, the lack of well-developed, old-growth pinyon-juniper woodland in the Bandelier area can be partly traced to the slow recovery of woodlands from the effects of Anasazi deforestation.

Conceptual Model of Piñon-Juniper (PJ) Ecosystem Changes on the Pajarito Plateau

Pleistocene climate/vegetation (mixed conifer forests) lead to formation of well-developed soils on mesas

Major climate change | Pleistocene
_ _
(ca. 10,000 years B.P.) | Holocene

Changes in climate and vegetation in the early Holocene cause episodes of aggradation and degradation in local canyons

Open, grassy PJ woodlands and savannas develop on mesas, with lower productivity PJ on rocky slopes. Relict soils protected from erosion by relatively dense, herbaceous, ground cover and litter. Periodic fire keeps PJ density down (fire return interval ≈15-40 years).

(ca. A.D. 1200-1550)

ANASAZI IMPACTS
❏ Cut and burned PJ
  • Increased fire frequency (?)
❏ Localized soil disturbance by farming, trampling, and habitation activities
❏ Decreased ungulate populations locally by hunting

Decreased PJ cover due to cutting and increased fire, favoring herbaceous vegetation. Localized erosion around habitation & farming sites; overall little change in landscape-wide erosion levels due to small size and dispersed location of farm "fields".

(late A.D. 1500's)

SPANISH COLONIZATION
❏ Domestic livestock introduced to region, use of Pajarito Plateau restricted by danger from the Navajo and Apache until after ca. 1850
❏ Heavier sheep use of lower cañon areas from Cañada de Cochiti, San Ildefonso, Santa Clara
❏ Cutting of PJ for fuel and domestic use near settlements

Only localized vegetation change and accelerated erosion, due to limited human use of the Pajarito Plateau.

Figure 3.

ANGLO SETTLEMENT

(post A.D. 1880)

❏ Continued increase in livestock numbers, especially in 1880's after railroads access area, large numbers of sheep and cattle are brought to the Pajarito Plateau; widespread use of the plateau for intensive grazing through 1930's

❏ Extreme droughts in 1890's and 1950's

❏ Selective cutting of PJ becomes more extensive through 1930's

❏ Widespread fires eliminated by intensive grazing; active fire suppression initiated and institutionalized ca. 1910

❏ Large numbers of feral burros in Bandelier National Monument from 1940's until 1983

❏ High deer numbers in Bandelier since 1940's

❏ Elk reintroduced, local population grows to thousands

PJ ecosystems, especially understory/soil subsystems, forced into disequilibrium:

❏ Decreased ground cover by grazing and hoof action from ungulates, rodents, rabbits, and ants
  • Decreased vegetation and litter cover, particularly in the interspaces between trees
    – Soil surface microclimate becomes more extreme
❏ Increased bare soil –> thresholds reached where precipitation becomes surface runoff instead of infiltration
  • Less water available for shallow-rooted herbs
❏ Increased soil erosion –> leading to further increase in bare soil and surface runoff in a positive feedback cycle (note: the same magnitude rainfall event causes more erosion than before)
❏ Increased precipitation intensity (?) from ca. 1880-1930 may have further increased surface runoff
❏ Decreased fire frequency (as inadequate ground fuels remain to carry fire) allows unimpeded tree establishment
❏ Increased PJ tree density and PJ invasion of former grasslands downslope and ponderosa forests upslope ◄
➤• Increased tree competition with herbs for water, nutrients, light, space (and allelopathic effects?)
  ➤ – Further decreases in herbaceous vigor and cover reducing herbaceous controls on tree establishment
❏ Droughts may have further reduced herbaceous vegetation, perhaps triggering erosion on additional sites by causing thresholds of exposed soil to be exceeded

❏ Herbaceous plant re-establishment becomes very difficult, even after livestock are removed, due to dominance of physical processes in the desertified interspaces:

  • Loss of organic matter litter/mulch at soil surface (therefore, drier surface soil and difficult surface microclimate), increased freeze/thaw soil displacement (disrupting seedling roots), nutrient/texture problems for seedling establishment in exposed clay-rich B-horizons, nutrients translocated and concentrated beneath trees, decreased seed sources, depleted soil seed pools, animal use of herbs and their limited seed sources (by ungulates, rodents, and ants)

❏ Soil erodes from uplands –> canyons –> Rio Grande/Cochiti Reservoir

❏ Bare soil –> bare rock, with even further increases in surface runoff and attendant erosion down-drainage

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Today: most local PJ woodland ecosystems are unstable from a soils perspective, with many moving towards "PJ rocklands"

Figure 3 (continued).

European settlement of the adjoining Rio Grande Valley, and the introduction of domestic livestock grazing, began in 1598 at today's San Juan Pueblo. During most of the historic period, livestock use of the Pajarito Plateau was apparently restricted by danger from Athabascan raiders (Navajo, Apache, Ute), although lower elevation areas near the valley's Spanish and Puebloan communities may have been heavily utilized by livestock (M. L. Smith [unpublished manuscript]). This constraint on use of the Pajarito Plateau eased by ca. 1850 but was not eliminated until the final suppression of Navajo raids in the 1860s. Still, at the time the Ramon Vigil Grant in the heart of the Pajarito Plateau was surveyed by the U.S. General Land Office in 1877, herbaceous vegetation was noted to be abundant, and livestock use was apparent. Cutting of pinyon and juniper for fuelwood and building materials was important in many areas on the Pajarito Plateau in the late 19th and early 20th centuries. The stubs of axe-cut junipers remain obvious in most pinyon-juniper woodlands north of Frijoles Canyon on the Plateau.

The development of railroad links to external commercial markets during the 1880s led to marked increases in the numbers of domestic livestock grazed on the Pajarito Plateau, beginning in 1880 on the Ramon Vigil Grant (Rothman 1989). Similar increases were reported from throughout New Mexico; there were about 1.3 million cattle and 3 million sheep in the state by 1888 (Wooton 1908). The resultant high intensity grazing apparently triggered ecological changes in local woodlands. Overgrazing caused sharp reductions in the herbaceous ground cover and associated organic litter, effectively suppressing the previously widespread fires. Cool season grasses, which green up early in the growing season, are thought to have been most affected by this year-long grazing pressure, so that today they are largely found only beneath the crowns of older woodland trees or on steep slopes. Reduced cover of herbaceous plants and litter led to decreased water infiltration and increased surface runoff from the typically intense local rainfall events, and thresholds were reached that initiated accelerated erosion. An increase in the intensity of extreme storm events in the late 1800s may have further exacerbated erosional processes. In any event, by 1913 grass cover was considered "scant" and a surveyor in 1938 identified inadequate water infiltration as a cause. Current woodland conditions in Bandelier display tree canopy coverage ranges of 12 to 45 percent, herbaceous plant coverage (basal intercept) of only 0.4 to 9 percent, and exposed soils covering between 38 and 75 percent of ground surfaces.

Overall, the most significant ecological changes in local pinyon-juniper woodlands in historic times involve diminished and altered herbaceous ground vegetation, fire suppression, increased tree densities, and accelerated soil erosion. However, the consequences and interrelationships among the variables are open to several interpretations.

Over the past century many young pinyon and juniper trees became established in the absence of thinning fires and competing herbaceous vegetation, with increases in tree density continuing to the present on mesic sites. Thus, tree densities increased within pinyon-juniper woodlands, while pinyon and juniper expanded their ranges upslope into ponderosa pine forests and juniper moved downslope into former grasslands. As these trees grew they became increasingly effective competitors for water and nutrients in the shrinking tree interspaces, directly limiting herbaceous plant establishment and growth and keeping much bare soil exposed; allelopaths in juniper needle litter may augment this process. While there are several reasons for the accelerated erosion within some watersheds, these changes apparently interacted as a positive feedback cycle in which decreased herbaceous ground cover promoted tree invasion and continued erosion, which in turn fostered further decreases in ground cover. Increased grazing pressure on residual herbaceous species and increased soil compaction in interspace areas by livestock and wildlife also contributed to the problem. As a result, large portions of the Pajarito Plateau are becoming pinyon-juniper "rocklands" as the soil mantle erodes away—this is most evident on the southerly, low elevation mesas of the park where shallower soils were already present before this modern erosion began.

The reestablishment of herbaceous ground cover under today's desertified mesa-top conditions is difficult. Heavy utilization of the current herbaceous vegetation by animals ranging from harvester ants and mice to increasing numbers of elk may be limiting the availability of seed sources in many woodland areas (Carlson 1988). Seedling establishment has been inhibited by changes in soil surface conditions. Losses of organic matter litter, which acts as a mulch, and porous nutrient-rich surface soils have resulted in reduced water infiltration and soil nutrient availability, and have caused the soil surface microenvironment to become more xeric and experience more

extreme temperatures. The relatively impermeable clay-enriched horizons that consequently are exposed present a more difficult nutritional and water-balance environment for prospective seedlings. Winter freeze-thaw activity churns the top soil layer and creates polygonal cracking patterns in bare soils that damage or kill the roots of seedlings that managed to establish successfully the previous summer. Interestingly, in Bandelier, herbaceous vegetation today is generally far more vigorous and dense on canyon walls than on the adjoining, eroding uplands, even on dry southerly aspects, as rock cobbles on the canyon slopes create a relatively stable, mulching substrate where adequate moisture and nutrients are available to the interspersed plants.

Once initiated, this pattern of desertification is apparently difficult to break (Evans 1988). Physical rather than biological processes now dominate these sites. Biological capital that once moderated the elemental forces has been dissipated, leaving harsh sites for plant establishment. Soils that likely formed under more mesic climate and vegetation conditions during the Pleistocene are eroding at unsustainable levels in many pinyon-juniper woodlands on the Pajarito Plateau today. For example, in 1993, erosion bridge measurements at 360 points on a 1 ha watershed in Bandelier revealed a mean degradation in the soil surface level of 0.34 cm between July and November (Wilcox et al. 1993). Also, herbaceous vegetation cover continues to decline in some areas (Potter 1985).

Simply eliminating the livestock grazing that apparently triggered the development of the current situation is not sufficient to halt the erosion. Livestock grazing ceased in 1932 over most of the Bandelier area in which erosion is currently occurring. However, the subsequent increase in the burro populations south of Frijoles Canyon may have contributed to soil degradation. North of Frijoles Canyon, where burros were never a significant factor, removal or reduction of domestic livestock was accomplished by 1943, with absolute exclusion of trespass livestock since the early 1960s; yet, serious erosion also occurs there and may even be more severe in areas like the detached Tsankawi Unit.

As a result of the pervasiveness of human activities in pinyon-juniper woodlands for most of the past millennia, current efforts by land management agencies to move toward ecosystem management, where desired conditions are based on the historical range of natural variability, will be challenging and possibly controversial. A better understanding of historic and prehistoric human interactions with the pinyon-juniper woodlands is needed to help define sustainable goals for managing these important ecosystems.

PINYON-JUNIPER WOODLAND MANAGEMENT

Woodland Control Programs

Livestock interests maintain that forage for livestock has declined as the pinyon-juniper type has increased in area and density since European settlement. While the invasion question is still being debated (Miller and Wigand 1994), research has demonstrated that total forage production declines as tree crown closure increases (Arnold et al. 1964).

In the period following World War II, efforts were started on western ranges to eliminate pinyon and junipers in favor of forage species. By 1961, 486,000 ha of Arizona pinyon-juniper lands had been treated using a variety of techniques such as cabling, bulldozing, individual tree burning, grubbing, and chopping (Cotner 1963). The treated sites were usually seeded with grasses once trees were removed. However, the number of hectares treated annually in Arizona began to decline by the late 1950s as the availability of productive and easily treated areas declined (Cotner 1963).

The value of pinyon-juniper control efforts has been controversial. Arnold and Schroeder (1955) indicated that herbage yields could be increased by removing juniper trees. Clary (1971) also reported increases in understory vegetation following removal of Utah juniper in Arizona; however, yields of seeded exotic grasses declined after 4 to 6 years, while native species tended to increase slowly over time. Seeding was generally unsuccessful in large conversion areas. Successful herbage production following tree removal depends on annual precipitation, pretreatment tree cover, and on pretreatment soil nitrate-nitrogen content (Clary and Jameson 1981). Production was also lower on soils derived from limestone. An increase of between 0.5 and 0.8 AUM per hectare was indicated for the most successful projects (Clary et al. 1974). The benefits of many treatments have declined over time. In a New Mexico study, Rippel et al. (1983) evaluated a treated area after 20 years, and found that the cover of grasses and forbs was greater in an undisturbed pinyon-juniper stand than in the cabled area.

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Control programs were also justified by the assumption that they increased water yields. The hypothesis held that replacing comparatively deep-rooted trees with shallower-rooted grasses would result in decreased evapotranspiration and increased runoff, which would eventually reach downstream reservoirs. However, while this mechanism works in vegetation types found on moister sites, the basic moisture requirements on dry sites are similar regardless of vegetation, and one vegetation type is about as efficient at using available moisture as another. Little opportunity exists for streamflow augmentation on warm, dry sites where annual precipitation is less than 460 mm and is exceeded by potential evapotranspiration (Hibbert 1979). Most pinyon-juniper woodlands fall into this category. Watershed research in Arizona at Beaver Creek (Clary et al. 1974) and at Corduroy Creek (Collings and Myrick 1966) failed to show significant water yield increases following control treatments. The only experiment to demonstrate an increased water yield (about 5 mm in an area where average annual precipitation was 463 mm) utilized aerial spraying of herbicides and did not allow the immediate harvesting of the dead, standing trees (Baker 1984). However, results from Beaver Creek (Clary et al. 1974) indicated that soils deeper than 30 cm within treated areas retained more soil moisture than did similar soils in untreated areas. This additional moisture would benefit vegetation on the site even if it did not contribute to streamflow.

There is a common belief that the active erosion and gullying observed in the woodlands and the related decline in long-term site productivity are the result of the tree cover (Gifford 1987). However, Gifford (1987) stated that there is no evidence to support this hypothesis and, in fact, existing limited research indicates otherwise. Erosion is a natural process but has accelerated because of reduced vegetation cover and overuse of channels and wet areas by livestock. The role of trees in soil stabilization is often ignored in the pinyon-juniper woodlands, although trees are planted throughout the world for this purpose. Reduced infiltration is one cause of overland flow and accelerated erosion. Infiltration rates are similar in wooded and chained areas (Evans 1988). Plots with pinyon or juniper litter had significantly lower total sediment concentrations and yields than plots with herbaceous cover or bare plots (Bolton and Ward 1992).

Sediment movement is greatest in the interspace areas. Interspace areas contributed the most runoff

and erosion on the litter plots studied by Bolton and Ward (1992). It is generally agreed that the characteristics of interspace areas have changed, especially since European settlement. While erosion has been attributed to the decline of herbaceous vegetation, there are other reasons for both factors. Wildlife and livestock concentrate on the herbaceous vegetation in interspace areas and use some areas as trails, contributing to reduced cover and increased soil compaction. Changes in the steepness of watershed channel gradients and slopes, because of erosion, have accelerated surface runoff rates in many areas, contributing to continued erosion and making reclamation more difficult. It is more difficult for litter layers to develop or seeds of herbaceous species to become established. Wilcox (1994) reported that interspace runoff and erosion vary spatially and temporally. They also vary with watershed size (large watersheds react differently than runoff plots), with fluctuations in soil moisture and soil infiltration capacity, and with degree of soil surface compaction throughout the year. Erosion from interspace areas with little bare soil was minimal but increased as the extent of bare ground increased. However, when the impacts of tree cover and interspace were integrated, as Wilcox (1994) also noted, sediment delivery was less from a small wooded watershed than from a non-wooded watershed (Heede 1987). Clary et al. (1974) concluded that there were no significant differences in sediment production on Beaver Creek between untreated watersheds and watersheds where trees had been removed.

It was anticipated that woodland control treatments would benefit wildlife because of increased forage. Numerous studies have analyzed the effectiveness and efficiency of such conversions, the relative success, and the responses of game and nongame wildlife. Expensive tools for improving range, chaining, and cabling only proved cost-effective in areas where posttreatment forage production potential was high (Short and McCulloch 1977). Goals of improving deer foraging habitat, if reached at all, were achieved only if more abundant and succulent spring forage resulted from the conversion and if converted tracts were small and interspersed within the woodland (Terrel and Spillett 1975). A study at Fort Bayard, New Mexico (Short et al. 1977), found that large clearings limited deer and elk use, because the animals would venture only a short distance away from cover. Because animal use declined as tree density increased, Short et al. (1977) recommended small clear-

ings interspersed within the stands for improved big game habitat. Simultaneous improvement of big game habitat and range appeared difficult because the small, interspersed nature of conversions that would benefit deer was contrary to the large, open tracts that would provide the greatest benefit to range (Short and McCulloch 1977).

Although additional spring forage can be beneficial to big game, the most valuable component of pinyon-juniper woodlands may be winter browse provided by shrubs and other woody vegetation typically removed by chaining and cabling (Terrel and Spillett 1975). The removal of the mid- and overstory by chaining or cabling also results in the loss of hiding and escape cover and important thermal cover for deer and other wildlife during the winter (Howard et al. 1987). Important questions to be answered are whether pinyon-juniper conversions truly improve foraging habitat for big game, and if so, is increased spring forage more important than the winter browse and thermal protection provided by partial overstory or intact pinyon-juniper habitats? Thus, the value of pinyon-juniper conversion as a tool in big game habitat management still remains a debated topic.

Knowledge of the effects of management practices in pinyon-juniper woodlands on wildlife and general ecosystem integrity is more important now with the greater emphasis on ecosystem management and multiple use. Tausch and Tueller (1995) determined that native plant species were best retained/augmented and mule deer winter use was higher in sites with a high species diversity and cover before chaining. Sites with little initial understory had a higher cover of introduced (seeded) species and cheatgrass (*Bromus tectorum*) and less deer use after chaining. Bird species diversity and use by the foliage/timber searching guild, aerial foraging guild, and hole nesting guild were lower on chained plots than unchained. However, species of the ground nesting and foraging guilds were not affected (Sedgewick and Ryder 1987). Causes for the declines in bird use on chained plots may have been related to changes in predominant vegetation type, amount and distribution of foliage, vegetation height, and canopy cover. Through these proximate factors, changes occur in factors that ultimately determine the presence or absence of the species such as food availability, microclimate, quantity and quality of nest sites, perch site availability, and protection from predators (Sedgewick and Ryder 1987).

The woodlands are considered a nutrient-poor ecosystem. Nutrients can be lost from the ecosystem by chaining and broadcast burning of slash. These activities in singleleaf pinyon (*P. monophylla*)-Utah juniper stands could result in a loss of approximately 13 percent of the total ecosystem nitrogen because of nitrogen volatilization (Tiedemann 1987). Assuming that 60 percent of the aboveground total nitrogen (about 855 kg per hectare) would be volatilized and a natural replenishment rate of between 1 and 2 kg per hectare per year, Tiedemann (1987) estimated that this lost nitrogen would be restored in 425 to 855 years. A study in Arizona (Perry 1993) found that 91 percent of the vegetative nitrogen was lost following prescribed burning of pinyon-juniper slash. Such large losses would result in lowered long-term productivity. Other nutrients such as phosphorus are also affected, especially if large amounts of litter are consumed in the burning (DeBano and Klopatek 1987, 1988; Perry 1993). In addition, burning also has a detrimental effect on soil microorganisms (Klopatek et al. 1990). However, soil nutrient levels may increase or remain constant in the top 5 cm following prescribed burning of slash that was not piled, because of oxidation of organic materials from the vegetative material (Perry 1993). More information concerning the effects of fire on pinyon-juniper soils is presented in Covington and DeBano (1990).

A benefit-cost analysis of tree control projects using data from throughout the Southwest demonstrated that the most successful projects only broke even (Clary et al. 1974). Fuelwood sales and potential losses in long-term site productivity were not included in these analyses.

Multiresource Management

Reevaluation of pinyon-juniper management strategies began in the 1970s, partially because of the increase in fuelwood demands resulting from the oil embargoes (Gottfried and Severson 1993). Ffolliott et al. (1979) found a 400 percent increase in wood usage in five Arizona markets between 1973 and 1978. The possibilities of sustained production of fuelwood and integrated resource management began to be considered, especially in mature woodland stands. The woodlands provide a full array of products including fuelwood, pinyon nuts, fence posts, Christmas trees, landscape trees, forage for livestock, habitat for common and rare and endangered wildlife species, and watershed protection. Demands for

these products and values continue to be strong or are increasing. The demand for fuelwood has fluctuated but continues to be high. Although current values are unavailable, approximately 227,000 m^3 of pinyon and juniper fuelwood were harvested in New Mexico in 1986 (McLain 1989). Some of the national forests that are located near population centers are concerned that demand will exceed supply within the next 50 years. The livestock industry is one important current and traditional use of the pinyon-juniper woodlands in the Middle Rio Grande Basin. Watershed protection, restoration, and site productivity are major concerns, especially in areas where past land uses have caused degraded conditions. There are issues concerning improving wildlife habitat for game species, nongame species, and threatened, endangered, and sensitive species. Most of the prehistoric archeological sites in the Southwest are concentrated in the pinyon-juniper zone because of the availability of resources and the moderate climate. Fifty-seven percent of 2,000 surveyed archeological sites at Bandelier National Monument are in juniper and pinyon-juniper woodlands. There also has been an increase in the use of woodlands for recreation and for second and primary home sites.

The public has also begun to recognize that the pinyon-juniper woodlands are connected to the culture and history of many rural and indigenous populations, and that their concerns must be integrated into land management plans. The woodlands have been used by American Indians since prehistoric times for construction timber, fuelwood, pinyon nuts, medicines, ceremonial items, and a place to hunt and gather food. The early European colonists and their descendants have used the woodlands for many of the same products. Most tribal and rural communities in the Southwest depend on fuelwood as the primary source of heating and cooking fuel, and also upon the commercial sale of fuelwood as a source of income. Birds, game, small mammals, and woodland predators are important for hunting, viewing, and traditional and religious purposes in American Indian cultures. Many aspects of the Zuni religion revolve around their relationship with the deer, which is hunted for traditional and recreational purposes. Zuni Indians also hunt game birds for meat and woodland songbirds for their feathers (Miller and Albert 1993).

Ecosystem management mandates the sustained productivity of the land while maintaining a diverse and healthy ecosystem. Recognizing the potential value of managing the woodlands for multiple prod-

ucts and benefits was the first step in the changing approach toward pinyon-juniper woodlands. Managers now have to develop prescriptions that meet their production goals and still produce or maintain productive and healthy stands. Naturally, sound prescriptions must account for the variability of habitat types and existing stand conditions. Management procedures also must be developed that will not damage archeological and historical sites within the woodlands. True ecosystem management should be based on an integrated planning effort that includes the inputs of managers representing the natural resource and related disciplines. Contributions of sociologists, community representatives, or marketing specialists could be useful, especially on private lands.

Not all sites have the potential to produce the full range of resource benefits, and this factor too must be evaluated. A classification for pinyon-juniper woodlands based on site productivity can aid management planning. The pinyon-juniper woodlands can be divided into high-site and low-site categories based on site productivity and stand volume (Conner et al. 1990; Van Hooser et al. 1993). Productivity is a measure of how well a site is able to sustain itself, and is determined by soil depth and texture, rockiness, slope, and presence of regeneration (Van Hooser et al. 1993). High-site lands produce wood products on a sustainable basis, while low-site lands include areas where volumes are too low to be included in calculations of allowable harvest levels. Some trees can be harvested from low-site lands, but they would only support a single harvest and the total volume harvested would be insignificant. Almost 86 percent of the pinyon-juniper and 80 percent of the juniper woodlands in New Mexico are in the high-site category (Van Hooser et al. 1993). High-site lands have the best potential for integrated resource management. The Bureau of Indian Affairs in Albuquerque tentatively defines commercial woodlands as those producing 0.4 m^3/ha of wood products annually.

The new ecosystem approach to pinyon-juniper management must be based on sound scientific information. However, our knowledge of the ecology of woodlands and impacts of management options is incomplete. The Rocky Mountain Forest and Range Experiment Station of the USDA Forest Service, personnel from land management agencies, and universities are attempting to fill gaps in our knowledge, but the emphasis on woodlands is relatively recent and many questions remain to be answered. The Rocky Mountain Station is currently conducting re-

search on tree regeneration ecology and silviculture; watershed management including soil erosion and site productivity; effects of stand treatments on wildlife habitat relationships; and tree mensuration (Gottfried 1992b).

Management of High-Site Woodlands

Silvicultural approaches

Silviculture provides the tools for manipulating the woodland tree cover to sustain production of wood products and maintain woodland health. One chief goal of silviculture is to obtain satisfactory tree regeneration for the future. Silviculture can also be used to improve forage production and wildlife habitat and to create an aesthetically pleasant landscape.

Managers from the USDA Forest Service, USDI Bureau of Indian Affairs, and other federal and state agencies are also attempting to develop prescriptions that would provide integrated resource management. Management prescriptions and objectives vary throughout the Southwest. Bassett (1987) reviewed the common silvicultural prescriptions and concluded that single-tree selection and two-step shelterwood methods are best for sustained stand health and productivity of woodlands. These methods are compatible with the dispersal patterns of heavy tree seed, provide protected micro-sites for regeneration, and are aesthetically acceptable. There are, however, some disadvantages, especially related to the costs associated with intensive management and potential damage to residual trees during initial and subsequent harvests.

Bassett (1987) presented a discussion of the trade-offs that must be evaluated in preparing a prescription. A single-tree selection treatment designed to reduce stand density but still retain uneven-aged structure and horizontal and vertical diversity is being studied by the Rocky Mountain Station in cooperation with the Heber Ranger District of the Apache-Sitgreaves National Forests at Heber, Arizona (Gottfried 1992b). Single-tree selection prescriptions also are being evaluated by the USDI Bureau of Indian Affairs in western New Mexico and southern Colorado (Schwab 1993). The effects of different stand densities on pinyon nut production are being studied jointly by the Rocky Mountain Station and the Albuquerque Area Office of the Bureau of Indian Affairs. Group selection, which creates small openings within the stand, is less common and needs fur-

ther study. Success from the forestry perspective would depend on achieving satisfactory regeneration from residual seedlings and seed, and from movement of seed into openings from the surrounding stand. Two-step and three-step shelterwood methods are being evaluated in New Mexico. A one-step shelterwood method can be used when advance regeneration is satisfactory.

The clearcut method and the seed-tree method generally result in unsatisfactory regeneration success because of poor seed dispersal. Small clearcuts can be appropriate when dwarf mistletoe control is necessary. Silvicultural prescriptions should be compatible with habitat type characteristics. Proper management for sustained production of the tree resources also requires additional growth and yield information related to site characteristics (Gottfried 1992a).

Wildlife-range approaches

Factors related to the proximity of suitable vegetation conditions and the availability of food, hiding and thermal cover, and nesting sites actually determine the distribution of most wildlife species, whether bird or mammal. Because of different species' habitat requirements, the same changes that degrade habitats for some species are likely to improve habitats for others. Although total numbers of small mammals increased in plots cleared by chaining or bulldozing in a New Mexico study, responses of individual species varied depending on habitat requirements (Severson 1986a). Woodrats and brush mice increased when slash was left, regardless of overstory. Pinyon mice and rock mice increased when slash was left and overstory was relatively intact but decreased if overstory was completely removed (Severson 1986a; Sedgewick and Ryder 1987). Kruse et al. (1979) also found that species preferring woodland habitats decreased in treated woodlands. Grassland species increased when the overstory and slash were completely removed but decreased when slash was left. Initial data indicate that fuelwood harvesting may negatively affect pinyon mice and positively affect deer mice populations and species diversity (Kruse 1995). Although grassland and other open woodland species may benefit from partial or entire removal of overstory, the amount of remaining mature woodland (and thus habitat for species that require a more dense canopy) should be considered.

Pinyon-juniper woodlands are used and manipulated for a variety of purposes (grazing, range im-

provement, fuelwood harvesting, recreation, wild-life habitat, etc.). A greater knowledge of species' habitat requirements and the effects of nonwildlife-related activities on wildlife resources may enable managers to select tools for achieving their goals that minimize detrimental effects or maximize beneficial effects on wildlife. For example, species that require midstory and understory plants may decline in mature pinyon-juniper habitats with dense canopies and thus may benefit from fuelwood harvests (Short and McCulloch 1977). In addition, the different hiding cover and overstory requirements of individual species suggest that slash disposal and degree of overstory removal are factors that may be manipulated to determine which species benefit from the treatment (Severson 1986a).

Current management is integrating livestock and wildlife with tree product objectives. A careful assessment of wildlife and other needs must be made to ensure tradeoffs in resource allocation are acceptable. Clearing small dispersed areas of trees benefits elk, mule deer, and livestock (Short et al. 1977). Openings create a more diverse landscape that favor many wildlife species. For example, small mammal populations may increase within cleared areas (Severson 1986a) and thus may attract more predatory birds and mammals. Birds that feed on insects associated with openings should also benefit from this landscape. However, openings should not be too large (Severson and Medina 1983) and the woodlands should not become fragmented. In many cases, the actual size of the openings may not be critical if continuous corridors of adequate width are maintained. Stands surrounding openings can remain untreated or may be partially harvested. Forage production is also stimulated in areas harvested using an overstory removal cut and in group selection openings.

Managers must decide if cleared wildlife-livestock areas should be maintained or if trees should be allowed to reoccupy the sites. If trees are allowed to reoccupy the openings, a management scheme could be created that involves a variety of seral stands. There is a need to define spatial and temporal patterns by habitat type that maximize plant and animal diversity. Springfield (1976), Severson and Medina (1983), and Short and McCulloch (1977) present reviews of range management and wildlife management within the woodlands.

Treatments that reduce tree densities, such as the single-tree selection and shelterwood method, should benefit livestock and native ungulates by providing

additional forage while maintaining some degree of thermal and hiding cover. Increased herbaceous cover will also help stabilize the soils on some sites. However, the impacts of residual trees on understory dynamics is unclear. Large reductions in tree canopy cover are necessary to improve total herbage yields (Arnold et al. 1964; Pieper 1990). However, while total herbage biomass and blue grama biomass decline with increased canopy cover, the biomass of cool-season grasses such as pinyon-ricegrass (*Piptochaetium fimbriatum*) and New Mexico muhly (*Muhlenbergia pauciflora*) actually increase with increased tree cover (Pieper 1990). Further research relating herbage production to stand density is being planned.

Many high-site areas treated during pinyon-juniper control programs have been reoccupied by healthy stands of trees over the past 30 to 40 years, often the result of advance regeneration that survived the initial treatment. If regeneration is vigorous and dense enough to result in a healthy tree stand, the area should not be treated again because successful regeneration of large openings is difficult. The young stands would be part of the diverse landscape required by many wildlife species. Increased herbage production would occur until the tree canopy closes.

Slash disposal

Slash disposal after harvesting or vegetation type conversion is another important issue in woodland management. Slash disposal may vary according to management objectives (Severson and Medina 1983). On any one management area, several slash treatments may be warranted and practical. It is generally accepted, based on work in the Great Basin (Tiedemann 1987), that burning slash in large piles is unacceptable because of the adverse effects on soils and overall site productivity. However, slash in small piles may be burned with the intent of creating areas containing earlier seral stages that increase floristic species richness on the treatment area. Other piles could be left unburned to provide habitat for small mammals (Severson 1986a). Slash piles can break up sight distances and provide security cover for wild ungulates. Slash can be scattered in some areas to provide protection for herbaceous growth and to provide nursery sites for young trees. On other sites, scattered slash could be burned in a cool fire to promote temporary increases in nutrient contents of the herbaceous forage components.

Slash also provides some erosion protection by retarding surface water movement and serving as a

place where sediment can accumulate and not be lost from the site. A study of several slash disposal treatments showed that a slash-scattered treatment resulted in the least surface runoff and sediment loss and in relatively higher soil moistures (Wood and Javed 1992). This treatment also had the best vegetation response, which helps protect the soil, slows runoff and erosion, and increases infiltration. Slash burning and complete slash removal had the reverse effect. Slash can also be placed into small gullies to reduce erosion.

Slash is often collected by older members of rural communities or American Indian tribes for cooking and heating purposes. It is an inexpensive and easily obtained resource. It also provides a useful activity for younger members of the community. There have been conflicts between these communities and land management organizations when slash is burned.

Single Resource Emphasis

While the wisdom of woodland control for production of forage for livestock on high-site public lands is questionable from economic and ecological perspectives, some private owners may still prefer this option. Some benefits of multiresource management can still be achieved. Fuelwood and other wood products should be harvested rather than leaving downed trees on site. This harvest provides a cash return and makes subsequent activities easier and more economical. One approach, even when livestock production is the main objective, is to create mosaics of tree-covered areas interspersed with grass-forb-dominated areas. Such a pattern should favor a mixture of cool-season and warm-season grasses (Pieper 1990). A mosaic landscape is beneficial for wildlife and livestock and is aesthetically pleasing.

Another approach is to create savannas by retaining some of the larger pinyon and juniper trees from the original stand. Such savannas can be more aesthetically pleasing than large openings and still provide some limited wildlife habitat benefits and shade for livestock. Although large savannas have drawbacks, this treatment should be integrated into a landscape that includes untreated and lightly treated stands and small openings.

Management of Low-Site Woodlands

Tree control to enhance forage production is easier to justify on low-site lands where management for tree products is not economically or biologically fea-sible. Forage production should be stimulated by normal range management activities, with the actual techniques depending on equipment demands and site characteristics. Stands of low stature and density could be the result of arid conditions that would affect the quantity, quality, and rate of replacement of grasses and forbs. Site factors, such as soil physical and chemical characteristics and annual precipitation, have to govern the appropriateness of treatments and the selection of forage species.

Even when tree control is desired, managers should consider the size and placement of openings and consider prescriptions recommended for high-site lands. Large openings are detrimental to deer and elk and to many nongame species. Mosaics of trees interspersed with cleared areas create a more acceptable landscape. The covered areas provide hiding and thermal cover for both wildlife and livestock. It is common to find cattle concentrating in pockets of residual trees within chained or cabled areas.

Regardless of the treatment and objectives on high- and low-site lands, proper grazing management is an important key to successful range improvement activities. Although data are scarce, there is a general belief that the poor response of native and introduced forage species to tree control activities can be related to poor livestock management. Animals were often allowed onto areas before the plants had become established. Some grazing deferral for at least two grazing seasons probably is necessary although the amount must be governed by site, climate, and forage species.

RESEARCH NEEDS

Numerous gaps exist in our knowledge of the ecology and management of the pinyon-juniper woodlands of New Mexico and the Southwest. Based on experiences, responsibilities, and needs, land managers and scientists have identified high priority topics that should be studied. Obviously, the research topics and their priorities vary. A list of recommended research and management activities was included as part of the proceedings from the 1993 Santa Fe pinyon-juniper symposium (Aldon and Shaw 1993). A subsequent meeting was held at the New Mexico State Land Department Office in Santa Fe to develop an action plan for managing New Mexico's woodlands for sustainability and social needs (Aldon and Shaw 1993). Achieving most of the goals in the plan would require additional basic and applied research.

Landscape and plant ecological studies provide the basis for high priority research opportunities (table 1). Ecological research in these areas is applicable to all aspects of ecosystem management. For example, stand dynamics information and predictive models would be needed for effective tree product and wildlife management, and for efforts to maintain and enhance biological diversity. Currently, many assumptions are being made about historic tree densities and encroachment of grasslands without the benefit of accurate historical information. Demographic studies would provide important information about changes in the woodlands related to climatic fluctuations, natural and human perturbations, and general land-use histories.

Enhanced biodiversity is central to ecosystem management. There is a need to develop agreements on desired conditions for the different pinyon-juniper ecosystems, particularly an understanding of the structural, functional, and spatial arrangements over time and space that will allow management for sustainability. How do management and natural processes affect plant and animal composition and density? How do they affect ecosystem stability? Priority studies would investigate the relationships between faunal and floral structure and community composition of different types of woodland stands. There is also a need to understand the major influences, processes, and relationships between trophic levels, for example, how mammals, birds, and insects influence cone production, seed dispersal, and regeneration, nutrient cycling, and food webs. An understanding of soil ecology is basic to the health of the entire ecosystem. The effects of land use on soil resources has often been ignored but has implications for the sustainability of all ecosystem components. Landscape fragmentation is a concern. How does fragmentation limit the efficiency of ecosystem processes and effectiveness of ecosystem functioning and, consequently, impact sustainability?

Woodland managers need further research on pinyon and juniper diseases and insects and their impacts on regeneration, growth, yields, and mortality. The effects of pinyon dwarf mistletoe and of flower and cone insects are of particular concern. There is a need to develop and evaluate various silvicultural prescriptions for promoting various management options, including enhanced understory composition and density. Growth and yield information, related to habitat type, is vital to sound management. Concerns about pinyon-juniper watershed conditions are especially important in New Mexico; effective and efficient methods are needed to restore watershed stability without compromising the integrity of woodland ecosystems.

Fire history, ecological impacts, and management require additional attention. Fire or the lack of natural fire, as has been noted, was an important factor in shaping the composition and structure of presettlement and present stand conditions. Misuse of fire, for example in some slash disposal activities, has often damaged site productivity. Managers are beginning to consider methods of reintroducing fire to the ecosystem but more information is needed. There are very few fire histories from the pinyon-juniper woodlands and only a few studies concerned with fire effects on soil resources.

Many concerns about management and the preservation of cultural resources exist. While some research has been conducted on the effects of fire on cultural resources in the Southwest (Knight 1994; Lent et al., in press; Lissoway and Propper 1990; Traylor et al. 1990), much of this work has been conducted in ponderosa pine forests, the work of Switzer (1974) and Eininger (1990) being exceptions. Given the inclination of many resource managers to increase the role of prescribed fire in these woodlands, it would be desirable to have better information on fire effects on cultural resources in woodland areas. The increase in the number of unauthorized roads and off-road vehicle use have implications for cultural, hydrological, and biological resources in the Southwest. More sociological and educational research is needed on ways to deter the public, as well as commercial pot-hunters, from degrading our heritage resources. Little is known about the effects of other ecological processes in pinyon-juniper woodlands on the integrity of cultural resources. The recent Bandelier Archeological Survey recorded extensive impacts to archeological sites from such phenomena as trees and large cholla cacti growing and tipping over in sites; animal burrows; trampling impacts from large mammals like elk; feral burro wallows; and erosion. About 76 percent of approximately 1,500 surveyed archeological sites were affected by one or more types of erosion, particularly displacement of surface artifact assemblages by sheet erosion (Head 1992). Increasing elk numbers in the Southwest has raised concerns that elk may impact archeological sites through trampling (much like cattle) and by facilitating erosion problems through grazing pressure on the limited herbaceous ground cover. More re-

Table 1.—Landscape and plant ecological research needs for the Middle Rio Grande Basin.

	Research topic	Justification	Examples
1	Spatial analysis of site and stand characteristics at the regional scale using remote sensing and GIS.	Provide a mapped data and information system for modeling efforts, regionalization of local research products, and proposed management actions.	Milne (in progress), University of New Mexico
2	Regional-scale biogeographic and biogeochemical models, integrated with models of stand dynamics.	These models provide useful tools for organizing ecosystem research, for investigating factors that influence ecosystems at various scales, and for forecasting ecosystem response to climate and land use at the regional scale.	MAPPS: Neilson and Marks 1994; TEM: McGuire et al. 1992; Rastetter et al. 1991; Forest-BGC: Running and Coughlan 1988; CENTURY: Parton et al. 1988
3	Stand dynamics models.	Simulation of forest successional and ecosystem process at the local scale: gap models can simulate tree establishment, growth, and mortality. These models can be used to assess sustainability of fuel harvesting of both dead or live wood, or to evaluate the impact of tree removal on stand structure. Models can be used to project changes in local and regional stand structure due to land use and climate. Simulations can be tested against historical reconstructions (see 4).	FORSKA-2: Prentice et al. 1993; HYBRID: Friend et al. 1993; SILVA: Kercher and Axelrod 1984; CLIMACS; Dale and Hemstrom 1984; ZELIG, Urban et al. 1993; FORMAN I: Samuels and Betancourt 1982
4	Historical studies of pinyon-juniper woodlands, particularly the last 2,000 years; this includes the use of archival information on land use, historical ground and aerial photography, long-term demographic disturbances, climatic reconstructions from tree rings, and packrat midden studies to determine ecotonal shifts.	Provide long-term data about baseline (background) conditions and natural variability in the more sensitive parts of the ecosystem (p-j/grassland or p-j/ponderosa ecotones); description of the range of possible trajectories. Better understanding of how climate, disturbance (e.g., fire) and land use maintain or shift ecotonal boundaries. Gage the regional and long-term impact of catastrophic droughts as well as wet episodes on ecotonal boundaries, age structure, and species composition.	Betancourt et al. 1993; work in progress through collaboration by Forest Service, USGS-Desert Laboratory, and University of Arizona-Tree Ring Laboratory (in progress)
5	Reconstruction and long-term monitoring of pinyon seed crops (masting) at the regional scale using cone-scar assays, tree-ring data, and annual field surveys.	Masting influences pinyon age structures, as well as population cycles of seed predators. Pinyon nuts are an important cash crop in New Mexico. Climatic influences on geographic and temporal patterns in bumper crops cannot be determined without reconstructing and monitoring seed crops at the regional scale.	Forcella (1981); Floyd (1987); Little (1940)
6	Regional seedling surveys carried out every two years for trend detection; first-year effort will be inclusive, subsequent years will be less intensive.	Detect trends in regeneration of pinyon-juniper woodlands relative to climate, land use, and site characteristics. Resolve controversies about trends in regeneration relative to fire suppression and grazing. Address if the wet episode of the 1980s and 1990s has produced a surge in pinyon and juniper recruitment.	None
7	Regional inventories of woody debris and fuel harvesting; quantify woody debris in undisturbed vs. disturbed stands; quantify regional availability and exploitation of wood debris as fuel.	Woody debris inhibits soil erosion, provides microsites for germination/establishment, offers shelter for fauna, and serve as storage and recycling points for nutrients. Fuel gathering is an important economic activity in some rural communities; it tends to concentrate near population centers. There is currently no regional assessment of fuel harvesting or of its ecological consequences.	Ernest et al. (1993); DeBano et al. (1987); Barth (1980)
8	Regional study of successional processes at woodland conversion sites along environmental gradients.	The long history of conversions in the 1950s and 1960s provides a useful framework to study changes in succession of both herbaceous and perennial plant cover and in nutrient distribution 30 to 40 years after wholesale removal of trees. Trees in p-j accumulate nutrients beneath their canopies; what were the long-term effects of different tree removal techniques on distribution and loss/gain of nutrients?	Rippel et al. (1983)
9	Water and sediment budgets at watershed and basin scales; develop models of water balance and sediment yield, storage, and transport.	Linkage with biogeographic and biogeochemical models; estimate erosion losses during 20th century.	Lane and Barnes (1987); Dortignac (1960); Hawkins (1960); Renard 1987; Milne (in progress), University of New Mexico

search on these topics would be useful to help resource managers assess how to best maintain the cultural resources in their care.

There is consensus among southwestern archeologists that a key need is for better information on interactions between prehistoric and historic human societies and woodland environments. Such information would also help define sustainability goals for management of these ecosystems. A focal issue is to ascertain the magnitude and causes of changes in woodland ecosystem structure and function in the Middle Rio Grande Basin during periods of human occupation, and to determine how those changes in turn affected the societies that were contributing to them (Samuels and Betancourt 1982). Toward this end, better paleoenvironmental information is needed, especially data on vegetation change, trends in soil erosion and development, and climatic reconstructions. Integrated geomorphological and archeological investigations relating patterns of soil erosion to human land use practices would be valuable, given the widespread perception that current high erosion rates are unsustainable and largely triggered by modern human agency.

There is a need for socioeconomic studies within the pinyon-juniper woodlands of the Middle Rio Grande Basin. Managers must be attuned to the needs and views of society. Sociological studies concerned with conflict and policy issue resolution techniques would be desirable. Analyses of policies that relate to the sustainability of natural resources have been the focus of similar studies throughout the world, but unfortunately, not in relation to the pinyon-juniper woodlands. A study is needed to assess current policies in relation to technical issues. Technical problems often are related to the lack of effective policies or the lack of proper implementation and compliance with these policies. Frequently, technical problems can be solved once suitable policies are available. There is a need for better, and perhaps more formal, communication and coordination among the land management and the research communities concerned with pinyon-juniper woodlands. Public education about the aesthetic and commercial values of the woodlands would enhance public support and understanding for ecosystem management. Economic considerations may not be important in setting management goals on sensitive or fragile sites but they should be evaluated in the preparation of most multiresource, ecosystem management decisions. Economic analyses of common prescriptions

would increase the information needed for management decisions.

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Chapter 7
Plants, Arthropods, and Birds of the Rio Grande

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INTRODUCTION

Human populations have increased dramatically along the Rio Grande since European settlement. Human use of water for irrigation and consumption, and human use of land for agriculture, urban centers, livestock grazing, and recreation have changed Rio Grande ecosystems by altering flood cycles, channel geomorphology, upslope processes, and water quality and quantity. Such abiotic changes have influenced the biological diversity and ecological functions of the Middle Rio Grande Basin, altering the distribution, structure, and composition of riparian plant and animal communities.

We review the literature and identify research needs pertaining to the flora and fauna of the Middle Rio Grande bosque, focusing on plants, arthropods, and birds. These groups serve as model taxa for monitoring population changes and trophic level interactions in response to natural and human-caused changes in function, structure, and dynamics of riparian ecosystems. Many arthropod species are first order herbivores, so the composition and structure of plant communities are likely to influence their presence, absence, and reproduction. Birds forage on food supplies that range from seeds, fruits, and leaves, to insects and small vertebrates. Thus, the distribution, dispersal, migration, and demography of avian species will likely be affected by changes in riparian plant communities and by interactions among plant and insect associations. Birds and insects are dispersal agents of seeds of many plant species, and so they contribute to the growth and composition of plant communities.

In this chapter, we focus on the Middle Rio Grande because of (1) the availability of cottonwood gallery forest in this stretch, (2) the extent of past and current research conducted in the bosque, and (3) the apparent public, political, governmental, and academic interest in this area owing to its urbanization, recreational opportunities, habitat alteration, water usage and pollution, and need for conservation and restoration. We refer to the Middle Rio Grande as the portion of the river, restricted to New Mexico, from Elephant Butte Reservoir to Cochiti.

RIPARIAN VEGETATION

Historical Overview

Riparian ecosystems, according to Lowe (1964), are associations of any kind in or adjacent to drainages and/or their floodplains. They are further characterized by species and/or life forms different from that of the immediate surrounding non-riparian association. Although riparian ecosystems have existed along the Rio Grande and its major tributaries for perhaps a million years (Scurlock 1988), they occupy less than 1 percent of the land area in New Mexico and adjacent states. Nevertheless, they are extremely important to the biological diversity and ecological integrity of arid southwestern ecosystems.

The Pleistocene epoch, lasting from around 2 million to 10,000 years ago, was characterized by southward glacial advances and retreats. Vegetation exhibited similar movement, by retreating south ahead of the advancing glacial ice and advancing to the north to occupy the land exposed by melting ice. Scurlock (1988) speculated that cottonwood bosque (woodland fringing a body of water) probably existed along the Rio Grande since the colder times of the early Pleistocene. During the late Pleistocene and

early Holocene epoch, the climate apparently dramatically changed to warmer and drier conditions. As a result, rich mixed coniferous forests expanded in range to occupy the area (Axelrod and Bailey 1976). As the climate became more arid, coniferous forests were replaced by woodlands, grasslands, and shrubland (Van Devender et al. 1984).

McKinley and Brown (1982) theorized that southwestern riparian deciduous forests reflect a contraction of the formerly widespread Early Tertiary mixed mesophytic forest. Riparian ecosystems are vernally adapted to Early Tertiary climates and retreated to pockets where the warm temperate climate persisted (McKinley and Brown 1982). Nineteenth century southwestern riparian plant communities, as we know them today, probably developed during this period of climatic change.

In his comprehensive chronological description of 19th century riparian vegetation along the Rio Grande, Scurlock (1988) speculated that stands of valley cottonwood (*Populus fremontii* var. *wislizenii*) and willow (*Salix* spp.) were interspersed with marshes dominated by sedge (*Carex* spp.), tule bulrush (*Scirpus acutus*), cattail (*Typha latifolia*), and saltgrass (*Distichlis spicata*) at the end of the last ice age. He also suggested that the first significant human impact on the Rio Grande riparian ecosystem was probably clearing of the bosque vegetation for cultivation between 1,500 and 2,000 years ago. Woodbury and Zubrow (1979) reported that many large American Indian farming villages were centered along the Middle Rio Grande valley by the mid 1500s, and Harper et al. (1943) estimated about 100,000 acres of former bosque vegetation was under cultivation by the mid 18th century.

The first comprehensive description of Rio Grande floodplain vegetation was authored by Watson (1912) who described open and more or less pure forests of valley cottonwood along the Rio Grande where the water table was near the surface in the open. According to Watson, the trees were small because native ranchers harvested them for fuel and fenceposts, although protected individual trees were veritable giants in girth. Scattered throughout this forest and especially along the banks of the streams were a few willows, clumps of *Baccharris wrightii* and *Cassia bauhinioides*, and an herb layer consisting of *Juncus balticus*, *Trifolium rydbergii*, *Aster spinosus* and a few grasses. Watson described this riparian forest as monotonously uniform and poor in species. Watson (1912) also described a riverbank wet meadow association dominated by *Juncus balticus* and *Houttuynia californica*. Associated species were *Baccharris wrightii*, *Helianthus annuus*, *Dyssodia papposa*, *Onagra jamesii*, *Amorpha fruticosa*, and *Rumex berlandieri*.

Van Cleave (1935) described five Rio Grande floodplain plant communities: (1) cottonwood-willow forests several hundred yards wide along the stream with little understory vegetation except scattered clumps of saltgrass; (2) grass-woodland bosque occupying elevated floodplain sites dominated by coyote willow (*Salix exigua*), cottonwood, salt cedar (*Tamarix pentandra*, *T. chinensis*), and Russian olive (*Elaeagnus angustifolia*) with a herbaceous understory of saltgrass, yerba mansa (*Anemopsis californica*), fleabane (*Erigeron philadelphicus*), and horseweed (*Leptilon canadense*); (3) wet meadow-like community, with the water table at or just below the soil surface, dominated by sedges, rushes (*Juncus* spp.), saltgrass, and yerba mansa; (4) swampland (marsh) dominated by cattail, sedges, spikerush (*Eleocharis* spp.), scouring rush (*Equisetum hyemale*), watercress (*Radicula nasturtium-aquaticum*), and buttercup (*Ranunculus cymbaliria*) and generally encompassed by a band of woody vegetation; and (5) small lakes occupied by aquatic plants.

Current Vegetation Composition and Structure

In New Mexico, floodplain riparian vegetation has probably been impacted more by human activities than any other type of riparian vegetation (Dick-Peddie 1993). Current Rio Grande floodplain vegetation greatly differs in both composition and extent from that described by Van Cleave (1935). Cottonwood and willow were, and remain, primarily restricted to the immediate floodplains. The bosque, though much reduced in extent, is still represented by some individual cottonwood trees of extremely large size. With some notable exceptions, the historic cottonwood and willow forests have been reduced to a narrow band of mid- to old-age forest stands between levees in the Middle Rio Grande floodplain. Many cottonwood/willow communities were lost to expanding agriculture, the demand for fuel and wood products, channelization and flood control projects, urbanization, transportation systems, inundation by large impoundments, and the introduction and escape of exotic plants.

The phreatophyte vegetation on the Rio Grande floodplain today is found in relatively hydric, mesic,

and xeric conditions (Campbell and Dick-Peddie 1964). Some species have moved into the bosque from up and down stream communities and other species have moved from adjacent upland plant communities, but the greatest factor influencing the composition of bosque communities, according to Campbell and Dick-Peddie (1964), has been the introduction of plants such as salt cedar and Russian olive.

In a comprehensive survey of the Middle Rio Grande, Hink and Ohmart (1984) recognized three major cottonwood-dominated community types with understories of Russian olive, coyote willow, salt cedar, seepwillow (*Baccharis wrightii*), indigo bush (*Amorpha fruticosa*), New Mexico olive (*Forestiera neomexicana*), and one-seed juniper (*Juniperus monosperma*). The most common subdominant species in the cottonwood/coyote willow type, named in descending order of abundance, were coyote willow, salt cedar, and Russian olive or seepwillow with a ground cover of mixed grasses and forbs; in the cottonwood/Russian olive type, Russian olive formed a monotypic understory with herbaceous plants being sparse to absent; and in the northern reaches of the Middle Rio Grande the cottonwood/juniper type was characterized by an understory of juniper (*Juniperus* spp.) mixed with Russian olive, New Mexico olive, hair-worm snakeweed (*Gutierrezia microcephala*), and rubber rabbitbrush (*Chrysothamnus nauseosus*). In addition to the cottonwood communities, Hink and Ohmart (1984) recognized a Russian olive community type dominated by young to intermediate-aged Russian olives interspersed among patches of young coyote willow, cottonwood, salt cedar, and seepwillow with a dense herbaceous layer of mixed grasses and forbs; and a marsh community type dominated by cattail with some tule bulrush, sedges, mixed forbs, and an occasional coyote willow. They found salt cedar to be a common understory species throughout the study area and a dominant species throughout much of the southern portion of the Middle Rio Grande. Campbell and Dick-Peddie (1964) also noted salt cedar was more common below Elephant Butte Reservoir than in the more mature woodland type upstream from Elephant Butte.

Introduced Plant Species

Salt cedar was introduced into the United States as an ornamental in the early 1800s (Horton 1964). Watson (1908) reported that salt cedar was commonly planted in Albuquerque as an urban ornamental. Salt cedar became naturalized and by the 1920s was a dominant shrub along many southwestern rivers (Horton 1977). Van Cleave (1935) also referred to both salt cedar and Russian olive as dominant plant species in the grass-woodland bosque floodplain of the Middle Rio Grande. The invasion of salt cedar on floodplains in New Mexico was rapid and dramatic. Scurlock (1988) reported salt cedar dominated 60,640 acres of the Rio Grande valley in 1947, and Robinson (1965) reported salt cedar occupied 155,000 acres in New Mexico by 1961.

Garcia (1903) described the presence of Russian olive, another Eurasian ornamental, at Mesilla Park, New Mexico, around the turn of the century. Wooton and Standley (1915) indicated that Russian olive was under cultivation at several locations throughout New Mexico. However, the exact date that Russian olive was introduced into the state is unknown (Campbell and Dick-Peddie 1964). Van Cleave (1935) reported Russian olive to be an important component of the floodplain vegetation, and Freehling (1982) suggested that Russian olive became naturalized and reached its present distribution in the Middle Rio Grande floodplain prior to 1935. Campbell and Dick-Peddie (1964) documented the spread of Russian olive throughout the valley north of Elephant Butte Reservoir, reporting that it grew equally well beneath heavy cottonwood overstories, in open areas, and in nearly pure stands of salt cedar. Freehling (1982) speculated that the Russian olive invasion into the Middle Rio Grande riparian woodlands was initiated by habitat alterations associated with land drainage.

Other exotic trees and shrubs have also become naturalized and invaded the Middle Rio Grande bosque ecosystem. For example, Crawford et al. (1993) reported that Siberian elm (*Ulmus pumila*), tree of heaven (*Ailanthus altissima*), and white mulberry (*Morus alba*) were rapidly becoming major components of riparian plant communities, particularly in the more urbanized areas of the Middle Rio Grande.

Loss of Cottonwood and Willow

The slow demise of cottonwood and willow and the rapid invasion by salt cedar and Russian olive appear to have begun in the 1930's, about the time major flood control efforts (construction of dams, levees, and channelization) were being implemented (Ohmart et al. 1977). In their comprehensive review

of the impacts of river damming on cottonwoods, Rood and Mahoney (1993) cited numerous articles that reported reduced forest abundance, reduced seedling abundance, and conditions unsuitable for seedling establishment downstream. Declines of downstream poplar forests (*Populus* spp.) were probably caused by hydrological alterations and geomorphological changes of the river corridor, although other factors included direct harvesting for food, fuel, and material, and grazing by livestock (Rood and Mahoney 1990).

Introduction and escape of salt cedar and Russian olive in the last 50 years have changed the successional stages and ultimate dominants of many Rio Grande plant communities (Campbell and Dick-Peddie 1964). However, regulated stream flow, either directly or indirectly, is thought to be the most important factor contributing to the decline of cottonwood and willow woodlands in riparian ecosystems (Rood and Heinze-Milne 1989; Fenner et al. 1985; Rood and Mahoney 1990; Brown et al. 1977; and Crawford et al. 1993). Campbell and Dick-Peddie (1964) speculated that, if left undisturbed, cottonwood would probably replace salt cedar in the upper Rio Grande valley but not downstream from Elephant Butte Lake. Even if predisturbance conditions were restored in the Middle Rio Grande floodplain, Russian olive upstream from Elephant Butte Lake and salt cedar downstream from the Lake would probably retain subdominant status at minimum.

Cottonwood and Willow Regeneration

Disturbance has played an integral role in establishing and developing native riparian vegetation in the Southwest. Flooding is the most common form of naturally occurring disturbance in riparian ecosystems (Szaro 1989). Glinski (1977) and Brady et al. (1985) suggested that flooding and aggradation were the major precursors in the natural sequence of cottonwood stand development on southwestern floodplains. However, disruption of normal flow patterns resulting from river impoundments can change the development of riparian communities (Szaro 1989). Riparian community development will deviate from normal as the programmed flow rate deviates in time and intensity from uncontrolled flow. Crawford et al. (1993) noted that Middle Rio Grande levees constructed in the 1920s and 1930s constrained the floodway and reduced the river's tendency to meander—a process considered critical to establishing native

bosque vegetation. Dams, channelization, levees, and agriculture are also reported to have adverse effects on regeneration of native riparian vegetation (Fenner et al. 1985; Rood and Heinze-Milne 1989; Rood and Mahoney 1990; and Barclay 1978). In contrast, however, Szaro and DeBano (1985) reported a case where dam construction increased the regeneration of riparian vegetation. They found a dramatic increase in regeneration of black willow (*S. gooddingii*), seepwillow, and salt cedar in deposited sediment immediately above the dam where flows from high intensity storms were stored to produce a near perennial flow.

Mahoney and Rood (1993) modeled the general hydrological elements necessary to establish riparian cottonwood seedlings. Glinski (1977) and Mahoney and Rood (1993) described the temporal aspects of hydrological cycles and their importance in cottonwood germination and seedling survival. The hydrological elements essential for cottonwood seedling establishment are river stage and rate of water table decline, but if either factor is improperly timed cottonwood establishment may fail.

Although the essential elements necessary for regeneration of native riparian plant communities are known, knowledge concerning the timing and specific quantitative characteristics of the essential regeneration elements is incomplete. For example, Rood and Heinze-Milne (1989) reported a situation in Alberta where the abrupt lowering of the water table, when water release from a dam was terminated, contributed directly to the loss of cottonwood seedlings. They implied that the rate of water table decline was more rapid than that needed for cottonwood root elongation, and therefore seedlings died from drought stress. Unfortunately, no quantitative data on maximum allowable rate or timing of water table decline were presented to predict optimum cottonwood establishment and survival.

In his report on tree establishment in riparian habitats, Anderson (1988) noted that practically nothing is known about the autecology and water requirements of native riparian plants. Likewise, little quantitative information is available regarding the specific regeneration requirements of cottonwoods and willows. Numerous authorities (Burns 1990; Rood and Mahoney 1993) report that cottonwood is able to regenerate from root and stem sprouts and from seed during favorable environmental conditions, yet these conditions are generally undefined. Schreiner (1974) reported most cottonwoods produce large seed

crops almost every year after they are 10 to 15 years old. Lightle (1969) noted that Fremont cottonwood (*P. fremontii*) generally flowers from April to May, and its seeds ripen and disperse in June to July. Schreiner (1974), however, reported that the longevity of poplar seeds under natural conditions may be only 2 weeks to a month. Thus, the window for successful natural regeneration of Fremont cottonwood from seed is very narrow. For successful regeneration, the timing and duration of rainfall or overflow events necessary for germination and seedling establishment must also correspond with the narrow window of seed viability.

Brinkman (1974) reported willow produce many small seeds that usually ripen in early summer, although seeds of some species mature in the fall. Like cottonwood seeds, willow seeds remain viable for only 2 weeks or less, and germination diminishes rapidly with age. We did not find information specific to seed ecology and germination requirements of coyote willow or black willow. Very moist exposed mineral soil is generally considered best for germination and vigorous early growth of willow (Pitcher and McKnight 1990). Brinkman (1974) also reported that root stock of young willow trees sprout prolifically, and propagation by cuttings is the usual method of artificial regeneration.

Anderson et al. (1978) and Anderson and Ohmart (1979) were successful in establishing black willow and Fremont cottonwood by watering the planted cuttings until roots reached the water table or sufficiently permanent supply of soil moisture. Anderson and Ohmart (1979) found that backhoeing or augering a hole to the water table for each cutting is good insurance that roots can penetrate to the water level. Anderson (1988) reported that Fremont cottonwood and black willow cuttings planted in holes augured to the water table exhibited a lower rate of mortality and grew up to three times the rate of cuttings planted in shallow-tilled holes. Artificial watering of cuttings planted in augered holes was still necessary until roots reached a permanent water supply.

The state-of-the-art knowledge on cottonwood and willow regeneration has not progressed substantially in the last 15 years. Natural regeneration of Middle Rio Grande riparian floodplain vegetation has essentially been precluded by unfavorable conditions produced by regulated water flow in combination with soil and light requirements—i.e., cottonwood and willow require nearly bare mineral soil and full sunlight for successful regeneration from seed. In addi-tion, aggressive salt cedar and Russian olive, combined with associated riparian grasses and forbs, apparently outcompete native cottonwoods and willows, limiting the regeneration success of native woody plants.

Glinski (1977), Carothers (1977), and Kauffman et al. (1983) noted that even when environmental conditions are conducive to cottonwood and willow regeneration, stands can be destroyed by excessive grazing by livestock. Crouch (1979) also reported that beaver contributed to the decline of many small cottonwoods in northeastern Colorado. Though cottonwood is not a desired construction material, its use for lumber and fuel does contribute to cottonwood loss.

Classification of Riparian Vegetation

Riparian zones were recognized and briefly described over a century ago by Townsend (1893) when he proposed a classification for New Mexico's Organ Mountain vegetation. Since then, numerous authorities have described and classified all or parts of the riparian and wetland vegetation of New Mexico (Pase and Layser 1977; Dick-Peddie 1993; Brown and Lowe 1974; Brown et al. 1977; Brown et al. 1980; and Hink and Ohmart 1984).

Dick-Peddie and Hubbard (1977) proposed a New Mexico riparian vegetation classification system based upon obligate species, and they assigned formation status to riparian vegetation due to its importance and relative independence of surrounding upland vegetation. Formations included a floodplain series and an arroyo scrub series in the arroyo-floodplain sub-formation. Donart et al. (1978) assigned regional status to New Mexico's riparian vegetation within the woodland formation. The riparian region was described by Donart et al. (1978) as four series: cottonwood-chilopsis (*Chilopsis* spp.) series, mesquite bosque series, walnut (*Juglans* spp.) series, and willow-sycamore (*Platanus* spp.) series with the cottonwood-chilopsis series subdivided into a desert willow (*C. linearis*)-narrowleaf cottonwood (*P. angustifolia*) association and a plains cottonwood association. In their classification of North America vegetation, Brown et al. (1980) characterized southwestern riparian deciduous forests and woodlands based upon tree height, canopy closure, and lifeform. They also identified a cottonwood-willow series and a mixed broadleaf series. Dick-Peddie's (1993) classification is most recent, wherein five riparian types

in New Mexico are described based upon elevation and hydrological conditions. These types are referred to as alpine, montane, floodplain-plains, arroyo, and the closed basin-playa-alkali sink riparian types.

Hink and Ohmart's (1984) classification system recognizes six structural types of Middle Rio Grande vegetation based upon two general factors: overall height of the vegetation and amount of vegetation in the lower layers. Their structural types were described as:

Type I—vegetation in all foliage layers and trees generally reaching 50 to 60 feet in height;

Type II—mature trees 50 to 60 feet in height with most of the foliage in a layer (30 feet in height with sparse patchy understory growth;

Type III—intermediate-aged trees with thick understories up to 30 feet in height but little above 30 feet;

Type IV—open intermediate-aged stands of trees with most of the foliage 20 to 40 feet in height, with widely spaced shrubs and sparse herbaceous vegetation;

Type V—dense stand of vegetation up to 15 feet in height that may contain some scattered taller trees and often includes a thick layer of herbs; and

Type VI—relatively sparse stand of herbaceous and/or shrubby vegetation with most of the foliage less than 5 feet high.

Szaro (1989), using quantitative community characteristics, identified 28 riparian community types in Arizona and New Mexico. Szaro's approach to community classification was based upon existing vegetation rather than on potential natural vegetation used by Kuchler (1964) to differentiate northern floodplain forests from southern floodplain forests. The existing vegetation approach permits resource managers to recognize, classify, describe, and discuss communities in common understandable language. However, in practical application the shortcoming is that not all communities fall neatly within a described type.

Most approaches to riparian classification have followed the more traditional floristic approach as used by Brown and Lowe (1974); Pase and Layser (1977); and Dick-Peddie (1993), although a notable exception is Hink and Ohmart's (1984) structural approach to riparian vegetation classification. In his treatise on riparian forest community types, Szaro (1989) posed the following question about community classification: "Is a classification based on species composition versus that based on growth form or even genera necessary?" After a review of literature on bird, reptile, and amphibian species relationships with plant taxa, Szaro (1989) found that not enough was known to determine if groupings such as "tall" or "short" willow communities made ecological sense. He speculated that as ecological relationships are examined in more detail, the need for specific floristic information will become more apparent.

Most riparian classification systems developed to date are general to accommodate the full range of natural variation that occurs within the plant community type. As a result, the classification system permits managers to inventory and discuss land units on a regional basis but the value of the classification system diminishes with respect to making site-specific management decisions. Broad scale classification systems represent an "average" community type and they frequently do not adequately address extremes of the type.

Uresk (1990) described a classification and inventory procedure sensitive enough to classify and inventory plant community successional stages. He verified the suitability of this classification procedure using vegetation of grasslands (Uresk 1990) and deciduous woody draws in the Northern Great Plains. Ecological stages were quantitatively identified with an estimated 95 percent reliability, based upon principal component analysis (Uresk 1990). Threatened, endangered, and sensitive plant and animal species were then correlated with seral stages of community types (D. Uresk, personal communication, USDA Forest Service, 1994). Thus indices for predicting presence, absence, and relative abundance of species of interest based on vegetation classification systems can be developed.

Research Needs

Long term sustainability of the natural Middle Rio Grande Basin riparian ecosystem is a growing concern among many resource users and management agencies. The detrimental effects of hydrological alterations, geomorphic changes, exotic plant species, and agricultural practices threaten the continued existence of natural riparian ecosystems. Crawford et al. (1993) recommended the development of a coordinated research program to study the ecological processes and biotic communities that characterize the Middle Rio Grande riparian ecosystem. The primary terrestrial research needs they listed were

(1) enhance existing cottonwood communities and create new native cottonwood communities, (2) contain the expansion of existing stands of nonnative vegetation, (3) study the ecology of nonnative species existing in the riparian ecosystem and develop ways to maximize their biological values, and (4) develop an integrated management plan compatible with biological quality and ecosystem integrity to avoid further fragmentation of the riparian ecosystem. Although some of these needs are under investigation, no satisfactory alternatives have been developed. Thus, the important and critical research need today is how to efficiently and effectively regenerate and sustain natural riparian bosque ecosystems.

To manage, restore, and sustain riparian ecological systems, managers need information on the following:

1. The tolerances of native riparian trees, shrubs, and herbs to natural and human-induced disturbances, especially fire, grazing, flooding (or lack of flooding), recreation, and urbanization.
2. Regeneration ecology, especially as it relates to the autecology of important riparian deciduous tree and shrub species such as Fremont cottonwood, black willow, coyote willow, seepwillow Arizona sycamore (*P. wrightii*), velvet ash (*F. velutina*), and little and Arizona walnuts (*J. microcarpa* and *J. major*).
3. The effects of abiotic factors (e.g., climate, sedimentation processes, nutrient availability, water quality, and channel geomorphology) on development, composition, and health of plant communities.
4. The ecological linkages between upslope processes such as erosion, arroyo development, and road construction and bosque community dynamics and function.
5. The relationships and responses of animal communities to historical and recent changes in riparian plant associations.
6. The effects of flooding and the effects of surface water-groundwater interactions on major ecological processes such as decomposition, nutrient cycling, and primary production.
7. Classification models and matrixes for predicting animal species composition, habitat use, and population change based on composition and seral stage of riparian plant associations.

At a symposium on importance, preservation, and management of riparian habitat, Patton (1977) reported that no comprehensive classification of riparian vegetation suitable either for research or management has been prepared for the Southwest. Brown et al. (1977) also noted that identification, classification, inventory, and mapping of habitats was needed in riparian zones. Although classification of riparian ecosystems has progressed, (Hink and Ohmart 1984; Dick-Peddie 1993; Szaro 1989), gaps in our knowledge still exist. Investigations to determine plant species composition and abundance for every identifiable successional stage of riparian vegetation was recommended by Patton (1977). Szaro (1989) also implied that a quantitative classification system for successional stages of riparian vegetation would be extremely useful for managing bird, reptile, and amphibian species. Once plant successional stages have been determined, Patton (1977) suggested the next logical step for research would be to identify animals that depend on a given stage or stages for their life requirements. Seral stage classification systems would not only be useful to wildlife managers but would provide land managers with the opportunity to predict changes in resource values associated with successional stage of the riparian type.

In the next two sections, we review the literature and research needs for arthropods and birds. These taxa were selected as model groups for evaluating trophic-level responses to structure, floristics, succession, disturbance, and human-induced changes in riparian plant communities. Many arthropod species are first order herbivores, so the composition and health of plant communities are likely to influence presence, absence, and successful reproduction of arthropod species. Birds forage on food supplies that range from seeds, fruits, and leaves to insects and small vertebrates. Thus, the distribution and demography of avian species are affected by changes in riparian plant communities and by interactions among plant and insect associations. In addition, birds and insects are dispersal agents of seeds of many plant species, so they contribute to the growth and composition of plant communities.

ARTHROPOD ECOLOGY

Before European settlement, the Rio Grande experienced periodic flood cycles. Renewal of native cottonwood (*Populus fremontii*) and willow trees (*Salix* spp.) depended on flooding. With the advent of irrigation and its subsequent constrictions and controls, the flood cycles of the Rio Grande have largely been

eliminated, and consequently, the native flora and fauna have changed. Although the diversity and abundance of the Rio Grande arthropod community far exceeds that of plants, mammals, birds, reptiles, and amphibians combined, the ecology of bosque arthropod communities has not been well-studied, and therefore their role and importance in ecosystem interactions and processes have yet to be determined.

Arthropods of the Rio Grande bosque occupy almost every habitat and niche, from the tree canopy to the river bed (Crawford 1993). Because many species are habitat- or site-specific, arthropods are successful indicators of ecosystem change and stress. Data on the density and distribution of arthropod species can be used to monitor changes in the bosque such as channel constriction, flood control, and the introduction of exotic plants and animals. Arthropods also play an important role in food webs and decomposition cycles in the bosque and may influence the development and composition of other trophic levels.

To more fully understand and account for the role and importance of arthropods in the Bosque, three main avenues of research need to be initiated on (1) the distribution and composition of arthropod communities in different vegetation strata and across the bosque landscape; (2) the role of arthropods in decomposition cycles; and (3) the position and influence of arthropods in trophic webs.

Distribution and Composition of Arthropod Communities

Evaluation of arthropod community structure is one means of determining historic conditions and the changes that have occurred. For example, molluscs were used by The New Mexico Bureau of Mines and Mineral Resources (1987) to interpret and define historic river drainages. Community structure can also indicate recent change. Molles and Crawford (1992) reported sharp ecological boundaries between communities of ground-dwelling forest arthropods and arthropods occupying open areas. Loss of periodic overbank flooding has undoubtedly led to dramatic changes in vegetation structure in riparian areas along the Middle Rio Grande, and such changes are predicted to have affected the abundance and distribution of invertebrate species (Crawford 1993).

At the landscape level, several habitats intermingle to form a mosaic, including aquatic/riverine areas, forests, shrublands, wetlands and marshes, and agricultural fields. Each habitat hosts unique arthropod communities, and their composition varies among habitat substrates, e.g., forest canopy vs. forest floor. In addition, arthropods migrate and disperse among habitat "islands" across the landscape mosaic.

Currently, the aquatic habitat consists primarily of the Rio Grande, which is a warm water river. It has a low velocity and high turbidity (Winger 1981). Generally, rivers associated with riparian vegetation tend to have more diverse shading, ponds, and channel characteristics that lead to higher biological diversity (US Bureau of Land Management 1993). There has been some research into the arthropod communities that inhabit the river, particularly as they pertain to the fish populations. The New Mexico Department of Game and Fish is creating a database that relates aquatic insects to environmental parameters and fish populations (Jacobi et al. 1993). In addition, both the river (Jacobi 1983) and the riverside drains (City of Albuquerque Hydrology Division 1991) have been sampled for macroinvertebrates. There have also been studies that sample for individual species, e.g., predatory diving beetles were studied by Zimmerman (1971).

Other aquatic habitats in the Rio Grande bosque include marshes and wet meadows. Ephemeral and permanent ponds and marshes were common historically, but most have been drained or replaced by agricultural lands. As much as 33 percent of New Mexico's wetlands have been lost since Spanish settlement (Dahl 1990) owing primarily to conversion to agricultural drainages and levees (Van Cleave 1935). The Isleta marshes and Los Lunas wetlands have been fairly extensively studied (Alexander and Martinez 1982; Molles and Pietruszka 1983). Some marshes and wet meadows have been restored, primarily in association with ditches, drains, and agricultural fields. The artificial wetland areas created by drainage ditches provide habitats for different communities of arthropods (N. Runyan, Department of Biology, University of New Mexico, 1994).

Little is known about the extent of use of the Rio Grande's aquatic habitats by aerial insect communities. Molles and Crawford (1992) have sampled the bosque's aerial insects with sticky traps, and Molles (M.C. Molles Jr., Department of Biology, University of New Mexico, 1994) is currently evaluating the diversity of mayflies along New Mexico rivers, but no conclusions have been made pertaining to how these arthropod faunas contribute to the general ecology or complexity of biotic communities along the Rio Grande.

Ellis et al. (1993, 1994) studied the effects of controlled flooding on arthropod communities of the forest floor in both native and introduced vegetation. Heinzelmann et al. (in press) examined the microhabitat selection of *Armadillidium vulgare*, an introduced ground-dwelling isopod.

Arthropod species composition and diversity in the bosque canopy is probably better known than arthropod community development in other vegetation stratas. Molles and Crawford (1992) studied the differences in diversity and abundance of canopy-dwelling arthropods between native cottonwood and introduced Russian olive and salt cedar trees in the Albuquerque bosque. In addition, Yong and Crawford (personal communication, 1994) investigated the impact of two species of leaf rollers on the leaf fall of cottonwoods at the Rio Grande Nature Center, a river state park in Albuquerque.

Research is needed on the effects of disturbance on arthropod communities by factors such as pollution, agricultural development, flooding, introduction of exotic plants, burning, and grazing. If disturbance significantly alters arthropod species composition and diversity, then the development and productivity of other biotic communities, such as plants and vertebrates used by or dependent on arthropods, may also be altered. Direct effects of air or surface-waste pollution on arthropods can be evaluated by comparing arthropod community structure and pollution levels in rural areas such as wildlife refuges to urban sites, or by conducting specialized experiments that assess effects of varying pollution levels on selected species in controlled environments. Water that is polluted from sewage, waste, industrial sources, and non-point sources may also influence the dynamics and health of aquatic arthropod communities by reducing or eliminating populations that are intolerant of pollution.

Stress or disturbance to the bosque plant community from grazing, pollution, burning, competition, or fragmentation may alter susceptibility of certain plant species to herbivory by arthropods, hence causing further changes to the vegetation and consequently the arthropod community. River management such as damming, channelization, flooding, conversion, and restoration affect the structure, composition, and regeneration of riparian tree and shrub communities. University of New Mexico researchers are evaluating some of these effects on the invertebrate fauna at the Bosque del Apache Wildlife Refuge (e.g., Ellis et al. 1993, 1994). Several introduced species of plants (Russian olive and salt cedar) and arthropods (*Armadillidium vulgare* and *Porcellio* spp.) are well-established in the bosque, and research is needed to determine how these introductions have influenced arthropod communities and animal species dependent on arthropods for food.

The Role of Arthropods in the Decomposition Cycle

Additional research is needed on the role of arthropods as detritivores, which serve a critical purpose in breaking down organic matter into energy and nutrients available to microbes, bacteria, and ultimately plants. The major sources of organic matter in the bosque are dead leaves, wood, roots, herbaceous vegetation, dead animals, and waste products. Arthropod and invertebrate detritivores in the bosque include earthworms, isopods, beetles, termites, crickets, fly larvae, and ants (Crawford 1993). As these detritivores move and forage, they disperse soil and soil microbes through their feces. Subsurface detritivores also aerate the soil (i.e., isopods, termites, and earthworms). In addition, mites and collembola are extremely diverse and important components of the decomposition cycle. All of these macro-detritivores regulate the decomposition cycle by controlling the amount of litter that is broken down. Soil microbes and bacteria then break these organic materials prepared by macro-detritivores into usable compounds. The temporal, spatial, and population dynamics of bosque detritivores are little known, and research is needed to estimate their importance in ecosystem functioning, especially under altered or recovering environmental conditions.

The Position and Impact of Arthropods in the Trophic Web

The position and role of arthropods in the ecological web of interactions is an important area of research. By serving as herbivore, predator, and prey in the food web, arthropods appear to be an important yet overlooked link between trophic levels. For example, a wide variety of bird, mammal (e.g., bats, shrews), amphibian, and reptile species feed on arthropods, and numerous arthropod species feed on plants or other arthropods. How the interactions and linkages among these different trophic levels affect overall structure, functioning, and productivity of riparian ecosystems along the Rio Grande is a ger-

mane topic of research. Arthropods may have an important regulatory role in controlling populations of plant species; for example, harvester ants are an important disperser of seeds, and cutworms and other lepidopteran larvae are significant herbivores (Crawford 1993). Some species may also act as regulators of other arthropod populations, providing an integrated system of checks and balances. If the integrity and energy flow of riparian ecosystems is dependent on arthropod interactions with other ecological components and trophic layers, then research designed to assess the consequences of human or natural disturbance on riparian ecosystems would be incomplete without further study of the arthropod role.

For many animal species, and especially birds, arthropods are the primary source of food. However, arthropods are often a patchy resource, and research is needed to determine if and how the patchy distributions of different species affect the diet, distribution, diversity, or abundance of predator species. Introduced tree species have different diversities and abundances of arthropods than native trees along the Rio Grande (Molles and Crawford 1992). So, does the species composition and abundance of birds inhabiting native and introduced riparian vegetation vary in relation to the patchiness, diversity, and abundance of the arthropod resource or to the area, physiognomic structure, and species composition of the plant community? To answer this question, the structures and composition of both arthropod faunas and plant communities must be measured in concert with censuses of bird species.

CONSERVATION OF RIPARIAN LANDBIRDS

Species Diversity

Birds are the most diverse vertebrate taxon in New Mexico, with 413 recorded species comprising 64 percent of the total terrestrial vertebrate species (Hubbard 1977). While riparian habitats of the Rio Grande comprise only a minor portion of the available habitat in New Mexico, they are extremely important to bird populations. Of the 325 landbird species with confirmed records in New Mexico (Hubbard 1978), a total of 241 species (74 percent) have been detected within the riparian habitat and adjacent agricultural areas of the Middle Rio Grande (table 1; see Appendix 1 at the end of this chapter), based on observations by Hink and Ohmart (1984),

Hoffman (1990), and the banding program of Rio Grande Bird Research Inc.

In addition to being rich in species, the Middle Rio Grande riparian habitat supports high densities of birds. The average density is 300–600 birds/100 acres and densities of over 1,000 birds/100 acres are recorded for some native riparian habitats such as cottonwood-willow in certain seasons (Freehling 1982; Hink and Ohmart 1984; Hoffman 1990). The high species richness and density in the Middle Rio Grande are consistent with the patterns observed in other Southwest riparian ecosystems (Hubbard 1971; Carothers et al. 1974; Ohmart and Anderson 1982; Rosenberg et al. 1982) and confirm the value of this limited riparian habitat to bird populations.

Most of the riparian avian species show a remarkable dependency on water-related habitat for breeding areas, wintering areas, and migratory corridors. Johnson et al. (1977) reported that of 166 breeding species in west Texas, southern New Mexico, and southern Arizona, 51 percent were completely dependent on riparian habitat, while another 20 percent were partially dependent on it. Of all the species listed as endangered by New Mexico Department of Game and Fish, 50 percent are associated with aquatic or riparian habitats. Johnson et al. (1977) estimated that loss of riparian habitat in the Southwest could result in the loss of 78 (47 percent) of the 166 avian species that breed in the region.

Only 54 (23 percent) species of the 241 landbird species in the Middle Rio Grande are residents and the rest are neotropical and short distance migrants (table 1). These migrants include summer residents (54 species, 22 percent) that breed in the area and are present during late spring and summer, winter residents (52 species, 22 percent) that are present for varying lengths of time between September and April, and the transient species (71 species, 30 percent) that occur in large numbers during spring and fall migrations. Based on the definition given by the Partners in Flight Program (1992), of the 241 landbirds in the Middle Rio Grande, 96 species (40 percent) are neotropical or long distance migrants (type A); 74 species (31 percent) are short distance migrants that breed and winter extensively in North America (type B); 4 species (2 percent) breed primarily south of the U.S./Mexican border and enter the United States along the Rio Grande Valley during the winter months (type C); and the remaining 67 species (27 percent) are residents or migrants not defined by the Partners in Flight list.

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Table 1.—Species, migratory status, population trend, and wintering and breeding habitats of landbirds using the Middle Rio Grande.

SPP[a]	PTR[b]	MS[c]	MD[d]	B–HAB[e]	W–HAB[f]	MRGR[g]	p[h]	n[i]
AMCR		R	R	F	V			
AMGO	3	W	B	A,FS	A,FS	0.19	0.62	310
AMKE	1	R	B	V	V	−0.49	0.18	4
AMRE	3	M	A	F	FS	0.15	0.71	2
AMRO	2	R	B	V	V	−0.49	0.18	148
ATSP		W	B	S	S	−0.38	0.32	4
ATFL	2	B	A	S	S	−0.59	0.09	3
BAEA		W	B	W	W			
BTPI	3	B	A	F	F			
BANS	3	B	A	W	W			
BARS	2	B	A	W	W	−0.08	0.84	3
BBWA		M	A	F	FS			
BEVI	3	B	A	F	S			
BEKI	3	R	B	W	W	0.31	0.42	2
BETH	3	A	B	S	S			
BEWR		B	B	F	S	0.75	0.02	46
BLPH		R	B	W	W	0.09	0.81	15
BAWW	3	M	A	F	FS,U	−0.69	0.04	3
BBMA		R	B	FS	FS			
BCCH		R	B	F	F	0.67	0.05	40
BCHU	3	B	A	FS	FS			
BCSP	3	M	A	S	S			
BHGR	2	B	A	F	F	−0.02	0.96	180
BTGN		R	R	FS	S			
BTBW		M	A	FS	FS,U			
BTYW	3	M	A	FS	FS			
BTGW		M	A	FS	FS,U			
BTSP	4	B	B	S	S			
BLWA	3	M	A	F	FS			
BLGR	2	B	A	S	S	0.42	0.26	265
BLJA		A	R	F	F			
BGGN	3	B	A	FS	FS,U	−0.47	0.21	3
BWWA		A	A	FS	FS,U			
BOBO	3	B	A	G,A	G,A			
BRBL	3	W	B	W,S	W,S			
BRSP	3	W	A	S	S	−0.34	0.38	166
BTHU	3	M	A	FS	FS			
BWHA		M	A	F	FS,U			
BRCO	3	A	C	F	F			
BRCR	3	W	B	F,U	F	−0.41	0.28	14
BRTH		W	B	S	S			
BCFL	3	A	C	S	S			
BHCO	4	B	B	V	A	0.73	0.03	2
BUOW	4	B	A	G	G			
BUSH		R	R	S	S			
CAWR		R	R	S	S			
CAHU	3	M	A	U	F			
CAWA	3	M	A	F,W	F	−0.55	0.13	1
CATO		R	R	S	S	0.14	0.73	1
CANW	3	R	R	S	S			
CAFI	3	W	B	F	FS			
CAKI	2	B	A	FS	FS	−0.27	0.48	61
CASP	2	M	B	G	G			
CEDW	3	W	B	F	F			
CCLO	3	W	B	G	GA			
CSWA	3	M	A	FS	FS			
CHRA		B	B	S	S			
CHSW	3	A	A	H	H			
CHSP	4	B	A	FS	FS	0.52	0.15	3823
CCSP	2	M	A	S,W	S	0.50	0.17	72
CLSW	2	B	A	W	W			
COGD		R	R	G,A	G,A			
COBO		R	R	H	H			
COBH	3	B	C	F,W	F,W			
COGR		B	B	FS	V			
CONI	5	M	A	V	V			
COPO	3	M	B	FS	FS			

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Table 1.—Continued.

SPP[a]	PTR[b]	MS[c]	MD[d]	B–HAB[e]	W–HAB[f]	MRGR[g]	p[h]	n[i]
CORA		R	B	V	V			
COYE	3	B	A	W	S	0.27	0.48	15
COHA	3	R	B	F	FS	0.55	0.13	1
CRCA		B	C	G,A	G,A			
CRTH		R	R	S	S	−0.27	0.48	1
CBTH		R	R	S	S			
DEJU	3	W	B	FS	FS	−0.58	0.10	804
DICK	3	M	A	S	S	−0.47	0.21	2
DOWO		R	R	F	F	0.12	0.75	8
DUFL	3	M	A	F,W	FS	−0.38	0.32	85
EABL	3	W	B	F	F			
EAKI	3	B	A	FS	FS			
EAME	4	W	B	GA	GA			
EAPH	3	M	B	F,W	F,W			
EUST		R	B	V	V			
EVGR		M	B	U	F,H			
FEHA	3	B	B	G	G			
FOSP	3	M	B	S	S			
GAQU		R	B	S	S			
GOEA	3	R	B	FS	FS			
GCKI	3	W	B	U	FS	−0.55	0.13	1
GCSP		W	B	S	S	0.27	0.48	1
GRWA	3	M	A	F	F,U			
GRSP	3	M	A	G	G	0.00	1.00	1
GRCA	3	B	A	FS	FS	−0.03	0.94	2
GRFL	3	M	A	S	S	−0.15	0.71	8
GHOW		R	B	F	F			
GTGR		R	B	W	V			
GRRO		R	R	S	S	−0.21	0.59	2
GTTO	3	W	A	F,U	S	0.07	0.86	124
HAWO		R	R	F	F			
HAFL	3	M	A	U	FS	−0.06	0.88	9
HAHA		R	R	W	W			
HASP		W	B	S	S	0.00	1.00	2
HETA	3	M	A	U	F			
HETH	3	W	B	F	FS	0.82	0.01	245
HOWA		M	A	F,W	FS	0.27	0.48	1
HOLA	4	B	B	G,A	G,A			
HOFI		R	B	S	S	−0.43	0.24	1579
HOSP		R	R	H	H	0.00	0.00	
HOWR	3	M	A	V	V	0.01	0.98	88
INDO		A	R	G,A	G,A			
INBU	3	B	A	S	S	0.09	0.83	6
KEWA		M	A	F	F			
LBWO		R	R	F	F			
LALO		W	B	G	G,A			
LARB	3	M	A	G	G,A	−0.45	0.22	4
LASP	4	M	A	S	S	0.33	0.39	385
LAGO	3	A	B	FS,W	FS,W			
LAZB	2	M	A	S	S	0.74	0.02	428
LEFL	3	M	A	FS	FS	0.21	0.59	2
LEGO	4	B	B	F	V	0.49	0.18	65
LENI	3	B	A	S	V			
LEWO	3	R	B	F	F			
LISP	3	W	A	S	S	0.40	0.30	250
LOSH	3	R	B	S	S	0.00	1.00	1
LEOW	3	B	B	F,W	F,W			
LUWA	3	B	C	FS	FS			
MGWA	3	M	A	FS	FS	−0.30	0.44	314
MAWA		M	A	FS	FS,M			
MAWR	3	W	B	W	W	0.52	0.15	5
MCLO	3	W	B	G,A	G,A			
MERL	3	M	A	F	V			
MIKI	3	B	A	F	U			
MOQU		R	R	FS	FS			
MOBL	4	W	B	U	V			
MOCH		W	B	F,U	F	−0.40	0.29	37

Continued on next page

Table 1.—Continued.

SPP[a]	PTR[b]	MS[c]	MD[d]	B–HAB[e]	W–HAB[f]	MRGR[g]	p[h]	n[i]
MODO	5	R	B	V	V	0.02	0.97	25
MOWA		A	A	FS	FS			
NRWS	3	B	A	W	W			
NAWA	3	M	A	FS	FS			
NOCA		A	R	S	S			
NOFL	5	R	B	F	F	0.03	0.97	22
NOGO	3	W	B	FS	FS			
NOHA	3	B	B	G	G,A	0.55	0.13	1
NOMO	2	R	B	S	V	−0.53	0.15	2
NOOR	2	B	A	F	S	−0.06	0.88	79
NOPA		M	A	F	FS			
NSWO		W	B	F	FS			
NSHR		W	B	F	FS	−0.14	0.73	1
NOWA	3	M	A	F,W	F,W	−0.26	0.51	9
OSFL	3	M	A	F,U	F	−0.14	0.94	1
OCWA	3	M	A	FS	FS	−0.23	0.54	401
OROR	3	M	A	FS	FS	−0.27	0.48	1
OSPR	3	M	B	W	W			
OVEN	3	W	A	F	FS	0.27	0.47	1
PABU	3	M	A	S	S	0.21	0.59	2
PARE	3	A	C	F	F			
PAWA		A	A	F,W	FS			
PEFA	3	W	A	W	V			
PHAI	3	B	A	S	S			
PISI	3	W	B	FS	FS	−0.26	0.49	265
PIJA		R	B	S	S			
PLTI		R	B	F	F			
PRFA	3	B	B	G	G			
PRWA		M	A	F,W	FS,U			
PUMA	3	B	A	V	V			
PYNU		M	B	F	F			
PYRR	R	R	S	S	S			
RECR		M	B	F	FS			
RBNU		W	B	F,U	F	−0.35	0.36	3
REVI	3	M	A	FS	S,U	0.41	0.27	1
RHWO		B	B	F	F			
RNSA	3	B	B	F	FS	−0.14	0.73	1
RTHA	2	R	B	FS	FS			
RWBL	5	R	B	W	G,A	−0.24	0.54	33
RNPH		R	R	S,A	S			
RODO		R	B	H	H			
ROWR	5	R	B	O	O			
RBGR	3	M	A	F	FS	0.00	1.00	2
RLHA		W	B	G	FS			
RCKI	3	W	B	U	FS	−0.08	0.84	109
RUHU		M	A	FS	FS			
RCSP		R	R	S	S			
RSTO	4	R	B	FS	FS	−0.56	0.12	106
RUBL		W	B	F,W	A			
SAGS	3	W	B	S	S			
SATH	3	W	B	S	S			
SAVS	3	W	B	G	G	−0.18	0.63	90
SAPH	4	B	B	S	S	0.25	0.52	6
SCQU		R	R	S	S			
SCTA		M	A	F	FS	−0.27	0.48	1
STFL	3	A	A	S,A	G,A			
SCOR	4	B	A	S	S			
SCJA		B	B	S	S	0.00	1.00	1
SEWR	3	W	B	G,W	G			
SSHA	3	W	B	F	F	0.06	0.88	5
STSP		W	B	W	S			
SEOW	3	W	B	G	G			
SOVI	3	B	A	F	FS,U	−0.31	0.41	31
SOSP	3	W	B	S,W	S,W	0.41	0.28	226
STJA		W	B	F	F	−0.55	0.13	2
SUTA	3	B	A	F	S	−0.19	0.63	4
SWHA	1	B	A	S	G,A			

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Table 1.—Continued.

SPP[a]	PTR[b]	MS[c]	MD[d]	B–HAB[e]	W–HAB[f]	MRGR[g]	p[h]	n[i]
SWTH	3	M	A	F	FS,U			
SWSP	·	W	B	W	S	0.49	0.19	8
TEWA	3	M	A	FS	FS,U	0.27	0.48	1
TOSO	3	W	B	U	FS			
TOWA	3	M	A	F,U	FS,U	−0.14	0.73	1
TRSW	3	B	B	W	W			
TUVU	2	B	B	V	V			
VEER	3	M	A	F,W	FS			
VERD		R	R	S	S			
VEFL	3	B	A	V	V			
VESP	4	M	B	S	G	−0.30	0.43	56
VGSW	1	M	A	F,U	FS			
VIWA	3	M	A	FS	FS	−0.41	0.28	118
WAVI	3	M	A	F	FS	−0.52	0.15	34
WAPI	3	W	B	W,S	W			
WEBL	4	M	B	F	F			
WEFL		M	A	F,U	F,U	0.13	0.75	9
WEKI	4	B	A	S,A	G,A	−0.72	0.03	24
WEME	4	R	B	G,A	G,A	0.36	0.34	10
WESO		R	B	FS	FS	−0.19	0.63	3
WETA	3	M	A	F,U	F,U	−0.78	0.01	139
WEWP	2	B	A	F	F,U	−0.18	0.64	36
WBNU		R	R	F	F	−0.47	0.20	13
WCSP	3	W	B	S	S	0.72	0.03	963
WTSP	3	W	B	FS	FS	0.53	0.14	6
WTSW	3	M	A	W,U	U			
WWDO	3	M	C	S	S			
WITU		R	R	F	F			
WISA	3	W	B	U	F			
WIFL	3	B	A	W,FS	FS	−0.21	0.59	55
WIWA	3	M	A	S,W	FS	0.66	0.05	827
WIWR		M	B	F,W	FS			
YWAR	3	B	A	S	S	−0.33	0.39	169
YBSA	3	M	B	U	U			
YBCU	3	B	A	F	FS,U	−0.45	0.23	5
YBCH	3	B	A	S	S			
YHBL	3	W	A	W	W			
YRWA	3	W	B	F	FS	−0.20	0.61	481
YTVI		M	A	F	F,U			
ZTHA	3	A	C	F,W	FS			

[a]SPP = species, based on Hink and Ohmart (1984), Hoffman (1990), and Rio Grande Bird Inc. banding program (personal communication). For species names, see Appendix (at the end of this chapter.

[b]PTR = population trend rank (Carter and Barker 1993). Species with higher rank are more vulnerable to extirpation.

[c]MS = migratory status. B = breeding resident, W = wintering resident, M = transient, and R = resident. The information is based on Hubbard (1975), The AOU Checklist of North American Birds (1983), and Hink and Ohmart (1984).

[d]MD = migration distance, is based on the Preliminary Lists of Migrants for Partners in Flight Neotropical Migratory Bird Conservation Program (1992). A = species breeding in North America and wintering primarily south of the United States (neotropical migrants); B = species breeding and wintering extensively in North America; C = species whose breeding range is primarily south of the U.S.–Mexico border and who enter the United States along the Rio Grande Valley and where the Mexico Highlands extend across the U.S. border; R = resident.

[e]B–Hab = major breeding habitat type(s), based on information from Hubbard (1978), AOU (1983), Ehrlich et al. (1988). A = agriculture lands, F = forest, FS = forest shrub, G = grassland, H = human related habitat, S = scrub, U = upland forest, V = variable, W = water related habitat.

[f]W–Hab = major wintering habitat type(s), based on information from Hubbard (1975), AOU (1983), Ehrlich et al. (1988). A = agriculture lands, F = forest, FS = forest shrub, G = grassland, H = human related habitat, S = scrub, U = upland forest, V = variable, W = water related habitat.

[g]MRGR = r value of the regression between year and number of birds captured/100 net–hours from 1985–1993 at Rio Grande Nature Center (data from Rio Grande Bird Research Inc., Albuquerque, NM).

[h]p = significant level of the regression analysis.

[i]n = total birds captured from 1985 to 1993 at Rio Grande Nature Center, Albuquerque, NM.

Recent Studies

Early research studies on bird use of riparian habitats of the Rio Grande were limited to breeding populations and game species (table 2). Monson (1946) was one of the first to note the importance of riparian habitats to various avian species in the Middle Rio Grande. The avifauna of Elephant Butte Marsh was documented by Hunndertmark (1978), whose study area supported the largest known rookery of nesting water birds in New Mexico. The New Mexico Department of Game and Fish conducted a long term gamebird population study in riparian areas during the 1970s (Zapatka 1980). Jojola (1977) reported 43 species including 20 migratory species during a breeding study at Isleta Indian Reservation. He also found that breeding density in the study area was low and suspected that this was related to habitat

Table 2.—Recent avian studies in the Middle Rio Grande, New Mexico.

Researcher(s)	Year	Study lacatian	Study season(s)	Objectives	Species studied
G. Mansan	1946	Rio Grande Valley Sacorro Caunty	Breeding	Field nate	Same species
A.E. Barell	1951	MRG	Breeding	Use af Russian Olive	Some species
H.T. King	1976	Southern New Mexica Basque	Breeding	Species abundance and habitat relatian	All species
J.R. Jajala Sr.	1977	Isleta Indian Reservatian	Breeding	Papulatian and habitat	Breeding species
D.C. Cole	1978	MRG, Bernardo ta San Felipe Puebla	Breeding	Vegetation structure and breeding bird density	Breeding species
C.A. Hundertmark	1978	Elephant Butte Marsh	Breeding	Inventory	Breeding species
R.J. Raitt & M.C. Delasantra	1980	Elephant Butte and Caballa Reservoirs	All seasans	Inventory	All species
T.P. Zapatka	1980	MRG	All seasans	Game–bird papulation	Maurning Dave
M. D. Freehling	1982	MRG	All seasons	Bird abundance in relation to Russian Olive	All species
V.C. Hink & R.D. Ohmart	1984	MRG	All seasans	Inventory, abundance, and habitat use	All species
Hunter et al.	1987	MRG	Summer	Breeding status	Breeding riparian–obligatars
S.W. Hoffman	1990	MRG	Spring, summer and winter	Inventory and abundance in relation to habitat	All species
G.H. Farley et al.	1994	MRG	All seasons	Use of different aged riparian farest	All species
D.A. Leal & R.A. Meyer	1994	MRG	All seasons	Cammunity campasitian and habitat impartance	All species

disturbance. Cole (1978) investigated the relationship between vegetation structure, breeding bird densities, and habitat utilization in five mature cottonwood stands from Bernardo to San Felipe Pueblo. These sites were dominated by closed canopies of mature cottonwoods with varying understory composition. She recorded 40 breeding or probable breeding species and 30 nonbreeding species from late May to August 1977. Borell (1951) and Freehling (1982) studied the use of Russian olive by riparian birds. Their data provide evidence that Russian olive is used by many landbirds for food (berry crops), cover, and nesting habitat.

The most systematic and thorough bird community study of the Middle Rio Grande was conducted by Hink and Ohmart (1984). During a two-year biological survey, they confirmed that avian species used Rio Grande riparian habitats extensively. They also found that species occupancy patterns varied with season, habitat type, and vegetation structure. A follow-up study of a less extensive scale was conducted by Hoffman (1990) who surveyed birds in the state parks of the Middle Rio Grande. He further described the relative abundance and diversity of birds in the riparian habitat. Four rare or endangered species were detected: bald eagle (*Haliaeetus leucocephalus*), willow flycatcher (*Empidonax trailii*), common black-hawk (*Buteogallus anthracinus*), and yellow-billed cuckoo (*Coccyzus americanus*). An assessment of population trends was intended but was hampered by too few years of data and variations in observers. However, he made several management recommendations for preserving and enhancing the avian resources in the Middle Rio Grande.

Recently, Farly et al. (1994) compared year-round avian use of revegetated riparian sites with mature cottonwood forest sites at the Bosque del Apache National Wildlife Refuge and at a site near Las Palomas, Sierra County. Their data suggest that the revegetated areas are especially important for neotropical migrants. Leal and Meyer (1994) studied species diversity and density of neotropical migrants during breeding and migration in representative riparian woodland types along the Middle Rio Grande. Comparing contemporary species composition to that reported from early records, they found that three historically "regular" species, red-headed woodpecker (*Melanerpes erythrocephalus*), purple martin (*Progne subis*), and hooded oriole (*Icterus cucullatus*), had disappeared from the Middle Rio Grande. Species with populations at the border of their ranges such as these three may be more susceptible to disturbance by dropping out of the system as habitats change. In contrast, Leal and Meyer's (1994) multivariate approach showed that sites having an exotic woody species component, i.e., a type of disturbance, had a positive influence on overall importance scores for migratory landbirds.

Thus, kind and change of habitat have helped determine presence, absence, and abundance of bird species along the Middle Rio Grande, but bird species may differ in their responses to various habitat factors such as seral stage, presence of exotic plant species, and degree of disturbance. To ultimately ensure that necessary habitats are provided for all native bird species, further research is needed to clarify differences in habitat selection among species. This involves developing a program of research that evaluates (1) patterns of species habitat use in different seasons and (2) underlying reasons for species presence, absence, and abundance, including roles of competition, predation, brood parasitism, and availability of food, cover, and nesting substrate, which ties into (3) linkages between habitat use and demographic factors such as nesting success, recruitment, and adult survival.

Population Trends

Population trends of neotropical and short-distance migratory landbirds in North America have received nationwide and worldwide attention in recent years as evidence documenting declines of many migratory bird populations has accumulated (Finch 1991). Unfortunately, population trend information is extremely limited in New Mexico, although Hoffman (1990) reported a decline in numbers of summer tanagers and yellow warblers using riparian habitats of the Middle Rio Grande.

The Breeding Bird Survey (BBS) coordinated by the U.S. Fish and Wildlife Service and Canadian Wildlife Service (Robbins et al. 1986, 1989a, 1989b) is a national data base providing quantitative information on temporal and spatial changes in breeding populations of landbirds. Using the last 10 years of BBS data, Carter and Barker (1992) derived a population trend rank (PTR) for migratory landbird species in each of the 11 western states. The PTR scale ranged from 1 to 5, with 1 = large increase ($\geq$ 5 percent/year); 2 = small increase (1 to 5 percent/year); 3 = trend unknown (between −1 percent and 1 percent/year); 4 = decrease (−1 percent to −5 percent/

year); and 5 = large decrease (> –5 percent/year). We evaluated those migratory landbird species of the Middle Rio Grande that had PTR assignments. Of the 161 scored species, 21 were ranked as having declining populations (rank 4 or 5), whereas 18 species were scored as having positive trends (rank 1 or 2; fig. 1; and table 1). Yet, a majority of the species (122 species, 76 percent) were ranked 3, trend unknown or minor. Three possibilities could explain a species being ranked 3: relative stable population size; small sample because of limited survey routes or lower detectability of the species; or no quantitative monitoring information exists for the species in the area. Because BBS routes are not designed to sample rare or long linear habitats such as riparian corridors and because the number of BBS routes in the western United States are insufficient for accurate trend determination (Finch 1991), the latter two reasons may very well explain why most Middle Rio Grande landbirds had ranks of 3.

Under the initiative of C.A. Hundertmark, Rio Grande Bird Research Inc. has studied landbirds at the Rio Grande Nature Center in Albuquerque, New Mexico, since 1979 by using mist nets (Cox 1994). The program has been standardized and the banding efforts have been relatively constant since 1985. The sample sizes are small for most of the species captured (see table 1) because the operations are staffed by volunteers and are limited to weekends. Regression analyses on the number of birds captured per year from 1984 to 1993 suggest that overall bird abundances within three taxonomic groups—tanagers, fly-catchers, and vireos—have declined (Finch and Yong, unpublished) (see table 1 for trends in individual species). On the other hand, wrens and several sparrow species showed significant or insignificant population increases (table 1). All the warbler species with a sample size (20 had a negative insignificant trend except Wilson's warbler, which had a significant positive trend ($r = 0.66$, $p = 0.05$).

Declines in populations have been attributed to events associated with both breeding and overwintering areas. The rapid rate of deforestation in tropical areas, for example, has been implicated in population declines of many forest-dwelling landbird migrants (Lovejoy 1983; Rappole et al. 1983; Robbins et al. 1989a). Other data point to the importance of changes in suitability of breeding habitat (Whitcomb 1977; Hutto 1988). For example, many forest-interior migrants are reported to be "area-sensitive" (Robbins 1980; Robbins et al. 1989b), which explains, in part at least, why fragmentation of forested breeding habitat has been implicated in population declines of migratory birds (Lynch and Whigham 1984; Wilcove 1988). Habitat succession and disturbance are additional factors that may explain bird population changes detected on the breeding grounds (Finch 1991).

Population trends and their relationship with breeding habitats of the Middle Rio Grande generally agree with findings based on regional and national trends. The banding data of Rio Grande Bird Research Inc. suggest that more forest-breeding migrants and long distance migrants have negative population trends than birds using other breeding habitats or those having short migration distances (figs. 2, 3). Unfortunately, no long-term studies have been conducted to link population trends of resident or migratory birds to habitat or landscape changes along the Rio Grande. We can speculate, however, that a variety of changes along the river are likely to have been influential in causing bird populations to change. Mostly related to increases in human populations in the Middle Rio Grande Basin (Crawford et al. 1993), these factors include (1) increases of exotic woody plants and associated loss of native vegetation, (2) draining and loss of marshes, (3) habitat succession, especially that associated with lack of cottonwood regeneration, (4) habitat conversion to urban and agriculture environments, (5) changing rates of cowbird parasitism, and (6) increasing disturbance of nesting birds by humans and domesticated animals.
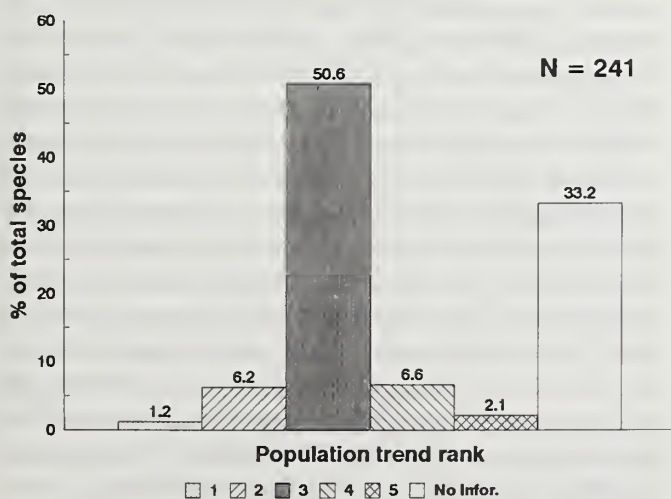

Figure 1.—Population trend rank (Carter and Barker 1993) of the middle Rio Grande landbirds (n = 241). Species with higher rank are more vulnerable to extirpation.
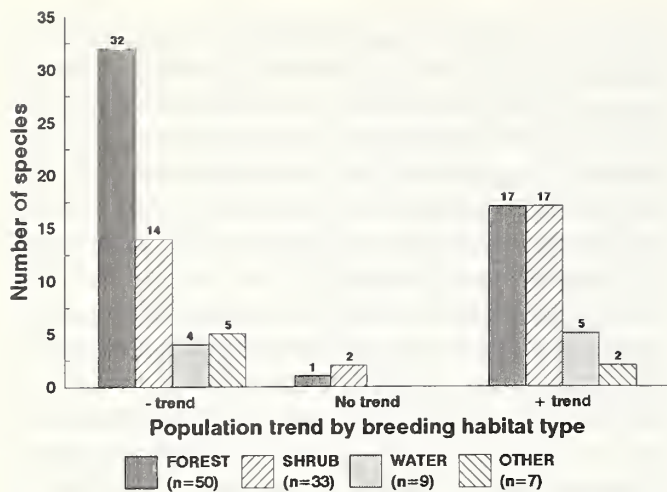
Figure 2.—Population trends in relation to the breeding habitats, based on the banding data at Rio Grande Nature Center.
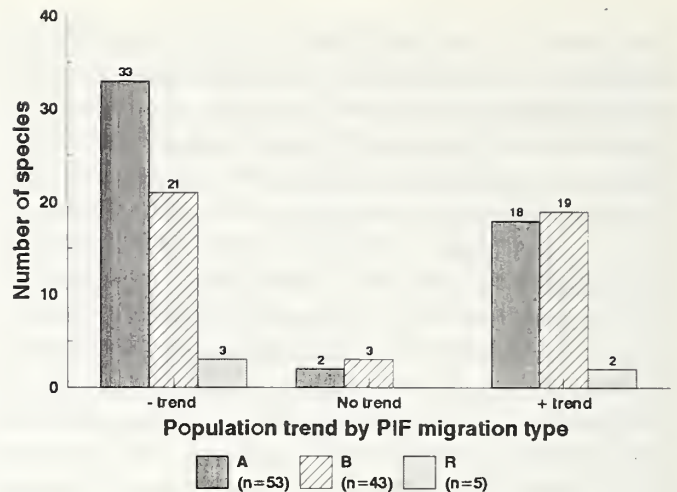

Figure 3.—Population trends in relation to the migration distance, based on the banding data at Rio Grande Nature Center. The migration distance is based on the Preliminary Lists of Migrants for Partners in Flight Neotropical Migratory Bird Conservation Program (1990). A = species breeding in North America and wintering primarily south of the United States (Neotropical migrants); B = species breeding and wintering extensively in North America; R = resident.

Use of Migratory Corridors

Riparian zones along the Middle Rio Grande are probably important stopover sites for landbirds migrating through desert country that might otherwise be inhospitable to some species. Yet, information on migratory bird use of riparian corridors during spring and fall passage is limited, especially for western drainages (Finch 1991). Neotropical and shorter distance landbird migrants that use the Great Plains-Rocky Mountain "flight route" may depend on riparian habitats for resting, for replenishment of energy stores, and as places to avoid unfavorable weather conditions during migration.

About one-third of the landbird species occupy the Middle Rio Grande only during annual migrations between their breeding and wintering grounds. Furthermore, although many short-distance migrants breed and winter in the United States, they have populations that use the Middle Rio Grande only as a stopover site. Studies from other areas suggest riparian systems may attract more than 10 times the number of migratory birds as surrounding upland sites during spring and fall migration (Stevens et al. 1977; Hehnke and Stone 1979).

When migrants stop over, they must adjust their foraging behavior to unfamiliar habitats, resolve conflicting demands of predator avoidance and food acquisition, compete with other migrants and resident birds for limiting resources, respond to unpredictable and sometimes unfavorable weather, and correct for orientation errors (Moore and Simons

1992). These problems are magnified when migrants cross inhospitable environments, such as deserts, and arrive at stopover sites with depleted energy stores. Consequently, riparian corridors may provide suitable habitat at an especially critical time for migrating birds. Riparian corridors may also facilitate orientation during migration by virtue of their "leading line" effect (Geyr v. Schweppenberg 1933).

Stopover time may vary with species, reflecting the relative importance or use of Middle Rio Grande riparian habitats as fueling sites during migration. Our banding data from spring 1994 at two sites along the Middle Rio Grande suggest that the species-specific stopover biology may be determined by migration distance (Finch and Yong, unpublished). For example, recaptured McGillivray's warblers, dusky flycatchers, and hermit thrushes have relatively short stopover lengths (1.5 days, 1.75 days, and 2.71 days respectively), and relatively large amounts of mass (fat) gain (4.07 percent, 13.44 percent, and 3.01 percent respectively) on average. However, blue grosbeak, a local breeding and short distance migratory species, has a longer stopover length (11 days) and small mass change (–0.15 percent) on average.

We also found that numbers of landbirds captured and counted in riparian habitats during spring migration are not the same among habitat types, sug-

gesting that migratory landbirds select different habitats during stopover. Selection could be species-specific based on our finding that certain species occurred in certain habitats more often than others did. For example, among four habitats of the Middle Rio Grande—cottonwood, mesquite, salt cedar, and agricultural fields— that we surveyed in 1994, the relative distribution of black-headed grosbeaks was 50.57 percent, 16.09 percent, 24.14 percent, and 8.00 percent respectively, while that of the closely related Blue Grosbeaks was 15.79 percent, 19.55 percent, 19.55 percent, and 45.11 percent, respectively (Finch and Yong, unpublished). Habitat use also changed through the migration season: more birds were detected from mid-April to the beginning of May than in later months and migrants were also distributed more evenly among habitats during this period. The seasonal habitat shifts of migrants may be due to changes in food availability, leafing phenology, competitive pressure, or predation rates of different habitats through the migration season.

The persistence of migrant populations depends on the bird's ability to find favorable conditions for survival throughout the annual cycle (Morse 1980). Consequently, factors associated with the *en route* ecology of migrants must figure in any analysis of population dynamics (Moore and Simons 1992). How well migrants "offset" costs of migration, i.e., satisfy their energy demands and meet contingencies that arise *en route*, determines the success of an individual's migration as well as the future status of the population itself. As stopover habitat is degraded or lost, cost of migration increases and the probability of a successful migration decreases.

Riparian habitats are under increasing pressure from agriculture, livestock grazing, logging, water management, and recreation (Tellman et al. 1993). More than 90 percent of the original desert riparian habitat in the West has been eliminated by flood control and irrigation projects (Knopf 1988). Effective conservation strategies for neotropical and short-distance landbird migrants that travel through the Southwest cannot be established without basic information on the importance of riparian corridors as stopover habitat.

To account for the habitat needs of migrating birds in management and restoration plans, evaluation of spring and fall use of desert riparian corridors by landbird migrants is urgently needed. We recommend that studies be designed to (1) identify species that use riparian habitats along the Middle Rio Grande and their seasonal pattern of passage; (2) quantify the volume and timing of spring and fall migration in association with the Middle Rio Grande; (3) characterize the *en route* habitats used by migrants, including daily and seasonal patterns of avian diversity and abundance among habitats; and (4) interpret the biology of landbird migrants when they stopover in riparian habitats. Specific questions on migrant biology and ecology that have yet to be answered are (1) How long do migrants stay at riparian stopover sites? (2) What is their energetic status when they stop over? (3) Do migrants (re)deposit energy stores during stopover? (4) How do these aspects vary among species and between seasons?

Different types of riparian habitats may vary in suitability for use by migrating landbirds. Moreover, alteration of particular riparian habitats may reduce or enhance suitability as a stopover area. Thus, responses of landbird migrants to variation in riparian habitats, including human-induced alteration caused by urban encroachment, burning, conversion, draining, and flooding, should be assessed. We need to know (1) whether, how, and why migrants select among riparian habitats; (2) how habitat variation affects stopover biology, including foraging behavior, stopover length, and rate of fat (re)deposition; and (3) how responses to different habitat types or to habitat changes vary among species.

Breeding Biology

During the nonbreeding portion of the life cycle, the major problem faced by landbirds is survival. During the breeding season, however, landbirds cope with the additional demands of finding nest sites, securing enough food to feed young, and protecting their nests against predators and brood parasites. Studies from other parts of the country indicate that population declines of some migratory landbird species may be linked to low reproductive success in unfavorable habitats (Whitcomb 1977; Lynch and Whigham 1984; Hutto 1988; Wilcove 1988).

Most breeding studies conducted along the Middle Rio Grande have been restricted to bird inventories (Manson 1946; Hundertmark 1978; Raitt and Delasantro 1980). Recent studies have focused on the habitat utilization and relative abundance of the species (Borell 1951; King 1976; Jojola 1977; Cole 1978; Freehling 1982; Hink and Ohmart 1984; Hunter et al. 1987; Hoffman 1990). Most of these studies are short term, applying seasonal survey(s) as the study

technique. BBS could provide some breeding information, but they are limited to areas with major roads and are not confined to riparian areas. Using survey data to infer the breeding biology of a species could also result in bias. For example, species detected on a BBS route could be foraging in the area but breeding somewhere else. Foraging birds could also be nonbreeding individuals, e.g., "floaters." Because foraging habitat may not represent breeding or nesting habitat, interpretations based merely on bird presence may give misleading results.

Intensive studies of breeding and demographic parameters are needed to decipher the population dynamics of birds breeding in riparian vegetation of the Middle Rio Grande. Not only do we need to identify the abundance and species of landbirds that breed in riparian habitats, we also need to determine whether their breeding populations are source populations (defined as those that exceed the carrying capacity of the habitat) or sink populations (in which reproductive outputs are inadequate to maintain local population levels). Knowledge of species habitat requirements in the context of macro- and microhabitat selection would help to clarify patterns of species distributions. In addition, an understanding of how variation among habitat types, structures, seral stages, conditions, landscape features, and land usages affect fitness components such as productivity and survival is essential for conserving landbirds.

To identify causes of population changes, information on population size must be coupled with data on the internal composition of a population, i.e., its demographics (Temple and Wiens 1989). For example, data on nesting success, yearly recruitment rate, survivorship, sex ratio, and age distribution can all provide valuable cues in distinguishing factors or events regulating a population. Moreover, such primary population parameters can provide early warning signals of population problems prior to actual declines.

Choice of habitats that increase reproductive output should be favored over evolutionary time. Hink and Ohmart's study (1984) suggests that habitat breadth and preference of breeding landbirds in the Middle Rio Grande may vary among species (table 3). Variation in relative availability of habitat types may affect the habitat selection of breeding birds and, hence, their reproductive success. A decrease of favorable breeding habitat (e.g., native cottonwood-willow) may increase competition among breeding individuals, forcing some birds to use less suitable or marginal habitats, which may reduce their productivity.

Breeding species may be sensitive to changes in microhabitats such as abundance of nest locations, foliage coverage, and understory structure. Unfavorable changes in microhabitats could reduce the chance of successful reproduction directly by increasing the probability of predation, brood parasitism, and/or competition for nest sites among breeding individuals, or indirectly by lowering food availability.

Factors that limit the breeding success of landbirds in the Middle Rio Grande may include predation, cowbird parasitism, mating success, food availability, weather, and flooding. Studies from other areas have suggested that nest predation is a major mortality factor, accounting for 50 percent or more of the nest failures in some locations. Experiments with artificial nests have shown that there are unusually high numbers of mammalian and avian nest predators near edges and in the vicinity of human habitations (Wilcove 1985); therefore edge-nesting birds may be more prone to nest failure. Cowbird parasitism, another important limiting factor, has reached such high levels in some areas that certain species seem to be unable to raise any young of their own (Brittingham 1983; Terborgh 1992). Unfavorable weather and starvation are the other frequent causes of some nesting mortality. The role and importance of these limiting factors may vary in relation to bird species, habitat composition and structure, seral stage, proximity to disturbance, and environmental conditions.

Potential Effects of Brown-headed Cowbirds

Over the last century, the distribution, abundance, and host range of the brown-headed cowbird has increased dramatically in the West because of anthropogenic habitat changes such as urbanization, deforestation, habitat fragmentation, and agriculture development (Rothstein 1994). Its remarkable colonizing ability comes from its brood parasitism behavior that frees it from nesting responsibilities; its foraging flexibility (apparently related to its emancipation from on-duty nesting), such that it can commute daily between widely disjunct feeding and breeding sites; its flexibility in mating systems; and its extraordinary fecundity.

Brood parasitism by the brown-headed cowbird has become one of the major threats to populations

Table 3.—Distribution of landbirds (percent of total birds detected) among habitat types during the breeding season[a].

SPP	C/RO[b]	C/CW	RO	DR	MH	SB/RV	Hb[c]	% Max. HB[d]
YBCU	42	45	12	1			1.02	27
LEWO		100					0.00	0
DOWO	47	47	1	5			0.91	51
HAWO	100						0.00	0
NOFL	60	31	5	4			0.95	53
WEWP	67	26	2	5			0.85	47
WEKI	70	14	4	10		2	0.88	49
BLPH				100			0.00	0
ATFL	53	38	7	2			0.97	54
BCCH	68	24	5	3			0.86	48
MOCH	85		15				0.42	24
WBNU	60	37	2	1			0.80	46
AMRO	46	42	6	6			1.06	59
GRCA	35	18	29	18			1.34	75
EUST	44	51					0.85	48
YWAR	35	13	43	9			1.58	88
COYE	3	9	12	29	47		1.18	66
YBCH	16	40	42	2			1.10	62
SUTA	66	19		15			0.87	49
BHGR	42	35	17	6			1.20	67
BLGU	24	30	30	15			1.40	78
INBU	24	52	4	20		1	1.11	62
SPTO	49	20	27	4			1.15	64
RWBL		3	21		76		0.64	36
YHBL				100			0.00	0
NOOR	25	56	12	7			1.11	62
LEGO	53	30	13	2		2	1.12	62
BHCO	40	28	20	12			1.17	65

[a]Modified from Hink and Ohmart (1984).

[b]Habitat type: C = cottonwood, RO = Russian olive, CW = coyote willow, DR = drain, MH = marsh, SB = sandbar, RV = river channel.

[c]HB = habitat breadth, calculated using the information theory equation: $HB = -\sum p_i \ln p_i$, where p_i is the proportion of the density of each species in the ith habitat type.

[d]Percent of maximum HB is calculated by dividing the HB for the species by the maximum possible HB value, which is $\ln 6 = 1.7918$ when all birds are evenly distributed among all six habitat types.

of many landbirds on their breeding grounds (Mayfield 1977, Brittingham and Temple 1983). Because of its abundance and fecundity, the cowbird has a potential to lower the recruitment rate of host species. Cowbird parasitism reduces host productivity because cowbirds remove host eggs; break host eggs; have shorter incubation periods than hosts, thus nestlings hatch earlier and have a competitive head start over host nestlings; produce larger eggs and nestlings than most hosts; and have faster nestling growth rates. Most Neotropical migrants use an open-cup nest strategy and overlap in timing of breeding with migratory brown-headed cowbirds, thus making them especially vulnerable to parasitism.

At least 10 landbird species, including southwestern species such as least Bell's vireo and southwestern willow flycatcher, have experienced population declines and local population extinctions since the cowbird's spread. These declines are attributed to brood parasitism, riparian habitat loss, and habitat fragmentation in the western United States (Rothstein and Robinson 1994). Both least Bell's vireo and willow flycatcher are riparian obligate breeders in most of their breeding ranges. The least Bell's vireo was designated as an endangered species by the U.S. Fish and Wildlife Service in 1982. The parasitism rate reached over 50 percent in the later 1970s throughout most of the vireo's breeding range (Goldwasser et al. 1980; Franzreb 1989). Removal of cowbirds (Beezely and Rieger 1987) from vireo habitat has greatly increased vireo productivity, and the species is much more numerous now than when the alarm about its near extinction was first raised in the late 1970s.

Southwestern willow flycatchers nest in cottonwood-willow associations and structurally similar riparian

vegetation. Its populations have declined throughout the Southwest through the 20th century. Although the cumulative long-term effects of cowbird parasitism on the southwestern willow flycatcher is unknown, it seems likely that parasitism is an imminent threat to the flycatcher's population persistence or recovery. This, coupled with continued loss, conversion, and deterioration of native riparian shrub habitats that flycatchers prefer, increases its vulnerability to local and widespread extinction. In July 1993, the USFWS proposed to list the species as an endangered species and to designate critical habitat under the Act. New Mexico contains a major portion of the southwestern willow flycatcher's historic and current range, and the Middle Rio Grande bosque in particular has been identified as critical habitat owing to the year-to-year presence of locally nesting pairs.

Earlier studies showed that cowbird abundance and parasitism rates decreased as distance of host nests increased from edges, although recent studies report that the "cowbird edge effect" varies within and among regions in response to landscape-level variation and cowbird abundance. The existing contiguous riparian zones associated with the Middle Rio Grande are comprised of long narrow strips of woodlands, representing typical edge habitat selected by host-searching cowbirds. In the southern half of the valley where the riparian zone is at its widest, the habitat is only 4–5 km across. Conversion of riparian habitats to agricultural or residential areas reduces the total width and area of the riparian zone, consequently decreasing the average distance from edges.

Little information is available on abundance and trends of brown-headed cowbird populations in the Southwest, and even less is known about how cowbird parasitism affects the population dynamics of landbird migrants using the Middle Rio Grande bosque. However, the dramatic environmental changes related to urbanization, livestock industry, recreation, agriculture, power lines, fences, and dam constructions within and surrounding riparian habitats along the Middle Rio Grande create suitable habitats and conditions for brown-headed cowbirds. During the 1994 spring migration of songbirds at Bosque del Apache National Wildlife Refuge, we found that the brown-headed cowbird was one of the most abundant species (244 individuals, or 9.16 percent of all the landbirds detected) (Finch and Yong, unpublished). The 244 observations were distributed evenly among habitats (23.77 percent, 23.36 percent, 27.46 percent, and 25.41 percent for agriculture, cottonwood, mesquite, and salt cedar habitat type respectively). Hoffman (1990) also reported that brown-headed cowbirds were abundant throughout the Middle Rio Grande bosque and speculated that local population declines of the summer tanager and yellow warbler were due to heavy parasitism.

BBS data indicate that New Mexico is one of the states with the lowest brown-headed cowbird breeding population (0–10 individuals/route, see Robinson et al. 1992). However, survey data may not reflect the true parasitism rate because parasitism levels vary locally. More intensive studies on cowbird distribution, abundance, and levels of nest parasitism are required before any decisions can be made regarding the extent to which cowbird management efforts are necessary. The vulnerability of landbird species to cowbird parasitism, as indexed by high rates of reproductive loss or failure, need to be determined. Knowledge of habitat features that stimulate, or conversely inhibit, nest searching facility of cowbirds or movement and reproduction of hosts is critical for managing and restoring habitats to enhance breeding success and juvenile dispersal of landbirds.

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Landbirds of the Middle Rio Grande

Code[a]	Common name	Scientific name[b]
AMCR	American Crow	*Corvus brachyrhynchos*
AMGO	American Goldfinch	*Carduelis tristis*
AMKE	American Kestrel	*Falco sparverius*
AMRE	American Redstart	*Setophaga ruticilla*
AMRO	American Robin	*Turdus migratorius*
ATSP	American Tree Sparrow	*Spizella arborea*
ATFL	Ash-throated Flycatcher	*Myiarchus cinerascens*
BAEA	Bald Eagle	*Haliaeetus leucocephalus*
BTPI	Band-Tailed Pigeon	*Columba fasciata*
BANS	Bank Swallow	*Riparia riparia*
BARS	Barn Swallow	*Hirundo rustica*
BBWA	Bay-breasted Warbler	*Dendroica castanea*
BEVI	Bell's Vireo	*Vireo bellii*
BEKI	Belted Kingfisher	*Ceryle alcyon*
BETH	Bendire's Thrasher	*Toxostoma bendirei*
BEWR	Bewick's Wren	*Thryomanes bewickii*
BLPH	Black Phoebe	*Sayornis nigricans*
BAWW	Black-and-white Warbler	*Mniotilta varia*
BBMA	Black-billed Magpie	*Pica pica*
BCCH	Black-capped Chickadee	*Parus atricapillus*
BCHU	Black-chinned Hummingbird	*Archilochus alexandri*
BCSP	Black-chinned Sparrow	*Spizella atrogularis*
BHGR	Black-headed Grosbeak	*Pheucticus melanocephalus*
BTGN	Black-tailed Gnatcatcher	*Polioptila melanura*
BTBW	Black-throated Blue Warbler	*Dendroica caerulescens*
BTYW	Black-throated Gray Warbler	*Dendroica nigrescens*
BTGW	Black-throated Green Warbler	*Dendroica virens*
BTSP	Black-throated Sparrow	*Amphispiza bilineata*
BLWA	Blackpoll Warbler	*Dendroica striata*
BLGR	Blue Grosbeak	*Guiraca caerulea*
BLJA	Blue Jay	*Cyanocitta cristata*
BGGN	Blue-gray Gnatcatcher	*Polioptila caerulea*
BWWA	Blue-winged Warbler	*Vermivora pinus*
BOBO	Bobolink	*Dolichonyx oryzivorus*
BRBL	Brewer's Blackbird	*Euphagus cyanocephalus*
BRSP	Brewer's Sparrow	*Spizella breweri*
BTHU	Broad-tailed Hummingbird	*Selasphorus platycercus*
BWHA	Broad-winged Hawk	*Buteo platypterus*
BRCO	Bronzed Cowbird	*Molothrus aeneus*
BRCR	Brown Creeper	*Certhia americana*
BRTH	Brown Thrasher	*Toxostoma rufum*
BCFL	Brown-crested Flycatcher	*Myiarchus tyrannulus*
BHCO	Brown-headed Cowbird	*Molothrus ater*
BUOW	Burrowing Owl	*Athene cunicularia*
BUSH	Bushtit	*Psaltriparus minimus*
CAWR	Cactus Wren	*Campylorhynchus brunneicapillus*
CAHU	Calliope Hummingbird	*Stellula calliope*
CAWA	Canada Warbler	*Wilsonia canadensis*
CATO	Canyon Towhee (Brown T.)	*Pipilo fuscus*
CANW	Canyon Wren	*Catherpes mexicanus*
CAFI	Cassin's Finch	*Carpodacus cassinii*
CAKI	Cassin's Kingbird	*Tyrannus vociferans*
CASP	Cassin's Sparrow	*Aimophila cassinii*
CEDW	Cedar Waxwing	*Bombycilla cedrorum*
CCLO	Chestnut-collared Longspur	*Calcarius ornatus*
CSWA	Chestnut-sided Warbler	*Dendroica pensylvanica*
CHRA	Chihuahuan Raven	*Corvus cryptoleucus*
CHSW	Chimney Swift	*Chaetura pelagica*
CHSP	Chipping Sparrow	*Spizella passerina*

Code[a]	Common name	Scientific name[b]
CCSP	Clay-colored Sparrow	*Spizella pallida*
CLSW	Cliff Swallow	*Hirundo pyrrhonota*
COGD	Common Ground Dove	*Columbina passerina*
COBO	Common Barn-owl	*Tyto alba*
COBH	Common Black Hawk	*Buteogallus anthracinus*
COGR	Common Grackle	*Quiscalus quiscula*
CONI	Common Nighthawk	*Chordeiles minor*
COPO	Common Poorwill	*Phalaenoptilus nuttallii*
CORA	Common Raven	*Corvus corax*
COYE	Common Yellowthroat	*Geothlypis trichas*
COHA	Cooper's Hawk	*Accipiter cooperii*
CRCA	Crested Caracara	*Polyborus plancus*
CRTH	Crissal Thrasher	*Toxostoma dorsale*
CBTH	Curve-billed Thrasher	*Toxostoma curvirostre*
DEJU	Dark-eyed Junco	*Junco hyemalis*
DICK	Dicksissel	*Spiza americana*
DOWO	Downy Woodpecker	*Picoides pubescens*
DUFL	Dusky Flycatcher	*Empidonax oberholseri*
EABL	Eastern Bluebird	*Sialia sialis*
EAKI	Eastern Kingbird	*Tyrannus tyrannus*
EAME	Eastern Meadowlark	*Sturnella magna*
EAPH	Eastern Phoebe	*Sayornis phoebe*
EUST	European Starling	*Sturnus vulgaris*
EVGR	Evening Grosbeak	*Coccothraustes vespertinus*
FEHA	Ferruginous Hawk	*Buteo regalis*
FOSP	Fox Sparrow	*Passerella iliaca*
GAQU	Gambel's Quail	*Callipepla gambelii*
GOEA	Golden Eagle	*Aquila chrysaetos*
GCKI	Golden-crowned Kinglet	*Regulus satrapa*
GCSP	Golden-crowned Sparrow	*Zonotrichia atricapilla*
GRWA	Grace's Warbler	*Dendroica graciae*
GRSP	Grasshopper Sparrow	*Ammodramus savannarum*
GRCA	Gray Catbird	*Dumetella carolinensis*
GRFL	Gray Flycatcher	*Empidonax wrightii*
GHOW	Great Horned Owl	*Bubo virginianus*
GTGR	Great-tailed Grackle	*Quiscalus mexicanus*
GRRO	Greater Roadrunner	*Geococcyx californianus*
GTTO	Green-tailed Towhee	*Pipilo chlorurus*
HAWO	Hairy Woodpecker	*Picoides villosus*
HAFL	Hammond's Flycatcher	*Empidonax hammondii*
HAHA	Harris' Hawk	*Parabuteo unicinctus*
HASP	Harris' Sparrow	*Zonotrichia querula*
HETA	Hepatic Tanager	*Piranga flava*
HETH	Hermit Thrush	*Catharus guttatus*
HOWA	Hooded Warbler	*Wilsonia citrina*
HOLA	Horned Lark	*Eremophila alpestris*
HOFI	House Finch	*Carpodacus mexicanus*
HOSP	House Sparrow	*Passer domesticus*
HOWR	House Wren	*Troglodytes aedon*
INDO	Inca Dove	*Columbina inca*
INBU	Indigo Bunting	*Passerina cyanea*
KEWA	Kentucky Warbler	*Oporornis formosus*
LBWO	Ladder-backed Woodpecker	*Picoides scalaris*
LALO	Lapland Longspur	*Calcarius lapponicus*
LARB	Lark Bunting	*Calamospiza melanocorys*
LASP	Lark Sparrow	*Chondestes grammacus*
LAGO	Lawrence's Goldfinch	*Carduelis lawrencei*
LAZB	Lazuli Bunting	*Passerina amoena*
LEFL	Least Flycatcher	*Empidonax minimus*
LEGO	Lesser Goldfinch	*Carduelis psaltria*
LENI	Lesser Nighthawk	*Chordeiles acutipennis*
LEWO	Lewis' Woodpecker	*Melanerpes lewis*
LISP	Lincoln's Sparrow	*Melospiza lincolnii*
LOSH	Loggerhead Shrike	*Lanius ludovicianus*

Code[a]	Common nome	Scientific nome[b]
LEOW	Long-eared Owl	*Asio otus*
LUWA	Lucy's Worbler	*Vermivora luciae*
MGWA	MocGillivroy's Worbler	*Oporornis tolmiei*
MAWA	Magnolio Warbler	*Dendroica magnolia*
MAWR	Morsh Wren	*Cistothorus palustris*
MCLO	McCown's Longspur	*Calcarius mccownii*
MERL	Merlin	*Falco columbarius*
MIKI	Mississippi Kite	*Ictinia mississippiensis*
MOQU	Montezumo Quoil	*Cyrtonyx montezumae*
MOBL	Mountain Bluebird	*Sialia currucoides*
MOCH	Mountoin Chickadee	*Parus gambelli*
MODO	Mourning Dove	*Zenaida macroura*
MOWA	Mourning Warbler	*Oporornis philadelphia*
NRWS	N. Rough-winged Swallow	*Stelgidopteryx serripennis*
NAWA	Noshville Worbler	*Vermivora ruficapilla*
NOCA	Northern Cardinal	*Cardinalis cardinalis*
NOFL	Northern Flicker	*Colaptes auratus*
NOGO	Northern Goshawk	*Accipiter gentilis*
NOHA	Northern Horrier	*Circus cyaneus*
NOMO	Northern Mockingbird	*Mims polyglottos*
NOOR	Northern Oriole	*Icturus galbula*
NOPA	Northern Porulo	*Parula americana*
NSWO	Northern Sow-whet Owl	*Aegolius acadicus*
NSHR	Northern Shrike	*Lanius excubitor*
NOWA	Northern Woterthrush	*Seiurus noveboracensis*
OSFL	Olive-sided Flycotcher	*Contopus borealis*
OCWA	Orange-crowned Warbler	*Vermivora celata*
OROR	Orchard Oriole	*Icterus spurius*
OSPR	Osprey	*Pandion haliaetus*
OVEN	Ovenbird	*Seiurus aurocapillus*
PABU	Pointed Bunting	*Passerina ciris*
PARE	Pointed Redstort	*Myioborus pictus*
PAWA	Polm Worbler	*Dendroica palmarum*
PEFA	Peregrine Falcon	*Falco peregrinus*
PHAI	Phoinopeplo	*Phainopepla nitens*
PISI	Pine Siskin	*Caduelis pinus*
PIJA	Pinyon Joy	*Gymnorhinus cyanocephalus*
PLTI	Ploin Titmouse	*Parus inornatus*
PRFA	Prairie Folcon	*Falco mexicanus*
PRWA	Proirie Warbler	*Dendroica discolor*
PRWA	Prothonotary Worbler	*Protonotaria citrea*
PUMA	Purple Mortin	*Progne subis*
PYNU	Pygmy Nuthatch	*Sitta pygmaea*
PYRR	Pyrrhuloxio	*Cardinalis sinuatus*
RECR	Red Crossbill	*Loxia curvirostra*
RBNU	Red-breosted Nuthatch	*Sitta canadensis*
REVI	Red-eyed Vireo	*Vireo olivaceus*
RHWO	Red-heoded Woodpecker	*Melanerpes erythrocephalus*
RNSA	Red-noped Sopsucker	*Sphyrapicus varius*
RTHA	Red-tailed Hawk	*Buteo jamaicensis*
RWBL	Red-winged Blockbird	*Agelaius phoeniceus*
RNPH	Ring-necked Pheasont	*Phasianus colchicus*
RODO	Rock Dove	*Columba livia*
ROWR	Rock Wren	*Salpinctes obsoletus*
RBGR	Rose-Breosted Grosbeak	*Pheucticus ludovicianus*
RLHA	Rough-legged Hawk	*Buteo lagopus*
RCKI	Ruby-crowned Kinglet	*Regulus calendula*
RUHU	Rufous Hummingbird	*Selasphorus rufus*
RCSP	Rufous-crowned Sparrow	*Aimophila ruficeps*
RSTO	Rufous-sided Towhee	*Pipilo erythrophthalmus*
RUBL	Rusty Blockbird	*Euphagus carolinus*
SAGS	Sage Sparrow	*Amphispiza belli*
SATH	Soge Thrasher	*Oreoscoptes montanus*
SAVS	Savannoh Sporrow	*Passerculus sandwichensis*

Code[a]	Common name	Scientific name[b]
SAPH	Say's Phoebe	*Sayarnis saya*
SCQU	Scaled Quail	*Callipepla squamata*
SCTA	Scarlet Tanager	*Piranga olivacea*
STFL	Scissor-tailed Flycatcher	*Tyrannus forficatus*
SCOR	Scott's Oriole	*Icterus parisorum*
SCJA	Scrub Jay	*Aphelocoma caerulescens*
SEWR	Sedge Wren	*Cistatharus platensis*
SSHA	Sharp-shinned Hawk	*Accipiter striatus*
STSP	Sharp-tailed Sparrow	*Ammodramus caudacutus*
SEOW	Short-eared Owl	*Asio flammeus*
SOVI	Solitary Vireo	*Vireo solitarius*
SOSP	Song Sparrow	*Melospiza melodia*
STJA	Steller's Jay	*Cyanocitta stelleri*
SUTA	Summer Tanager	*Piranga rubra*
SWHA	Swainson's Hawk	*Buteo swainsoni*
SWTH	Swainson's Thrush	*Catharus ustulatus*
SWSP	Swamp Sparrow	*Melospiza georgiana*
TEWA	Tennessee Warbler	*Vermivora peregrina*
TOSO	Townsend's Solitaire	*Myadestes townsendi*
TOWA	Townsend's Warbler	*Dendroica townsendi*
TRSW	Tree Swallow	*Tachycineta bicolor*
TUVU	Turkey Vulture	*Cathartes aura*
VEER	Veery	*Catharus fuscescens*
VERD	Verdin	*Auriparus flaviceps*
VEFL	Vermillion Flycatcher	*Pyrocephalus rubinus*
VESP	Vesper Sparrow	*Pooecetes gramineus*
VGSW	Violet-green Swallow	*Tachycineta thalassina*
VIWA	Virginia Warbler	*Vermivora virginiae*
WAVI	Warbling Vireo	*Vireo gilvus*
WAPI	Water Pipit	*Anthus spinoletta*
WEBL	Western Bluebird	*Sialia mexicana*
WEFL	Western Flycatcher	*Empidonax difficilis*
WEKI	Western Kingbird	*Tyrannus verticalis*
WEME	Western Meadowlark	*Sturnella neglecta*
WESO	Western Screech-owl	*Otus kennecotti*
WETA	Western Tanager	*Piranga ludoviciana*
WEWP	Western Wood-Pewee	*Contopus sordidulus*
WBNU	White-breasted Nuthatch	*Sitta carolinensis*
WCSP	White-crowned Sparrow	*Zonotrichia leucophrys*
WTSP	White-throated Sparrow	*Zonotrichia albicollis*
WTSW	White-throated Swift	*Aeronautes saxatalis*
WWDO	White-winged Dove	*Zenaida asiatica*
WITU	Wild Turkey	*Meleagris gallopavo*
WISA	Williamson's Sapsucker	*Sphyrapicus thyroideus*
WIFL	Willow Flycatcher	*Empidonax traillii*
WIWA	Wilson's Warbler	*Wilsonia pusilla*
WIWR	Winter Wren	*Troglodytes troglodytes*
YWAR	Yellow Warbler	*Dendroica petechia*
YBSA	Yellow-bellied Sapsucker	*Sphyrapicus varius*
YBCU	Yellow-billed Cuckoo	*Coccyzus americanus*
YBCH	Yellow-breasted Chat	*Icteria virens*
YHBL	Yellow-headed Blackbird	*Xanthocephalus xanthocephalus*
YRWA	Yellow-rumped Warbler	*Dendroica coronata*
YTVI	Yellow-throated Vireo	*Vireo flavifrons*
ZTHA	Zone-Tailed Hawk	*Buteo albonotatus*

[a]*Species codes are from Bird Banding Laboratory, National Biological Survey.*
[b]*Scientific names are based on the A.O.U. Check-list of North American Birds (1983).*

Chapter 8
Fish Fauna

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INTRODUCTION

The Rio Grande was recently classified as one of
the most endangered or imperiled rivers in North
America (American Rivers 1993). Originating in
southwestern Colorado, it passes through New
Mexico and forms the international boundary be-
tween the United States (Texas) and Mexico. In its
2,000+ kilometer course to the Gulf of Mexico it
passes through several major impoundments, is used
in numerous irrigation diversion dams, and sustains
massive groundwater pumping of its aquifer, espe-
cially in major metropolitan areas.

This paper addresses the fish fauna of only the
Middle Rio Grande Basin. This reach is demarcated
at the upstream boundary by the confluence of the
Rio Grande and Rio Chama near Española, New
Mexico, with the downstream boundary at the head-
waters of Elephant Butte Reservoir (fig. 1). Two ma-
jor mainstream Rio Grande reservoirs, Elephant Butte
and Cochiti, were completed in 1916 and 1975, re-
spectively. Within this river-reach lie three major
mainstream diversion structures that divert water
into 1,280 km of levees, drains, and canals between
the town of Algodones and the Bosque del Apache
National Wildlife Refuge near Socorro. Two of these
diversion dams, Isleta and San Acacia, have the ca-
pability under low flow conditions to divert all wa-
ter from the Rio Grande, thereby potentially elimi-
nating all surface flow from a 177 km reach of river
between Isleta and Elephant Butte Reservoir.

In addition to the Rio Chama, two major Rio
Grande tributaries drain upper elevation, forested
lands of north central New Mexico. The Jemez River
enters the Rio Grande from the west just upstream
of Bernalillo and the Santa Fe River just below Cochiti
Reservoir. Lands drained by these tributaries are pri-
marily under United States Forest Service adminis-

tration and management. Historically, these land-
scapes were under the moderate influences of the
American Indian tribes. However, commencing with
the Spanish explorations and evidenced today by the
extant Land Grant holdings, human influences have
increased markedly since the 1500s. Diversion of sur-
face flow and alteration of streams and rivers coin-
cided with agricultural development and were the
beginning of successive modifications to historic
stream courses and flows that continue now. Ripar-
ian vegetation, especially cottonwood (*Populus*), has
declined dramatically with changes in flow (Howe
and Knopf 1991). In addition, nonnative plants such
as tamarisk and Russian olive have invaded and be-
come a large component of the riparian vegetation.

GENERAL STATUS

Historic collections of fishes by Cope and Yarrow
(1875) and Dr. W.J. Koster (former Curator of Fishes,
University of New Mexico) provided documentation
of a relatively diverse and a largely endemic Middle
Rio Grande Basin fish fauna (table 1). Many native
species disappeared from the northern portion of the
mainstream Middle Rio Grande Basin by the early
1960s. The last collection of two mainstream cyprin-
ids, speckled chub (*Macrhybopsis aestivalis*) and Rio
Grande bluntnose shiner (*Notropis simus simus*), was
in 1964 just downstream of the present location of
Cochiti Dam (Bestgen and Plantania 1988, 1989, 1990;
Platania and Bestgen 1988). Rio Grande silvery min-
now (*Hybognathus amarus*) is the only endemic short-
lived mainstream cyprinid that survives in the Rio
Grande in New Mexico (Bestgen and Platania 1991;
Cook et al. 1992).

Based on our determinations, of the 45 native and
nonnative species of fishes reported in the Middle
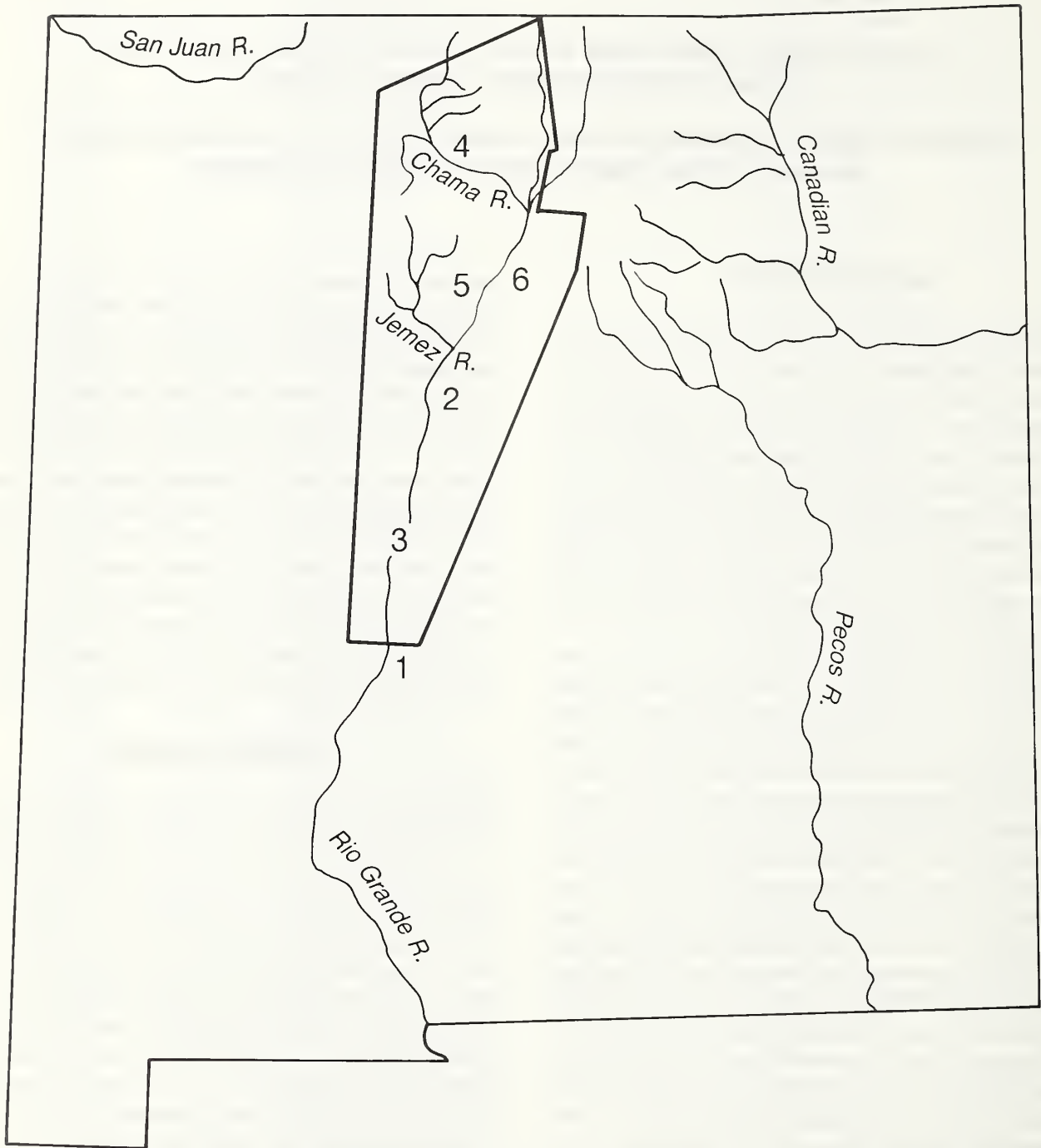Rio Grande Basin, only 17 (38 percent) are native and

Figure 1.—Hydrologic map of New Mexico indicating the reach of the Rio Grande referred to as the "Middle Rio Grande." Elephant Butte Reservoir (1), Metropolitan area of Albuquerque (2), Santa Fe River (3), Chama River (4), Jemez River (5), and Cochiti Reservoir (6) are indicated.

Table 1.—List of Middle Rio Grande (New Mexico) fishes and their residence status. N = native; I = introduced; En = endemic. Platania determinations are considered to be the most complete and up to date.

Toxa	Middle Rio Gronde[a]	Smith ond Miller[b]	Sublette et ol.[c]	Toxa	Middle Rio Gronde[a]	Smith ond Miller[b]	Sublette et ol.[c]
Acipenseridoe				Ameiurus natalis	I	—	I
Scaphirhynchus platorhynchus (shovelnose sturgeon)	N	N	N	(yellow bullhead)			
				Ictalurus furcatus	N	N	N
Anguillidoe				(blue cotfish)			
Anguilla rostrata (Americon eel)	N	N	N	Ictalurus punctatus (channel catfish)	I	—	I
Clupeidoe				Pylodictis olivaris	I	—	I
Dorosoma cepedianum (gizzord shad)	I	—	N	(flothead cotfish)			
Dorosoma petenense (threadfin shod)	I	—	I	Solmonidoe			
				Oncorhynchus clarki virginalis (Rio Gronde cutthroat trout)	En	En	En
Cyprinidoe				Oncorhynchus mykiss	I	—	—
Campostoma anomalum (centrol stoneroller)	I	—	I	(rainbow trout)			
Carassius auratus (goldfish)	I	—	—	Salmo trutta (brown trout)	I	—	—
Cyprinella lutrensis (red shiner)	N	N	N	Salvelinus fontinalis (brook trout)	I	—	—
Cyprinus carpio (common corp)	I	—	I	Cyprinodontidae			
Dionda espiscopa (roundnose minnow)	I	—	N	Lucania parva (rainwater killifish)	I	—	I
Gila pandora (Rio Gronde chub)	En	En	En	Poecillidoe			
Hybognathus amarus (Rio Gronde silvery minnow)	En	En	En	Gambusia affinis (western mosquitofish)	I	—	N
Macrhybopsis aestivalis (speckled chub)	N	N	N	Percichthyidoe			
Notemigonus crysoleucas (golden shiner)	I	—	—	Morone chrysops (white bass)	I	—	I
Notropis jemezanus (Rio Grande shiner)	En	En	En	Centrorchidoe			
Notropis orca (phontom shiner)	En	En	En	Lepomis cyanellus (green sunfish)	I	—	I
Notropis simus simus (bluntnose shiner)	En	En	En	Lepomis gulosus (warmouth)	I	—	I
Pimephales promelas (fotheod minnow)	N	N	N	Lepomis macrochirus (bluegill)	I	—	N
Platygobio gracilis (flotheod chub)	N	N	N	Lepomis megalotis (longear sunfish)	I	—	I
Rhinichthys cataractae (longnose dace)	N	N	N	Micropterus dolomieui (smollmouth boss)	I	—	I
Catostomidoe				Micropterus salmoides (lorgemouth bass)	I	—	I
Carpiodes carpio (river corpsucker)	N	N	N	Pomoxis annualris (white croppie)	I	—	I
Catostomus commersoni (white sucker)	I	—	I	Pomoxis nigromaculatus (black croppie)	I	—	I
Catostomus (Pantosteus) plebeius (Rio Gronde sucker)	N	N	N	Percidoe			
Ictiobus bubalus (smallmouth buffolo)	N	—	N	Perca flavescens (yellow perch)	I	—	I
Ictoluridoe				Stizostedion vitreum (walleye)	I	—	I
Ameiurus melas (block bullheod)	I	—	I				

	Middle Rio Gronde[a]	Smith ond Miller[b]	Sublette et ol.[c]
Number of notive species	17	16	21
Number of endemic taxo	6	6	6
Number of introduced species	28	—	22
Total number of species	45	—	43

[a]Determination by Platania (1993).
[b]Determination based on Smith and Miller (1986); introduced species not reported.
[c]Determination reported by Sublette et ol. (1990).

6 (13 percent) are endemic (table 1) (Platania 1991a, 1991b, 1993; Lang and Altenback 1994; Propst et al. 1987). Sublette et al. (1990) suggested four additional species (gizzard shad, *Dorosoma cepedianum*; roundnose minnow, *Dionda episcopa*; western mosquitofish, *Gambusia affinis*; and bluegill, *Lepomis macrochirus*) were native to this river system. Lee et al. (1980), however, suggested roundnose minnow and bluegill were introduced into the Middle Rio Grande Basin.

We have a more conservative estimate of the number of native fish species and recognize 17 confirmed native species. Of the native species, five have been extirpated from the Middle Rio Grande and two are extinct (table 2). Among the surviving species, the Rio Grande silvery minnow is federally and state listed as endangered (USDI 1993, 1994; New Mexico State Game Commission 1984) and the Rio Grande shiner (*Notropis jemezanus*) is a federal "notice of review" species (USDI 1991). Rio Grande cutthroat trout, *Oncorhynchus clarki virginalis*, the most southerly occurring of the cutthroat trout complex (Behnke 1992), is one of the species addressed in a U.S. Forest Service regional habitat conservation assessment (Rinne 1995c; Young 1995). Bluntnose and phantom shiners (*Notropis orca*) are listed as endangered by the State of New Mexico (Chernoff et al. 1982; New Mexico State Game Commission 1987). In summary, over 40 percent of the native species of the Middle Rio Grande have been eliminated from this reach of river.

Rio Grande cutthroat trout was listed as a Forest Service sensitive species and a "management indicator species" (Stefferud 1988). The American Fisheries Society listed the subspecies as "protected" (Johnson 1987) and of "special concern" (Williams et al. 1989). Stefferud (1988) has provided the most recent review and description of the management of this cutthroat trout subspecies. In New Mexico, Rio Grande cutthroat trout is considered a sport species and subjected to State Game Commission regulations.

The New Mexico Department of Game and Fish has the legislative mandate to "preserve the natural diversity and distribution patterns of the State's native ichthyofauna" (New Mexico Wildlife Conservation Act 1974). Under this directive, the state has the dual objectives of maintaining Rio Grande cutthroat trout while ensuring that its populations are not diminished to the point of special regulations. The state's program is coordinated with the Forest Service's land and resource management plans (U.S.

Forest Service 1986, 1987). The National Forests, through best management practices, monitor water quality in cutthroat trout streams to meet state water quality standards. Also, the New Mexico Department of Game and Fish initiated a broodstock program in 1987 that is currently being refined (Cowley 1993). Both the New Mexico Department of Game and Fish and the Colorado Division of Wildlife have draft management plans for Rio Grande cutthroat trout (Colorado Division of Wildlife 1992; Stumpff 1992).

As of 1992, 77 populations of Rio Grande cutthroat trout were thought to occur in northern New Mexico in its historic range (Stumpff 1992). Of these, 42 were designated pure populations based on morphometric, meristic, and genetic analyses. The other 35 populations displayed some degree of hybridization with rainbow trout. In Colorado, 39 populations exist, 34 of which are pure. The 20-year effort to accurately document the distribution of Rio Grande cutthroat continues at present. During summer 1994, six new populations of potentially pure Rio Grande cutthroat trout were found through cooperative efforts of the U.S. Forest Service and New Mexico State University.

THREATS TO NATIVE FISH FAUNA

Impacts on Low Elevation, Mainstream Reaches

The principal threats to the remaining Middle Rio Grande fish fauna are water diversion and pumping for municipalities. Annual discharge is generally highest during spring runoff between March and June. By comparison, the period of lowest discharge is from July to October and coincides with peak irrigation demand. During these months the need for irrigation water, combined with the potential lack of precipitation and resulting streamflow, may result in loss of surface flow and drying of extensive reaches of the mainstream river channel. For example, flow in the Rio Grande downstream of Isleta Diversion Dam is mainly the result of significant summer monsoon convectional storms, and is supplemented by unpredictable irrigation return flow. Sustained flow in this river reach sometimes returns only following the termination of irrigation at the end of October. Further, water diversion has been (and continues to be) a factor in reducing both water quantity and quality in upper elevation tributary streams and rivers at the northern extent of the Middle Rio Grande (Rinne, 1995c).

The sporadic and cyclic desiccation and re-wetting of the mainstream Rio Grande channel severely impacts habitat availability, life cycles, and population levels of fishes throughout the Middle Rio Grande. During low-flow periods, fish are often trapped in pools where they may more readily fall prey to introduced game fishes (table 1). Even in absence of predation, fish trapped in intermittent pools may ultimately succumb due to declining water quality prior to re-connection of sustained flows. Fish appear to have a tendency to move upstream during periods of low-flow thereby concentrating populations

Table 2.—Residence (i.e., geographic distribution in the Middle Rio Grande), relative abundance, and legal status of native fishes of the Middle Rio Grande, New Mexico.

Taxa	Residence[a]	Population[b]	Federal[c]	NM[d]
Acipenseridae				
Scaphirhynchus platorhynchus (shovelnose sturgeon)	N	Exr	—	—
Anguillidae				
Anguilla rostrata (American eel)	N	Exr	—	—
Cyprinidae				
Cyprinella lutrensis (red shiner)	N	C	—	—
Gila pandora (Rio Grande chub)	En	R	—	—
Hybognathus amarus (Rio Grande silvery minnow)	En	R	End	2
Macrhybopsis aestivalis (speckled chub)	N	Exr	—	—
Notropis jemezanus (Rio Grande shiner)	En	Exr	NOR2	—
Notropis orca (phantom shiner)	En	Ext	—	1
Notropis simus simus (bluntnose shiner)	En	Ext	—	—
Pimephales promelas (fathead minnow)	N	C	—	—
Platygobio gracilis (flathead chub)	N	C	—	—
Rhinichthys cataractae (longnose dace)	N	C	—	—
Catostomidae				
Carpiodes carpio (river carpsucker)	N	C	—	—
Catostomus (Pantosteus) plebieus (Rio Grande sucker)	N	R	—	—
Ictiobus bubalus (smallmouth buffalo)	N	R	—	—
Ictaluridae				
Ictalurus furcatus (blue catfish)	N	Exr	—	—
Salmonidae				
Oncorhynchus clarki virginalis (Rio Grande cutthroat trout)	En	R	—	—
Number of native species	17			
Number of extirpated taxa	5	29.4%		
Number of extinct taxa	2	11.8%		
Number of eliminated taxa	7	41.2%		

[a]N = native, I = introduced, En = endemic.

[b]Exr = extirpated from the Middle Rio Grande in New Mexico, Ext = extinct, C = common, R = rare.

[c]End = endangered, NOR = notice of review classification. Source: U.S. Department of the Interior (1993).

[d]1 = Endangered Group 1 classification (endangered), 2 = Endangered Group 2 classification (threatened). Source: New Mexico Department of Game and Fish (1988).

below mainstream diversions. Below these areas, there is not only a greater probability of encountering predation, but also increased disease due to stress. Such concentration and crowding at the base of dams potentially increases the probability of the loss of a major portion of the native fish fauna during natural events such as de-oxygenation or human-caused activities such as spills of toxic materials.

In the mainstream Rio Grande, the number of introduced sport fishes is large (table 1); however, they are not currently considered the major reason for decline of the native species. Game species reach their greatest abundance immediately after cessation of spring runoff and decline in abundance throughout the summer during periods of reduced streamflow and potential loss of surface flow. Predatory species (particularly centrarchids and percichthyids) seem less tolerant than native species of harsh physical-chemical conditions such as decreasing water volumes of intermittent pools, increasing water temperatures, and lowering dissolved oxygen levels.

Of the 10 surviving native fishes of the Middle Rio Grande, five are rare or have relatively restricted distributions. Three of those five taxa (Rio Grande chub, *Gila pandora*; Rio Grande sucker, *Catostomus plebeius*; and Rio Grande cutthroat trout) were known to occur historically, but at unknown abundances, in the mainstream Rio Grande. They are now most abundant in upper elevations, in more cool to cold water tributaries (Koster 1957). The other two species (Rio Grande silvery minnow and smallmouth buffalo, *Ictiobus bubalus*, are warmwater fishes restricted to the mainstream Rio Grande.

Impacts on Upper-Elevation Tributary Rivers and Streams

Rio Grande cutthroat trout evolved with cypriniform (i.e., cyprinid and catostomid) species in middle to upper elevation (2,000–2,600 m) montane streams. It was once widespread in the upper Rio Grande and Canadian River basins of northern New Mexico and south-central Colorado, and in the headwaters of the Pecos Rivers, (Sublette et al. 1990; Behnke 1992). It may have occurred as far south as Chihuahua, Mexico (Behnke 1992). This fish, the only true native coldwater species in the Middle Rio Grande Basin, has been reported from only two mainstream localities downstream of Cochiti Reservoir.

Currently, Rio Grande cutthroat trout is restricted primarily to headwater tributaries within its native

range. Its southernmost distribution is Indian Creek on the Lincoln National Forest and Animas Creek on the Gila National Forest, in southern New Mexico. It ranges north to headwater tributaries of the Rio Grande in the San Juan and Rio Grande National Forests in southwestern Colorado. There are also a few lake and introduced populations (Colorado Division of Wildlife 1992; Stumpff 1992).

Probably the greatest impact on the Rio Grande cutthroat trout has been the introduction of nonnative salmonids, principally rainbow trout (*Oncorhynchus mykiss*), brook trout (*Salvelinus fontinalis*), and brown trout (*Salmo trutta*) (Behnke 1980, 1992; Behnke and Zarn 1976; Sublette et al. 1990). Of these, rainbow trout, also a spring spawner, readily hybridizes with Rio Grande cutthroat trout. As suggested for other native southwestern trouts (Rinne 1985, 1988; Rinne et al. 1981), the other two salmonid species appear to compete with the Rio Grande cutthroat trout for food and space. Although extensive efforts have focused on the effect of hybridization with rainbow trout, the nature and extent of the effects of competition and predation by other introduced salmonids with native cutthroat trout have been unstudied.

No precise historical data are available on how many kilometers of stream once served as habitat for Rio Grande cutthroat trout. However, the distribution of this subspecies may have declined to only 5–7 percent of its historic range (Stumpff 1992). Because most stocks are now isolated in headwater habitats, gene flow among populations is virtually nonexistent. Winter habitat conditions, stream intermittency, deteriorating water quality conditions resulting from drought and water diversion, and the potential effects of the aftermath of wildfire (Propst et al. 1992) increase the probability of losing more Rio Grande cutthroat trout populations.

An apparently near equal impact is that of habitat degradation and loss. Domestic livestock grazing has occurred on lands surrounding the Middle Rio Grande Basin since the arrival of the Spanish expeditions (Scurlock 1986). By 1830, ranchers were annually herding hundreds of thousands of sheep to supply mining areas of northern New Mexico (Williams 1986). In 1860, 830,000 sheep were being grazed in northern New Mexico; by 1880, that number had increased to about four million.

Currently, livestock grazing is partially controlled by permit on National Forest lands. However, this land use potentially has a major impact on the habi-

tat of Rio Grande cutthroat trout (Behnke and Zarn 1976; Sublette et al. 1990; Behnke 1992). These impacts include trampling of streambanks and removal of streamside vegetation (Platts 1978, 1979, 1981, 1982, 1991). Both undercut banks and streambank vegetation serve as resting and hiding cover for trout (Boussu 1954; Meehan et al. 1991). Loss of streamside vegetation facilitates the elevation of stream temperatures in the summer (Brown and Krygier 1970) and the development of anchor ice in winter. Nevertheless, neither the effects nor extent of grazing on the trout habitat requirements of Rio Grande cutthroat trout have been specifically studied.

Timber harvesting also may affect cutthroat trout habitat through the loss of streamside vegetation and large woody material (Sedell et al. 1991) but these potential impacts also remain undocumented in southwestern streams. Removal of vegetation affects surface runoff and stream hydrographs, and in turn trout habitat and populations (Chamberlin et al. 1991).

Irrigation diversions accompanying the immigration of early settlers into northern New Mexico (Scurlock 1986; Sayles and Williams 1986) resulted in the loss of streams that very likely provided Rio Grande cutthroat trout habitat (Sublette et al. 1990). This dewatering, as an impact on cutthroat populations, has not been studied either.

Cutthroat trout are known for their characteristic low aggression (Nilsson and Northcote 1981), ease of being caught (Behnke 1980), and low vagility (Heggens et al. 1991). Behnke (1992) suggested that brown trout dominated the Rio Chiquito near Taos, New Mexico, because the Rio Grande cutthroat were easier for anglers to catch. However, detailed information on the effects of angling on Rio Grande cutthroat trout are not available.

Introduced species, principally rainbow trout and brown trout and white sucker (*Catostomus commersoni*), to tributary streams may have an even greater impact on the cutthroat trout than does reductions in habitat quantity or quality (Rinne, 1995c). The habitat of the Rio Grande cutthroat has become fragmented because of loss of stream connectivity resulting from the loss of streamflow and habitat quality progressing downstream. The remaining suitable habitats for the Rio Grande native trout appear also suitable for introduced salmonids. Rainbow and brown trout have been either observed or demonstrated to have a detrimental impact on two other native southwestern trouts, Gila trout (*Oncorhynchus gilae*) and Apache trout (*Oncorhynchus apache*) when they co-occur (Rinne 1985; Rinne and Minckley 1985; Rinne 1988; Rinne 1991a, 1991b; Rinne and Minckley 1991). Hybridization, competition for food and space, and direct predation probably reduce or extirpate local populations and distributions.

Rio Grande sucker co-occur in upper elevation streams with Rio Grande cutthroat trout and Rio Grande chub (*Gila pandora*). White sucker, which is native in New Mexico to the Pecos and Canadian River drainages, has been widely established throughout the New Mexico portion of the Rio Grande (Sublette et al. 1990) where it readily hybridizes with the Rio Grande sucker. The Rio Grande sucker still occurs in many montane tributaries of the Middle Rio Grande (Rinne, 1995b). However, because the Rio Grande sucker was nearly extirpated in the headwaters of the Rio Grande in Colorado, the distributional patterns and interaction mechanisms of the two congeners must be monitored.

The endemic Rio Grande chub is widely distributed throughout the Rio Grande Basin in New Mexico and Colorado and is the most abundant member of the two cypriniform fishes (Sublette et al. 1990; Rinne, 1995a). The Rio Grande sucker is known from only one population in the headwaters in Colorado and has disappeared from several historic localities in northern New Mexico. Habitat degradation competition with the introduced white sucker is most frequently cited as the reason for the decline of the Rio Grande sucker (Sublette et al. 1990).

RESEARCH NEEDS

Warmwater Species

Rio Grande silvery minnow, the last remaining endemic mainstream Middle Rio Grande cyprinid, was recently accorded federal endangered status (U.S. Department of the Interior 1994). This fish historically occurred from near Abiquiu, New Mexico, to the Gulf of Mexico. It now occurs only in about 5 percent of its former range—a reach of stream restricted to the Middle Rio Grande between Cochiti Dam and Elephant Butte Reservoir. Long-term studies designed to determine the species' life history attributes, habitat associations, and relative abundances were initiated in 1987. Additional research activities on reproductive biology and the early life-history of the Rio Grande silvery minnow were initiated in summer 1994.

Cold Water Species

Based on available information, Rinne (1995c) suggested that the following areas of research should be pursued (not listed in order of importance):

1. Distribution and genetic analyses of populations.
2. Habitat (spawning, rearing, over-wintering) evaluation.
3. Effects of introduced salmonids.
4. Basic life history (reproduction, age-growth, production, parasites and diseases, food) delineation.
5. Response of this subspecies to land management activities.
6. Fish-habitat relationships.

Research efforts should be closely meshed and integrated with management plans of the U.S. Forest Service and the management plan for the Middle Rio Grande Basin. Information from the above six areas will facilitate management activities to restore this rare native trout to its former range and abundance. Further, researchers should be opportunistic and proactive in synchronizing research efforts with those of the New Mexico Game and Fish Department and the University of New Mexico.

Extensive efforts have been expended in surveying streams to locate populations of Rio Grande cutthroat trout and determining their genetic purity. A priority should be to continue these efforts. It is critical to know the size and distribution of the resource across the landscape before it can be either properly managed or effectively researched.

The remaining areas of research (i.e., 2–6 above) should be pursued both by cooperative efforts with management agencies and by initiating new independent research efforts. First, the basic life history attributes of the subspecies should be determined. Secondly, the spawning, rearing, feeding, and resting (cover) habitat requirements need to be delineated. The relationships of the subspecies and its habitat also need to be investigated. Simultaneously to this effort should be the study of the effects of land management practices on these life history components. Great efforts should be made to conduct this research in the concept of "ecosystem," or the newly adopted "ecology-based multiple use management" philosophy in Region 3 (U.S. Forest Service 1992).

Finally, research needs to be conducted on whether and how introduced salmonids (principally brown and rainbow trout) limit Rio Grande cutthroat trout populations. In addition, interactions of the Rio Grande cutthroat trout with the other members of the native fish community should be investigated.

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Chapter 9
Belowground Ecosystems

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INTRODUCTION

The USDA Forest Service defined ecosystem management as "an ecological approach to achieve multiple-use management of national forests and grasslands by blending the needs of people and environmental values in such a way that national forests and grasslands represent diverse, healthy, productive, and sustainable ecosystems" (June 4, 1992, letter from Chief FS). This approach spans many different scales, both in time and space. It also implies that we need to carefully analyze and evaluate interactions between different parts of the ecosystem, including how humans interact and impact ecosystems.

The belowground component is essential for all terrestrial ecosystems and harbors many of the fundamental mechanisms underlying large-scale ecosystem behavior. The soil, with its chemical and biological properties, is responsible for important processes such as biogeochemical cycling. Soils contain a wide array of organisms ranging from microflora and fauna (nematodes, fungi, cyanobacteria) to macroorganisms (earthworms, ants, termites). They also provide a nutrient and hydrologic reservoir crucial for organism survival both below and above the ground. Thus, soil systems are much more complex than above-ground systems.

One way to promote sustainable ecosystems is to develop and apply ecological theory to managing ecological systems (Lubchenco et al. 1991). Most individuals think of ecological processes operating in relation to land surface, i.e., two-dimensionally. However, soil organisms exist and operate in three dimensions—numbers and processes are usually expressed as a function of volume rather than area. Ecological principles and concepts such as Bergmann's Rule, Gloger's Rule, carrying capacity, pollination, etc., were developed largely around macroorganisms in a two-dimensional paradigm. Some of these principles and concepts may have less relevance, are difficult to apply, and/or are not equally applicable when the third dimension, the belowground, is added (Edwards and Stinner 1988). By adding this dimension, spatial and temporal scales are drastically reduced (e.g., bacterial turnover) or markedly extended (e.g., long-lived recalcitrant organic matter). Because of the difficulties inherent to the study of belowground systems, emphasis has frequently been placed on either process rates, i.e., the black box approach, or on the individual organisms responsible for the process, i.e., autecological approach. At a regional scale, little experimental attention has been placed on community structure and energetics and on interactions among soil populations. Neither of these approaches alone can adequately explain how ecological principles perform in a three-dimensional soil system.

Despite its expanse, very little information in the Southwest exists on belowground ecosystem functions, such as decomposition, carbon and nitrogen pools and fluxes, and mycorrhizal relationships. The operation of many soil processes helps determine above-ground structure and function (Allen 1991, Klopatek et al. 1992). To understand and manage entire ecosystems, it is necessary to comprehend how the belowground systems operate and how they are affected by disturbance. This information then needs to be integrated when assessing stability of ecosystems. The object of this chapter is twofold: one, to explain why soil systems are an integral part of ecosystem management; and two, to discuss how disturbances such as fire, grazing, and climate change may affect two key belowground components—nutrient cycling and mycorrhizae—in Southwestern arid and semiarid ecosystems.

CONCEPTUAL BACKGROUND AND TERMINOLOGY

Belowground

In soil-vegetation systems, soils are the resource base where nutrients and moisture are stored. Regu-

lation of nutrient availability to vegetation is, in part, a property resulting from actions of soil biota on substrate quality and quantity. Sustainability, in a general sense, depends upon the synchrony between vegetation demand, the microbial processes regulating the storage and flux of nutrients, and the return of nutrients and organic carbon through the death and decomposition of plants. Soil storage, in turn, depends not only on the immediate actions of biota but upon their past activities. Thus, the structure of the soil, its ability to hold water and nutrients, and indeed to sustain life, is the result of long years of activity by soil biota and interaction with the vegetation. Current management activities affecting belowground ecosystems within the Middle Rio Grande Basin include: grazing, prescribed burning, fuel wood harvesting, timber management, mining, agricultural development, and urbanization/recreational development and use. Table 1 lists factors involved in sustaining ecosystems and describes how belowground ecosystems are altered as a result of human disturbances.

Mycorrhizae

A mycorrhizae is a mutualistic (symbiotic) relationship between fungi and the plant roots of a host plant (Harley and Smith 1983). The fungi function to serve as nutrient and water absorbing organs for the

Table 1.—Belowground ecosystem productivity factors.

Factors that regulate belowground ecosystem productivity
- Temperature (climate)
- Moisture inputs (climate and hydrology)
- Soil nutrient supply, demand, and cycling (site quality)
- Plant reproductive strategies such as seed source and mortality
- Resource competition (water, nutrients, light, and space)
- Perturbations, both natural and human
- Soil (e.g., texture, depth, parent material)
- Site stability (community composition and successional stage)
- Topographic setting and landforms

Factors that may decrease ecosystem productivity
- Decrease in plant cover and diversity (e.g., by grazing, wood harvesting, and agricultural development.)
- Loss of soil (e.g., by vegetative losses, compaction, runoff, and erosion.)
- Loss of nutrients (e.g., by denitrification, nitrogen volatilization, leaching, and erosion.)
- Decrease in number and diversity of soil flora and fauna and mycorrhizae (e.g., due to vegetative changes, loss of symbiont, photosynthetic decline, and soil disturbances.)

plant (Menge et al. 1978; Mosse 1973; Powell and Bagyaraj 1984; Safir 1987), whereas the plant provides photosynthate (carbon source) for the fungi (Mosse 1973). In fact, nearly all nutrient uptake (and in some cases total uptake) is due to this fungi. A second significant contribution the fungi play is protection against invading parasitic organisms (Davis and Menge 1981; Powell and Bagyaraj 1984; Schonbeck and Dehne 1977). There are two main divisions of mycorrhizae, ecto- and endomycorrhizae. Ectomycorrhizae are associated with coniferous forest trees such as pine, spruce, and fir. In contrast, endomycorrhizae, or more specifically VA mycorrhizae, are formed by the majority of all land plants, (e.g., ferns, grasses, cacti, shrubs, and trees). Although the study of mycorrhizae is fairly recent, the relationship between plant and fungi is not. In fact, one of the first land plants, Rhynia (Chaloner 1970), was found to be colonized by mycorrhizae (Kidston and Lang 1921, Nicolson 1975).

Nutrient Cycling

Nutrient cycling is defined as the movement of chemical elements in a cyclical fashion. Often it is referred to as biogeochemical cycling since biological organisms and their geological (atmosphere or lithosphere) environment play an active role in the cycle. Nutrient cycles are composed of four elements in belowground systems: (1) nutrient demand, (2) storage capacity, (3) rate of nutrient return to the soil, and (4) nutrient retention. Two of the most critical nutrients for plant development are carbon and nitrogen (tables 2 and 3). Nitrogen, being the backbone of nucleic acids (proteins), is an indispensable component of all living creatures. The elements of carbon and nitrogen are good examples of biogeochemical cycling as they have gaseous phases in the atmosphere, are stored components in the soil, and are cycled through both plants and microbes. Although nitrogen can enter the soil through a number of avenues (table 2), its cycling is completely dependent on microbes. Nitrogen cycling has a five step process: biological fixation, assimilation, mineralization, nitrification, and denitrification (figure 1).

Carbon Cycling

Carbon is continually fixed (CO_2) into organic form by way of photosynthetic organisms (both plant and microbe) (table 3). Once fixed and converted into

Table 2.—Nitrogen sources (inputs) and sinks (losses).

N inputs	N losses
• precipitation	• denitrification
• dry fallout	• leaching
• transported sediment	• run-off and outflow
• inflow of drainage water	• ammonia volatilization
• nitrogen fixation	• harvesting
• human & animal activates	• erosion
• litter fall	

Table 3.—Carbon sources (inputs) and sinks (losses).

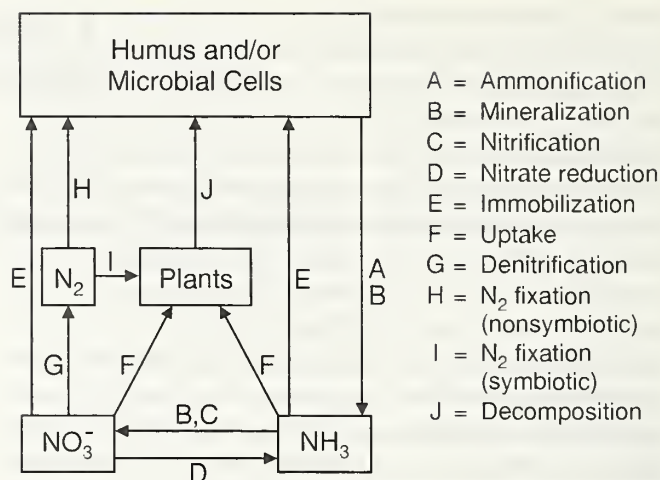| Carbon sources (inputs) and sinks (losses)	
C inputs	C losses
• CO_2 from the atmosphere	• respiration
• rock parent material	• erosion
• abscised debris from above-ground	• vegetation removal
• decomposing plant material	
• decaying animal and microbial cells	

Figure 1.—Pools and fluxes of the nitrogen cycle. Adapted from *Introduction to Soil Microbiology*, second edition, by Martin Alexander (New York: John Wiley & Sons).

A = Ammonification
B = Mineralization
C = Nitrification
D = Nitrate reduction
E = Immobilization
F = Uptake
G = Denitrification
H = N_2 fixation (nonsymbiotic)
I = N_2 fixation (symbiotic)
J = Decomposition

organic form, carbon cycling and decomposition of organic material is dependent on microbial activity. Organic matter is central to the cycling of plant nutrients, influences water relations and erosion potential, and is a key factor in soil structure and stability (Tisdale and Oades 1982). In arid and semiarid systems, decomposition of organics is initiated by invertebrates that break down organic material into smaller fractions (Santos and Whitford 1981, Santos et al. 1981). Soil microbes and microinvertebrates further break down organic fractions. As organic residues decompose, they become part of the soil organic matter (SOM). SOM is composed of several fractions: (1) active SOM fraction consists of live microbes and microbial products, along with soil organic matter, with short turnover times (approximately 1–5 years), e.g., sugars and amino acids; (2) slow SOM is physically protected and/or in a chemical form with more biological resistance to decomposition, with intermediate turnover times (20–40 years), e.g., hemi celluloses; (3) passive or recalcitrant SOM may also be physically protected, with the longest turnover times (200–1500 years), e.g., lignin (Parton et al. 1987). Thus, through decomposition, microbes convert organic material into plant available nutrient forms, followed by re-releasing carbon into the atmosphere as CO_2 (i.e., respiration), hence, completing the cycle.

GLOBAL CHANGE

Ecosystem Effects

Current projections suggest a global warming between 1.5 and 4.5° C in the coming century (IPCC estimates, Mitchell et al., 1990 Schneider 1989). Schneider (1989), Neilson (1989), and others have shown, using general circulation models (GCM's), that the Southwest will not only experience a rise in temperature but a change in precipitation, confounding the already low water availability both above- and belowground. Neilson (personal communication) indicates that, as a result of this increase in temperature, areas will undergo a shift in precipitation from snow to rainfall events. In spite of high variability in predicted rainfall, soil moisture is anticipated to decrease in most of the Southwest (Manabe and Weatherford 1987, Washington and Meehl 1989). The effects of a temperature increase and soil moisture depletion may have profound consequences on the productivity, diversity, and extent of natural resources in this region resulting in major shifts in vegetation types. Schlesinger et al. (1990) suggest that climate warming may cause significant changes in global biogeochemical cycles that will then be further disrupted by positive feedbacks, resulting in a shift from semiarid to arid systems. Emanuel et al. (1985) also suggest that potential global climate warming may seriously affect the arid and semiarid southwestern United States, forecasting a 17 percent

increase in the desert land area (i.e., desertification). These predicted changes caused by climate warming will have effects on vegetation types and carbon storage and flux rates in southwestern ecosystems.

In arid or semiarid biomes, there appears to be a continuous change in species composition from the core to the edges, although plant life-form appears to be a more uniform characteristic over a larger area. These transitions between different biomes or ecosystems are a function of a wide range of processes that operate on many time and space scales. The environmental driving functions (e.g., temperature and moisture) causing these transitions are likely to exercise significant control on ecosystem level processes (e.g., primary productivity and nutrient cycling) (NATO 1993; Risser 1995; Turner 1989). Resource dynamics and resource limitations for commodities such as water and nutrients often significantly differ between biomes or across transition zones (e.g., deserts to grasslands and grasslands to pinyon juniper woodlands). For example, structural differences in leaves between grasses, shrubs, and trees affect nutrient cycling and decomposition rates. Presence of woody shrubs and trees affects properties such as ecosystem biomass, nutrient storage, and microclimate. These structural differences are often accompanied by distinct differences in carbon pools and partitioning of resources. Since species move about individualistically in the face of climate changes, studies of change need to be conducted at multiple spatial scales in order to anticipate the changes that also occur at multiple temporal scales. Thus, the relationship between vegetation and climate is symbiotic but not exclusive because soils, fauna, and human activities all impact vegetation (Klopatek et al. 1992, Riebsame et al. 1994).

Belowground Responses

Belowground processes are inextricably linked in time and space with biosphere responses to global climate change. Three direct effects of climatic change that may have important impacts on belowground systems are increases in atmospheric CO_2, increases in global temperature, and changes in precipitation patterns. At present, we are unable to predict the consequences of these changes to soil systems with any certainty as they have the potential for both amelioration or exacerbation of global climate change effects. Unfortunately, we have little direct experimental evidence available to predict these effects.

Responses of plants to climate change such as loss of plant cover, and changes in plant species diversity, density, or biomass, will regulate to some degree the belowground environment. Increasing CO_2 alone will primarily affect belowground systems through changes in photosynthate allocation. In a three-year CO_2-enrichment study of yellow poplar, Norby et al. (1992) showed increased carbon allocation belowground, although whole plant carbon storage did not change. This increase in carbon availability has implications for mycorrhizae and nitrogen fixers as well as other rhizosphere organisms (Norby 1987, O'Neill 1987). Confounding the potential for CO_2 enrichment effects on soil processes is the possibility of a concomitant rise in global temperature due to increases of greenhouse gases. As mentioned above, there is widespread agreement among scientists that during the next 35 years there will be a global temperature increase by about 1° C due to increases of greenhouse gases (NSF 1991). There is less agreement on the degree to which soil temperatures will rise and precipitation regimes will change as a result of increasing air temperature. Changes in soil temperatures will not only directly affect distribution and numbers of organisms, but also affect the rates at which theses organisms process nutrients.

A predominant source of carbon for the soil compartment is plant litter and its subsequent decomposition. Decomposition is controlled by several factors including temperature, moisture, soil structure, and litter quality (Waring and Schlesinger 1985). Temperature and moisture regulate many ecosystem functions as they are the most critical driving forces in ecosystems (Swift et al. 1979). The resulting effect of temperature and moisture on decomposition will also vary according to the litter quality of that biome (Berg et al. 1990). Litter quality, typically referring to the carbonaceous component, and its relationship to the limiting nutrient(s) in an ecosystem, often defines the rate at which decomposition may proceed. Past studies have suggested that the ratios of carbon: nitrogen, lignin:nitrogen, and/or cellulose:nitrogen are the most significant indicators of the rate of decomposition (Moorhead and Reynolds 1991; Meentemeyer 1978; Schlesinger and Hasey 1981; Aber and Melillo 1982). High nutrient concentration in relation to stored energy (low carbon:nutrient ratio) will promote a higher rate of decomposition (Berg et al. 1982). Small changes in temperature or moisture may have a negligible effect on the decomposition rates of litter of poor quality, whereas a slight

change in either factor could greatly alter the decomposition rate of litter of good quality (Meentemeyer 1984, Berg et al. 1993). Since microbes and soil animals control processes such as decomposition, changes in litter quality that affect decomposers will be reflected in soil microfauna and eventually other compartments of the food web.

Research on the effects of global change on carbon cycling vary. Models derived from eastern deciduous forests show that decomposition rates may be depressed with CO_2 enrichment but may be offset if increased soil temperatures stimulate microbial activity and water is not limiting (Anderson 1991; Melillo et al. 1982; Whipps 1990) . The process model presented by Paster and Post (1995) demonstrated that decomposition rates increased with higher temperatures and limited soil water, but the model predicted a decrease in productivity as a result of decreasing litter quality through increased lignin:nitrogen ratios. The effect of global change on belowground processes in the Southwest are uncertain as predictions for aboveground vegetation responses significantly differ (e.g., Parton et al. 1995, Schlesinger et al. 1990). If regional spatial shifts in vegetation GCM's forecasting occur (Solomon and Shugart 1993), they will have an effect on carbon dynamics across the landscape (Berg et al. 1990; Anderson 1991; Klopatek et al. 1992). Research by Klopatek C. et al. (1995a, 1995c) and Klopatek J. et al. (in press) has focused on how potential climate change may affect carbon pools and fluxes, documenting the relative pool sizes and aggradation rates of carbon as they change across the ecotonal boundaries from one system to another in the Southwest. They have shown that decomposition rates of different litter types of the Southwest significantly differ due to difference in climate (figure 2). Their experiment shows that the rate of decomposition was not significantly different between xeric sites (Great Basin shrublands and ecotones) with those of more mesic sites (ponderosa pine and ecotones). They have also shown that pinyon-juniper communities do not differ in their rate of decomposition from either the lower (DS) or upper elevational (PP) sites. This information substantiates their earlier contentions that PJ, with its different physiognomic and edaphic physiographic and climate characteristics, is truly an ecotonal area between mesic (PP) and xeric (DS) ecosystems (Klopatek 1987; Klopatek et al. 1988; Klopatek et al. 1990; Klopatek and Klopatek 1995). Such research has the potential to demonstrate a large
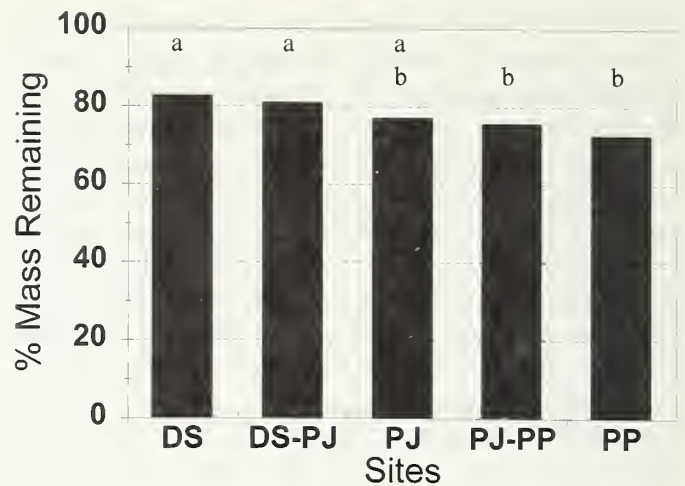

Figure 2.—The effects of climatic factors (i.e., temperature and moisture) on the rate of decomposition in blue grama (BOGR), one-seeded juniper (JUMO) and pinyon pine (PIED). Litter was placed along a gradient from a desert scrub site (DS), a transition zone (DS-PJ), a pinyon-juniper woodland (P-J), a second transition zone (PJ-PP) and a ponderosa pine forest (PP) (adapted from Klopatek et al. 1995c).

range of environmental changes that may come about as a result of climate change.

FIRE AND GRAZING EFFECTS

Ecosystem Effects

It has been reported that over 40 percent of the arid lands in North America have undergone severe to very severe desertification within the last 100 years (Dregne 1977, Schlesinger et al. 1990). Desertification has been directly attributed to heavy grazing (Costello 1972, Sheridan 1981). Grazing by domestic livestock has long been associated with decreases in ecosystem productivity (Chew 1982). The Rio Grande Basin has been grazed for centuries and has experienced long-term declines in plant and soil productivity (Conley et al. 1992; Daddy et al. 1988; Orodho et al. 1990; Webster and Wright 1987; Wilcox and Wood 1988). Both wild and prescribed fires are reoccurring phenomena in the Basin (Swetnam and Betancourt 1990). Prescribed burning has been a long-standing management activity in southwestern systems (personal communication, USDA Forest Service, Region 3) because it is thought to increase grass production. It is unclear what the long-term effects of burning are on overall ecosystem productivity in this

region, unlike intensively studied grassland areas such as the Kanza Prairie. Limited information on the post-fire successional patterns of the major vegetation types in the Southwest is available (e.g., Moir and Dietrich 1988, Swetnam and Betancourt 1990). However, the time for belowground systems to recover following fire and grazing and the subsequent long-term effects of these disturbances on primary productivity in the Rio Grande Basin is not well understood. An additional complication in the understanding of fire effects is the consequence of global warming, as increased fire frequencies are predicted during periods of dry years with a concomitant increasing risk of large forest fires (Sandenburgh et al. 1987, Turner and Romme 1990).

Recent studies have shown that repeated prescribed burning may cause significant changes in surface runoff and sediment production (Emmerich and Cox 1994; Weltz and Wood 1986; Weltz et al. 1989). Soil erosion, as a result of disturbance, is thought to be one of the major causes of nutrient loss in arid and semiarid ecosystems (Schlesinger et al. 1990). Chronic disturbances such as grazing and fire also produce significant changes in the cycling of nutrients, e.g., nitrogen, carbon, and phosphorus. Studies indicate that fire alters the biogeochemical cycling patterns in southwestern forested ecosystems. Fire acts as a rapid mineralizing agent and releases ammonium-N that is later converted into nitrate-N under conditions favorable for nitrification (Klopatek 1987; Klopatek et al. 1991; Kovacic et al. 1986). Inorganic P also is released by burning, but it too is quickly chemically immobilized (DeBano and Klopatek 1987) and may no longer be readily available for plants. Production of NO_3-N presents a large potential loss of nitrogen from the ecosystem because it is easily leached from soils following precipitation events or denitrification. Organic carbon (litter and humus) following fire also decreases, usually a direct result of combustion. This potential loss of carbon has a great impact on nitrogen cycling as bacteria responsible for nitrification increase following burning (Klopatek et al. 1991). These bacteria do not require organic carbon, hence they convert readily available ammonium into nitrate. The above interactions strongly suggest that loss and retention of nutrients during and following fire are important processes affecting the long-term productivity of arid and semiarid ecosystems and must be better understood before these ecosystems can be managed on a sustainable basis in the Southwest.

Belowground Responses

Although the Rio Grande has undergone a variety of perturbations that continue today, no studies specifically address the effects of fire and grazing on the belowground microbial community in the Basin. Research is being conducted in the transition zone between Chihuahuan Desert and Great Plains grasslands. This area is composed primarily of C_3 and C_4 grasses, small shrubs, and scattered juniper trees. Most of the species (other than weedy invaders) are colonized by mycorrhizae, specifically, vesicular-arbuscular (VA) mycorrhizae (Klopatek, unpublished). It has been well documented that many plants have a strong dependency with mycorrhizal fungi. Without mycorrhizae many plants show a decreased growth rate or fail to grow past the germination stage (Harley and Smith 1983; Mosse 1973; Powell and Bagyaraj 1984). Studies have shown that this relationship is fragile and can be easily disturbed (Bethlenfalvy and Dakessian 1984; Daft and Nicholson 1974; Janos 1980; Klopatek 1991; Klopatek and Klopatek 1995; Reeves et al. 1979; Warner et al. 1987; Williams and Allen 1984; Zac and Parkinson 1982). These studies show that as the severity of disturbance increases, e.g., from livestock grazing (Bethlenfalvy and Dakessian 1984; Klopatek and Klopatek 1987; Reece and Bonham 1978) to surface mining (Allen and Allen 1980; Gould and Liberta 1981; Klopatek and Klopatek 1984, 1995; Zac and Parkinson 1982), there is a corresponding decrease in the frequency of VA mycorrhizae propagules and/or colonization.

Fire has been shown to impact ectomycorrhizae in other forest ecosystems (Mikola et al. 1964, Schoeneberger and Perry 1982), but until recently, little was known about the response of VA mycorrhizal symbionts to fire. Klopatek et al. (1988) showed that after a simulated fire, VA mycorrhizal colonization was reduced when burning temperatures exceeded 90° C, and that soil water availability played an important role in VA mycorrhizal survival. Klopatek found that dry soils were more of a detriment than wet soils because of higher resultant temperatures. Subsequently, Klopatek (1991) and Klopatek et al. (1994) demonstrated that mycorrhizae decreased even more significantly in field-burn studies (figure 3). In that study, although greater pre-burn mycorrhizal percentages were found in the plants grown in field soils than in the soils from the laboratory microcosms study, burning was significantly
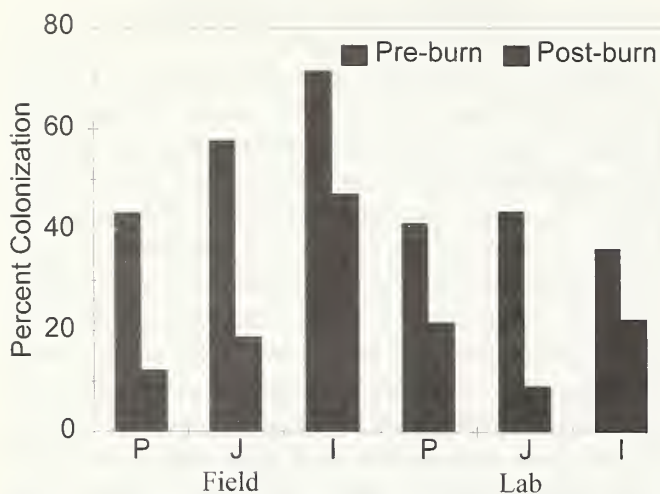
Figure 3.—Comparisons of VA mycorrhizal colonization on host plants grown in unburned and burned soils from under pinyon (P), juniper(J), and interspaces (I) between field and laboratory studies (adapted from Klopatek et al. 1994).

correlated with temperature. But, the effects of burning in the field were even more pronounced. In the field, it was also demonstrated that the length of time that the area burned played a role in the reduction of mycorrhizae. Canopy covered patches, having greater burning temperature and longer burning duration, were more effected by burning than interspaces (figure 3). This was due to the greater fuel loads under canopies. Five years following the fire, interspaces had recovered from the burn, but canopy covered patches had not (Klopatek, unpublished).

Results of other studies on mycorrhizal response in semiarid ecosystems vary. Gibson and Hetrick (1988) found significant reductions of three VA mycorrhizal species following a fire in the tall grass prairie of Kansas. In a similar experiment, Bentivenga and Hetrick (1991) stated that burning temporarily increased mycorrhizal activity in a tall grass prairie ecosystem. Dhillion et al. (1988) found that colonization levels of VA mycorrhizal fungi in little bluestem roots were significantly reduced on burned sites when compared to unburned sites but increased significantly after one growing season. Their results suggest that the response of VA mycorrhizal fungi to fire may be attributed to changes in the host plant rather than to the direct effect of fire. Fire temperatures did not reach a level high enough to kill all the plants, thereby leaving a large residual VA mycorrhizal pool in the soil and in plant roots. In fact, they showed that fire actually stimulated plant growth.

In contrast, Vilarino and Arines (1991) examined a forested ecosystem in Spain one year following a wildfire and found lower soil propagule densities and lower VA mycorrhizal colonization in post-fire herbaceous vegetation than in neighboring unburned areas. Although they had no information on the VA mycorrhizal distribution or activity prior to the fires, Vilarino and Arines (1991) suggest that VA mycorrhizae are negatively affected by fire and that mycorrhizal recovery in forested ecosystems is a slow process. In addition, they theorized that topographical and pedological properties may have played an important role in the losses and reestablishment of mycorrhizae on their study areas.

The time required for mycorrhizal populations (with emphasis on VA) to recover after fire in arid and semiarid systems is not well understood. Janos (1984), MacMahon (1987), and Allen (1991) have all suggested that mycorrhizal fungi are essential in the recovery of an ecosystem, facilitating plant establishment by regulating nutrient flow from the soil to the plant. Although researchers have documented plant succession and nutrient dynamics following disturbance, little work has been done to integrate these patterns with mycorrhizal succession. Determining how mycorrhizal and nutrient dynamics affect landscape patterns is important to understanding how ecosystems operate within the Middle Rio Grande Basin and crucial when assessing long-term ecosystem productivity and sustainability. Studies on belowground ecosystem ecology can provide highly useful information that has been up til now a missing dimension of the knowledge needed to manage the Middle Rio Grande Basin.

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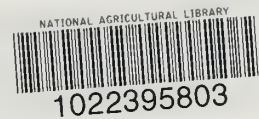
Cover Photos

Front photo by Sandia Laboratories, Cooperative Monitoring Center and Earth Data Analysis Center, University of New Mexico. Image was created from a mosaic of two Landsat Thematic Mapper (TM) scenes acquired in August and September 1992. Landsat TM bands 4, 3, and 2 are displayed in red, green, and blue. The spatial resolution of the image is 28.5 meters.

Back photo by National Aeronautics and Space Administration. This infrared view of the Albuquerque area was photographed in April 1993. The false colors of the infrared film enhance the mixed agriculture along the Rio Grande and show the variations of desert land use on the left side. The Rio Grande dominates the center of the photo with the oldest part of Albuquerque located close to the river. City growth is channeled by the Sandia Mountains to the east and the southern edge of the Jemez Mountains to the north. Interstate Highway 40 runs east-west through Albuquerque. Kirkland Air Force Base is near the center of the photo.