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# Characterization of the Southwest United States for the Production of Biomass Energy Crops

Martha S. Salk
A. Gray Folger

ENVIRONMENTAL SCIENCES DIVISION
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ENVIRONMENTAL SCIENCES DIVISION

# CHARACTERIZATION OF THE SOUTHWEST UNITED STATES FOR THE PRODUCTION OF BIOMASS ENERGY CROPS

Martha S. Salk

and

A. Gray Folger*

ENVIRONMENTAL SCIENCES DIVISION
Publication No. 2791

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## ABSTRACT

SALK, MARTHA S., and A. GRAY FOLGER
Characterization of the Southwestern United States for the Production of Biomass Energy Crops. ORNL/TM-10203. Oak Ridge National Laboratory, Oak Ridge, Tennessee. 172 pp.

The southwest United States, an area of diverse climate, topography, terrain, soils, and vegetation, is characterized to determine the feasibility of growing terrestrial energy crops there. The emphasis in the study is on delineating general zones of relative resource and environmental suitability, which are then evaluated to estimate the potential of the region for energy crop production.

The parts of the region in which average annual precipitation is at least 30 cm (12 in.) and the frost-free period is at least 120 days/year are considered to be minimally suitable for biomass energy crops. Of the approximately 190 x $10^6$ ha (469 x $10^6$ acres) in the study region, just over 40% meet both of the criteria. Maps of additional climate and land characteristics (i.e., evaporation, soils, vegetation, slope, land use/cover, and land ownership) were generated for this potentially suitable, or reduced, area. The reduced area falls roughly into three major subregions: an eastern region in Colorado, New Mexico, Oklahoma, and Texas; a central area primarily in Arizona; and a western area almost exclusively in California. In addition, there are small scattered areas in Nevada, Utah, southwestern Colorado, and northwestern New Mexico that meet the criteria.

Of the 34 vegetation types in the potentially suitable area, 5 cover almost 62% of that area. Two of these ecosystems, grama-buffalo grass and mesquite-buffalo grass, are almost entirely located in the reduced area and are, therefore, adapted to the climatic conditions in the reduced area. The other three most common types--juniper-pinyon woodland, grama-tobosa shrubsteppe, and trans-Pecos shrub savanna--are found both in the reduced area and in the part of the study region that does not meet the climatic criteria for the reduced area. Species in these three vegetation types are, therefore, adapted to climatic conditions that occur in the reduced area in years when the precipitation and/or frost-free period is less than average. These species are good candidates for biomass energy crops because they are able to survive in years when the weather is more severe than average.

Productivity of many ecosystems in the Southwest, including the reduced area, is low in comparison with other geographic regions of the United States. Thus, the Southwest has a lower potential for producing energy from terrestrial crops than other parts of the country, but species adapted to that environment could be grown there to contribute to the national energy supply. While it may be difficult to justify the production of crops in the Southwest solely for their energy content unless energy prices rise significantly, multipurpose projects in which energy production is one aspect may be feasible.

The data compiled for this study can be used both to provide a set of species for screening as biomass energy crops for the Southwest and to identify areas where previously selected energy crops would grow best. Species that perform best in a given set of environmental conditions can be exploited in this way rather than by attempting to alter the environment to suit the needs of other plant species.

Species with the following characteristics are most likely to be suitable biomass energy crops in the Southwest: exhibit root or stump sprouting, have $C_4$ or CAM metabolism, have nitrogen-fixing symbionts, withstand moisture limitations and other climatic extremes, have multiple uses, and produce valuable by-products.

Further research, particularly on a site-specific basis, must be done before a definite decision can be made as to whether the Southwest is an area in which biomass energy crop production should be encouraged.

# 1. INTRODUCTION

## 1.1 BACKGROUND

The 1973-1974 oil embargo forced the United States to examine its dependence on imported oil for a sizable fraction of its energy needs. Part of the emphasis became to find domestic sources of energy to replace and/or supplement imported oil so that the United States would be more self-reliant in terms of its overall energy needs. One of the energy sources that has been under investigation since then is biomass, and a Biofuels Program was implemented in the Department of Energy (DOE) to facilitate the development of such resources. Feedstocks in that program include woody crops, herbaceous energy crops, microalgae, and municipal solid wastes. In addition, the Biofuels Program encourages identification of biofuel technologies leading to integrated regional fuel supply systems, since development of optimum resources in each region of the country would eliminate some of the need for distribution of fuels between regions.

The southwestern United States is one section of the country that has not been systematically evaluated for its bioenergy potential. In general, the Southwest is a region of arid and semiarid climate, high insolation, complex topography, and low primary productivity. Nevertheless, it may offer significant potential for bioenergy production because much of the land there is not used for conventional agriculture.

This study is a first step in determining the potential of the Southwest for terrestrial energy crop production. The emphasis is on delineating and characterizing general zones of relative resource and environmental suitability in the region, using geographic data analysis techniques. The size and characteristics of these zones will then provide a basis for estimating the potential of the region for energy crop production.

## 1.2 OBJECTIVES

The primary objective of this study is to examine the productivity of natural and managed ecosystems of areas in the southwestern United States that appear to have the potential for supporting the production of energy crops and, if it seems possible, to lay the groundwork for further investigations in this region. This investigation is specifically intended to support the Short Rotation Woody Crops (SRWC) and Herbaceous Energy Crops (HEC) programs managed at Oak Ridge National Laboratory (ORNL) for DOE. Both of these programs need a systematic characterization and preliminary evaluation of the condition and potential of the Southwest in order to plan future research in biomass energy. Specifically, the programs' needs with regard to the Southwest are:

1. a screening of regional conditions to identify the most promising areas upon which to focus subsequent studies;
2. a characterization of the most promising land areas; and
3. a basis for evaluating potential research that can be used to rank these efforts within the region and among regions.

A critical question to be asked is whether energy crop production should even be considered under conditions in which most conventional agricultural crop production is not viable. However, since energy crop production is a relatively undeveloped technology with objectives and possibilities somewhat different from those of conventional agriculture, an affirmative answer is conceivable if innovative production systems can be developed. Such systems must be harmonious with the prevailing environmental conditions, sustainable, and cost-effective. Production systems that involve perennial species, low intensity/low cost management, and/or high-value energy products, for example, might prove to be viable in the Southwest.

## 1.3 APPROACH

This study is patterned after an earlier investigation that evaluated the potential resources of the southwest United States for the production of microalgae (Maxwell et al. 1985). In that study, maps of climate, land, and water resources were selected from a variety of sources; brought to a uniform scale of 1:2,500,000; converted into digital format; and overlayed, using a computerized Geographic Information System (GIS). The current study for terrestrial energy crops uses similar procedures and much of the data from the microalgae study (e.g., the region, map scale, and GIS are the same). However, additional mapped data were selected and converted into digital format so that composite maps could be generated by combining various overlays of different map data.

The analysis has been based primarily on an ecological perspective. Instead of estimating the potential of a few select species (e.g., jojoba and guayule), the naturally occurring vegetation and its relationships with the environment are broadly examined to evaluate the prospects for energy production (Lipinsky and Kresovich 1979). These naturally occurring species are, by definition, adapted to the prevailing environmental conditions, but in most cases they have not been systematically examined for their energy production potential.

Thus, the first step in this investigation was to produce maps that identified areas in the Southwest where the resources and environment were most suitable for terrestrial energy crop production. The second step was to characterize the most suitable areas in terms of their environment and resources. The third step was to suggest research activities to identify possible crops, cropping techniques, and site characteristics that may affect the management, productivity, or cost of potential energy crops.

## 1.4 LIMITS AND RESTRICTIONS

There are several restrictions that limit the scope of this study. First, this report emphasizes only the potential for growing crops for energy. Plants can also be grown to provide fibers, hard vegetable waxes, natural rubber, hydrocarbons, nonfuel oils, and food (Johnson and Hinman 1980, Balandrin et al. 1985, Lipinsky and Kresovich 1979). However, growing biomass to produce these nonfuel products, even with fuels as by-products, is not addressed in this report.

Second, riparian areas are not discussed, even though they have a high potential for growing biomass energy crops (Everitt 1980). Wetlands in the Southwest, including riparian communities, have rarely been differentiated or shown on maps (Minckley and Brown 1982). They tend to be small relative to other communities but have an importance and biological interest disproportionate to their limited geographic occurrence. Riparian areas also raise significant questions about water rights issues, which are very controversial in the West. Therefore, riparian areas must be considered to be exceptions to the statements presented here.

Finally, because energy costs associated with irrigation will continue to be a major factor in determining the feasibility of biomass energy crops in the Southwest (Foster and Brooks 1981), only irrigation during initial planting and establishment of a biomass energy crop should be considered feasible.

# 2. THE SOUTHWEST UNITED STATES

There is no generally accepted definition of the region called the Southwest. For the purposes of this investigation, the Southwest is defined to include all of the states of Colorado, Utah, Nevada, New Mexico, and Arizona and those portions of California, Texas, and Oklahoma between the 100th meridian that bounds the east side of the Texas Panhandle and the 120th meridian that forms the western border of Nevada (Fig. 2.1).

## 2.1 GEOGRAPHY

The study area, defined by political and cartographic boundaries, encompasses a great variety of natural environmental features and conditions in terms of geology, topography, climate, soils, flora, and fauna. The physiographic regions included in the study area (Fig. 2.2) are the Basin and Range and Colorado Plateau physiographic provinces, as bounded by the Pacific and Rocky Mountain Cordillera and a portion of the Great Plains to the east (Lobeck 1932). The diverse terrain in the Southwest exerts a major influence on patterns of climate, soil, and vegetation in the region.

Much of the southwest region of the United States is desert. Deserts are essentially climatic phenomena characterized, in general, by low precipitation, low relative humidity, high potential evaporation, and related conditions such as clear skies, high insolation, windiness, and large variations in temperature. The major deserts in the Southwest, the Great Basin, Mojave, Sonoran, and

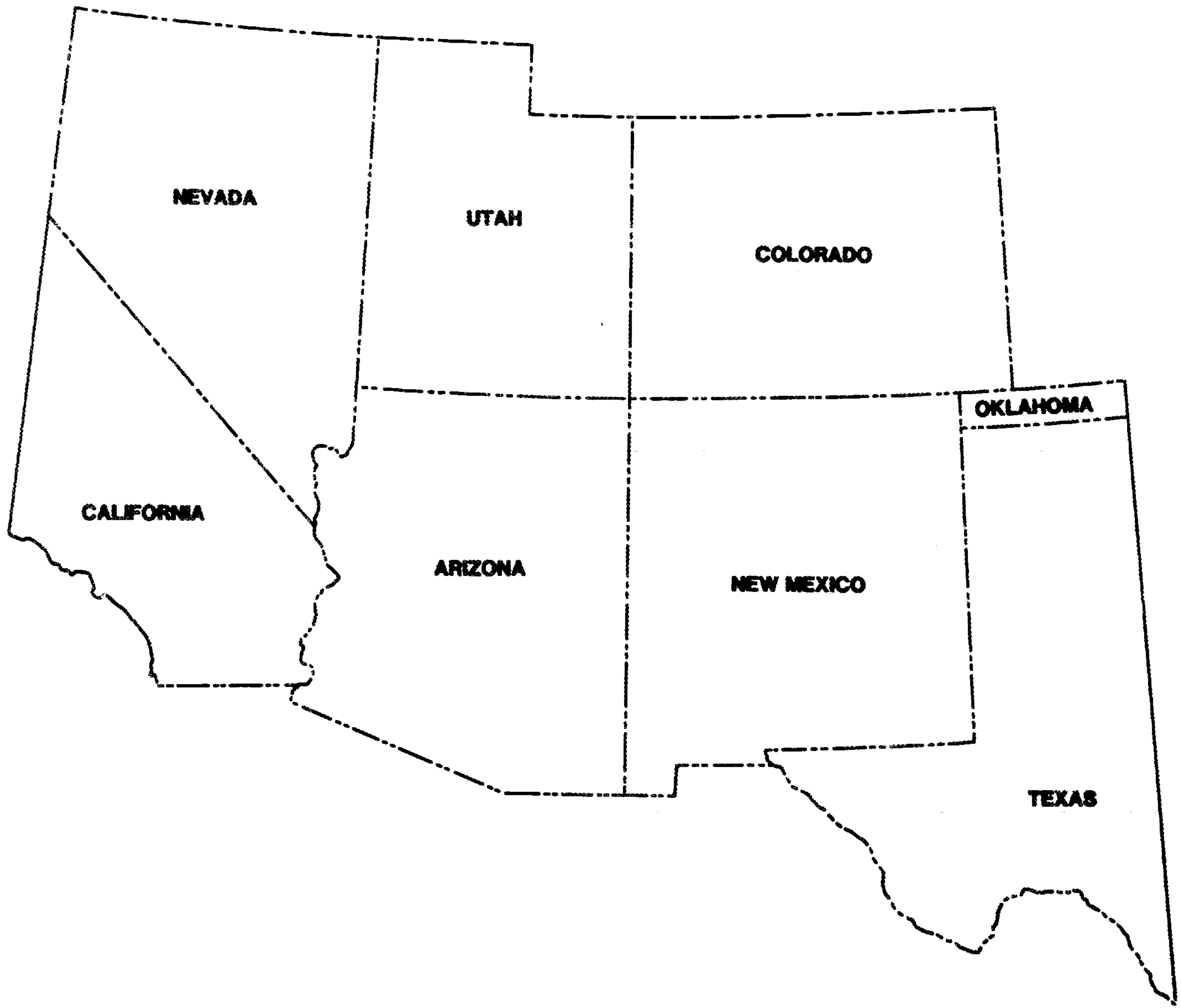


Fig. 2.1. The southwest United States study region.

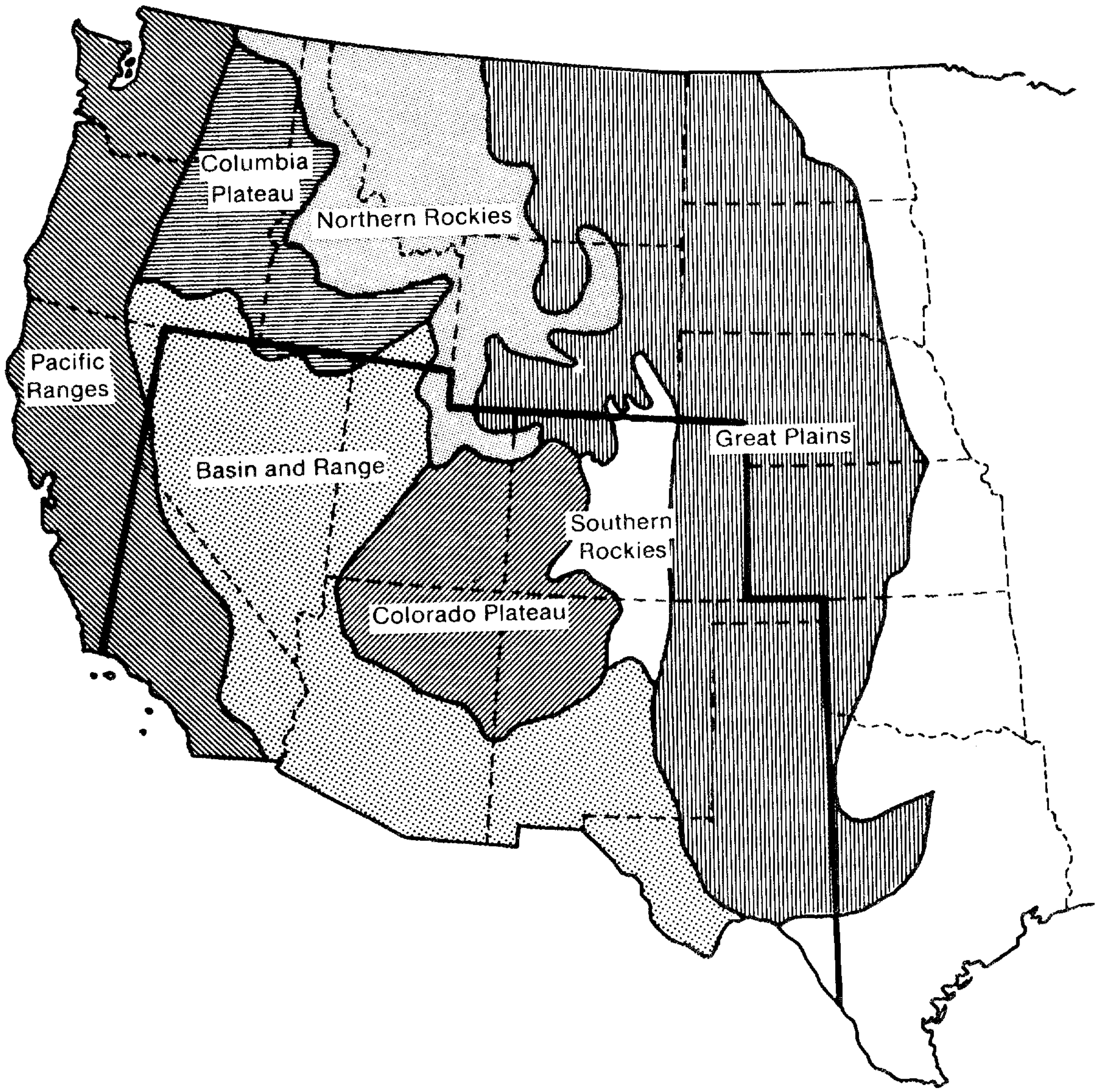


Fig. 2.2. Major physiographic provinces of the western United States. Dark lines indicate the study region. Source: A. K. Lobeck, 1932, rev., Physiographic provinces (Map), Sheet no. 59 in The National Atlas of the United States, U.S. Department of the Interior, Geological Survey, Reston, Virginia.

Chihuahuan, generally coincide with the Basin and Range physiographic province (Fig. 2.2).

Within the Basin and Range region, as well as along its edges, are north-south trending mountain ranges. Many of the basins are closed and have internal drainages that result in playa lakes, dry lakes, and/or salt flats. Otherwise, drainage is accomplished by river systems, primarily the Colorado and Rio Grande, that originate in high mountains and pass through the arid areas. The deeply dissected, complex terrain in the Colorado Plateau region is attributable to the influence of the Colorado River drainage system.

## 2.2 CLIMATE

The climate in the Southwest is quite variable. Figures 2.3 and 2.4 indicate the national patterns of normal annual total precipitation and mean length of freeze-free period, respectively (USDC 1977). The complex isoline patterns in the Southwest are due to the highly irregular topography there. The weather in the Southwest can vary significantly both between and within years. For example, the dates for mean annual freeze-free period in the North American deserts may vary a month or more between years (Jaeger 1957), while southeastern Arizona has a variation in annual mean precipitation that is greater than any other part of the contiguous United States (Cox et al. 1983).

Although the Southwest is generally arid, precipitation varies greatly within and among seasons and years and among locations separated by only short distances (Herbel 1979). In general, average


Fig. 2.3. Normal annual total precipitation for the United States in inches. Source: Climatic Atlas of the Unites States, 1977, rev., U.S. Department of Commerce, National Oceanic and Atmospheric Administration, National Climatic Center, Asheville, North Carolina.

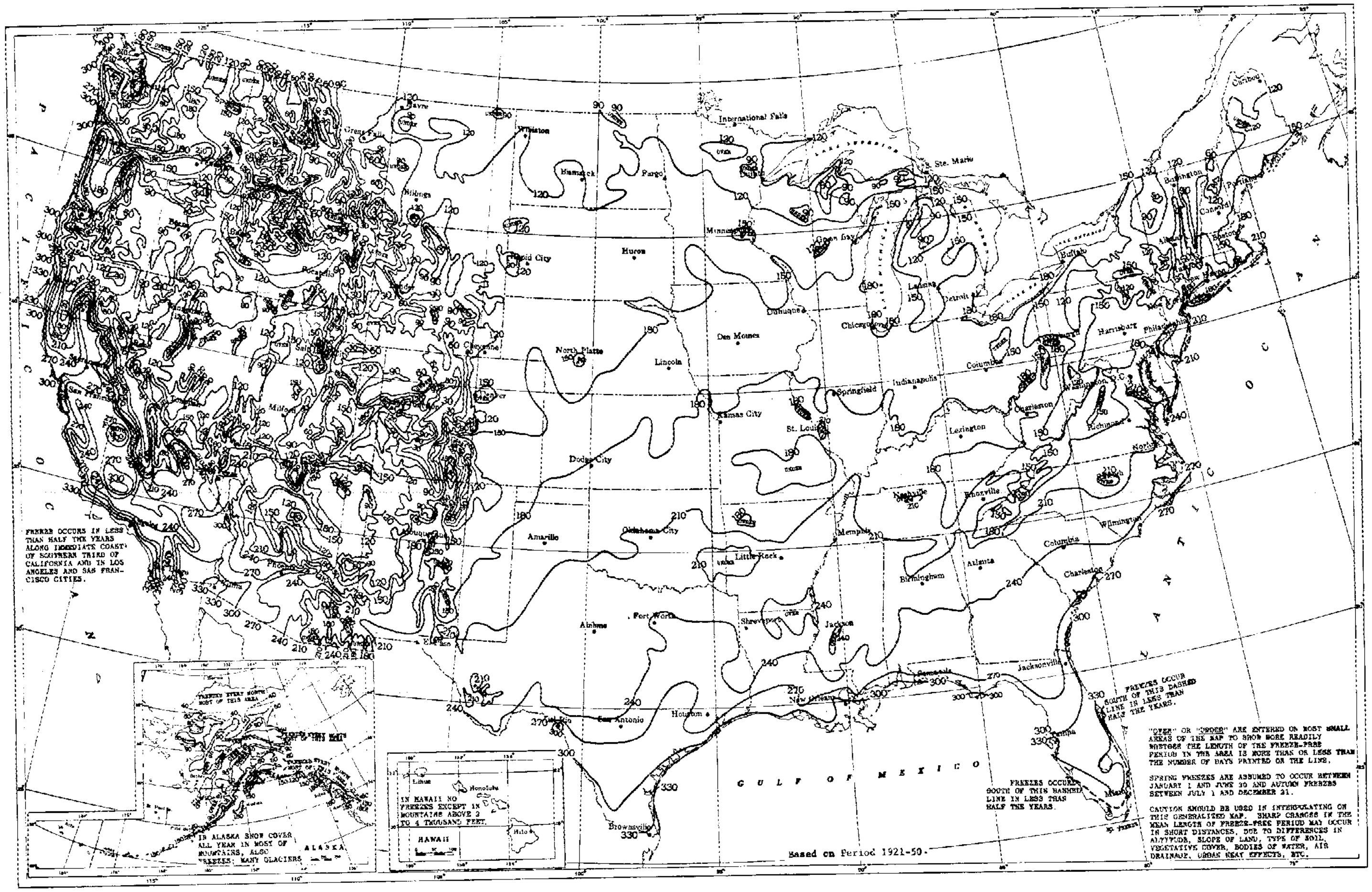


Fig. 2.4. Mean length of freeze-free period for the United States in days. <u>Source</u>: Climatic Atlas of the Unites States, 1977, rev., U.S. Department of Commerce, National Oceanic and Atmospheric Administration, National Climatic Center, Asheville, North Carolina.

annual precipitation increases with altitude, while the length of the frost-free period decreases. Average annual precipitation in the Southwest varies from less than 10 cm (4 in.)/year to over 122 cm (48 in.)/year, with most of the region receiving the lesser amounts (Fig. 2.3). The values of mean annual precipitation in the more arid parts of the region are not, however, too informative because of the high variability from year to year (Bell 1979). In general, as the mean annual precipitation decreases, the variability of annual precipitation increases. Further, the most arid parts of the area may occasionally experience precipitation in a single event that approaches or exceeds the mean annual value. In contrast, months and even years may pass without significant precipitation (Herbel 1979). Seasonal variations in precipitation in arid and semiarid regions (Fig. 2.5) influence the adaptations seen in plants for exploiting the available moisture (Pyke 1972).

Temperature also shows extreme diurnal, seasonal, and spatial variations in the Southwest. The dry atmosphere and clear sky transmit both incoming solar radiation and outgoing terrestrial long-wave radiation readily, causing large diurnal temperature changes near the surface and severe seasonally cold and/or hot periods. Local variations in temperature are further enhanced in regions of rugged topography by the effects of insolation contrasts, air drainage, and adiabatic lapse rates. For example, in the basin and range region, a strong temperature inversion is created during a typical winter night.Basin temperatures are then as cold as or colder than those of

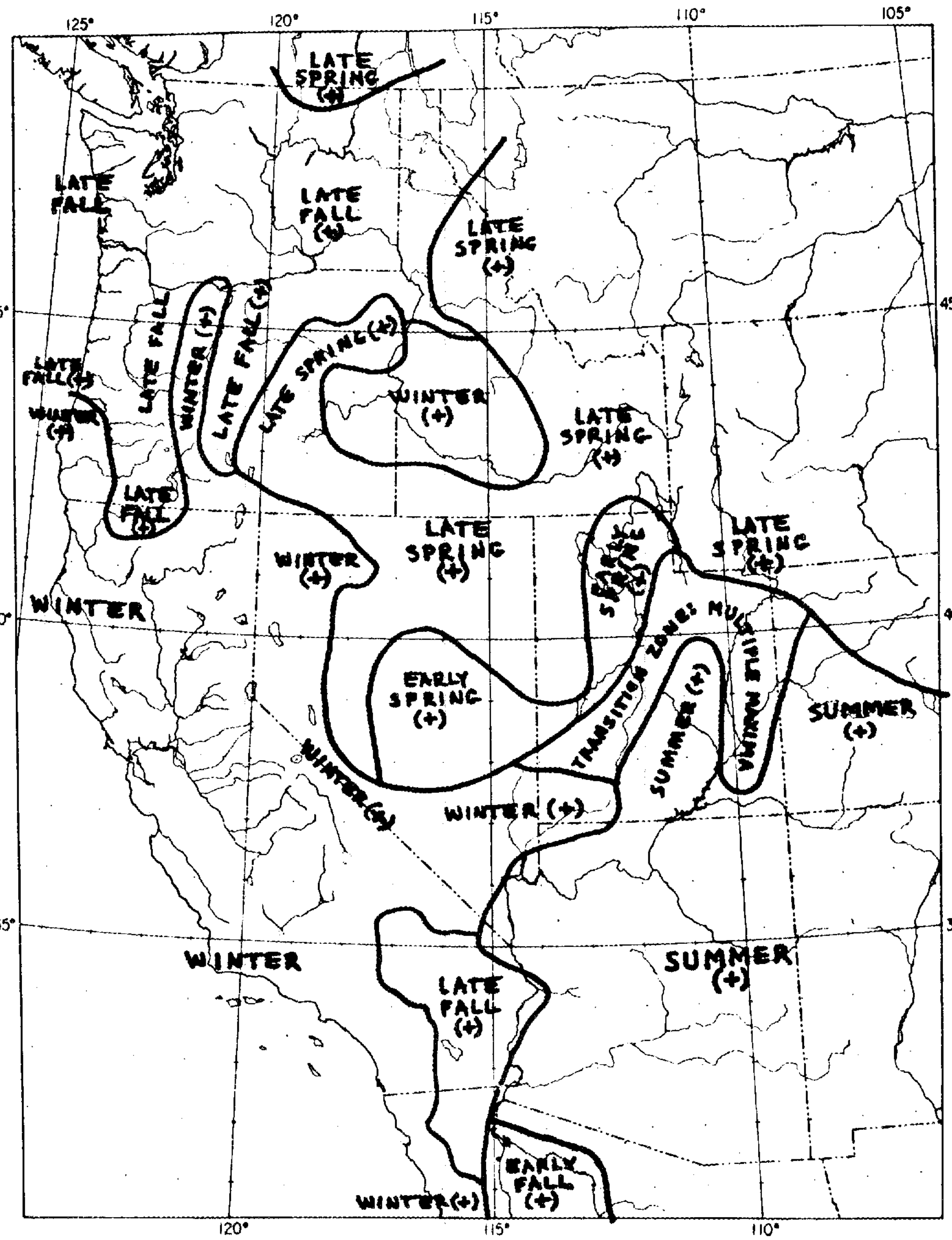


Fig. 2.5. Season of primary precipitation maximum ("+" indicates the occurrence of secondary maxima). Winter = Jan.-Feb.; early spring = Mar.-Apr.; late spring = May-June; summer = July-Aug.; early fall = Sept.-Oct.; and late fall = Nov.-Dec. Source: C. B. Pyke, 1972, Some meteorological aspects of the seasonal distribution of precipitation in the western United States and Baja, California, UCLA-WRC-W-254, University of California Water Resources Center, Los Angeles.

the mountain peaks, while the warmest conditions occur on the lower mountain slopes (Logan 1968). These temperature extremes affect the patterns of local vegetation in the Southwest.

Evaporation in the region also varies significantly in time and space, particularly on the drier, leeward side of the major mountain ranges. In general, the reliability of the delineations of evaporation is poor for the mountainous West because it is based on a sparse network of data.

## 2.3 SOILS

A generalized soil map of the study region by the Soil Conservation Service (SCS) (USGS 1970) (Fig. 2.6 and Table 2.1) presents the types and patterns of soils in the study area. The principal soil orders in the study region are Aridisols, Mollisols, Entisols, and Alfisols. In comparison with soils of humid regions, desert soils such as those in many parts of the study region are restricted in geographic extent and generally less well developed (Smith 1968). Soils are often limited to flat and gently sloping surfaces, while steeper slopes and uplands are dominated by exposed bedrock. Physical and chemical processes, as opposed to biological processes, exert a major influence. The differentiation of the soil profile into distinctive horizons is less pronounced than in soils of humid regions because there is less leaching and less moisture available for chemical activity. Alteration of parent materials is minimal, resulting in soils of closely similar chemical characteristics. More developed soils, including Aridisols with

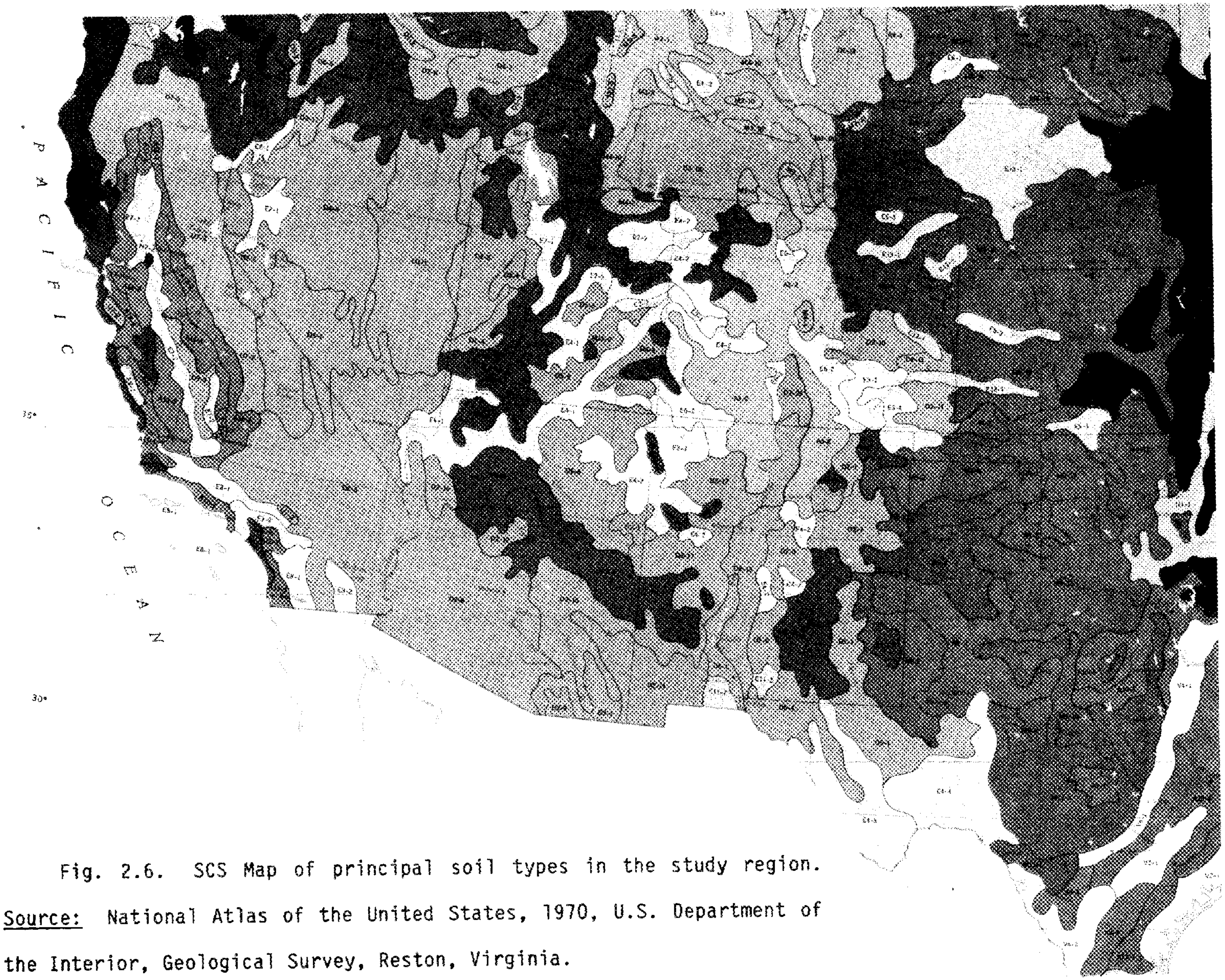


Fig. 2.6. SCS Map of principal soil types in the study region.

Source: National Atlas of the United States, 1970, U.S. Department of the Interior, Geological Survey, Reston, Virginia.

Table 2.1. Soils in the study region

| Map | Orders/definitions | Suborders with definitions | Great groups[a,b] |
|---|---|---|---|
| A | ALFISOLS: Soils that are medium to high in bases (base saturation at pH 8.2) and have gray to brown surface horizon and subsurface horizons of clay accumulation; usually moist, but during the warm season of the year some are dry part of the time. | BORALFS-Alfisols of cool to cold regions; used for woodland, pasture, and some small grain. | Cryoboralfs-Boralfs of cold regions. (A3-2) |
| | | USTALFS-Alfisols that are in temperate to tropical regions. Soils mostly reddish brown; during the warm season of the year, they are intermittently dry for long periods; used for range, small grain, and irrigated crops. | Haplustalfs-Ustalfs that have a subsurface horizon of clay accumulation that is relatively thin or is brownish. (A9-2,4,5) |
| | | XERALFS-Alfisols that are in climates with rainy winters but dry summers; during the warm season of the year these soils are continually dry for a long period; used for range, small grain, and irrigated crops. | Durixeralfs-Xeralfs that have a hardpan (duripan) that is cemented with silica. (A11-1) |
| | | | Haploxeralfs-Xeralfs that have a subsurface horizon of clay accumulation that is relatively thin or is brownish in color. (A12-1,2,3) |
| | | | Palexeralfs-Xeralfs that have an indurated (petrocalcic) horizon |

Table 2.1. (continued)

| Map | Orders/definitions | Suborders with definitions | Great groups[a,b] |
| --- | --- | --- | --- |
| A | ALFISOLS (Cont.) | | cemented by carbonates or a horizon having one of both of the following: a thick reddish clay accumulation or a distribution that is clayey in the upper part and abruptly changes in texture into an overlying horizon. (A13-1) |
| D | ARIDISOLS: Soils that have pedogenic horizons, are low in organic matter, and are never moist as long as 3 consecutive months. | ARGIDS-Aridisols that have a horizon in which clay has accumulated with or without alkali (sodium); used for mostly range and some irrigated crops. | Duragrids-Argids that have a hardpan (duripan) that is cemented with silica. (D1-1) |
| | | | Haplargids-Argids that have a loamy horizon of clay accumulation with or without alkali (sodium). (D2-1 through 5,7 through 18, 20) |
| | | | Natrargrids-Argids that have a horizon of clay and alkali (sodium) accumulation. (D3-3,4) |
| | | ORTHIDS-Aridisols that have accumulations of calcium carbonate, gypsum, or salts more soluble than gypsum but have no horizon of accumulation of clay; may have | Calciorthids-Orthids that have a horizon in which large amounts of calcium carbonate or gypsum have accumulated. (D5-1,4,5,6) |

Table 2.1. (continued)

| Map | Orders/definitions | Suborders with definitions | Great groups[a,b] |
|---|---|---|---|
| D | ARIDISOLS (Cont.) | horizons from which some materials have been removed or altered; used altered; used for mostly range and some irrigated crops. | Camborthids-Orthids that have been removed or altered but have no accumulation of large amounts of calcium carbonate or gypsum. (D6-1,3,5,6) |
| E | ENTISOLS: Soils that have no pedogenic horizons. | FLUVENTS-Entisols that have organic-matter content that decreases irregularly with depth; formed in loamy or clayey alluvial deposits; used for range or irrigated crops in dry regions and for general farming in humid regions. | Torrifluvents-Fluvents that are never moist as long as 3 consecutive months. (E2-1,2) |
| | | ORTHENTS-Loamy or clayey Entisols that have a regular decrease in organic-matter content with depth; used for range or irrigated crops in dry regions and for general farming in humid regions. | Torriorthents-Orthents that are never moist as long as 3 consecutive months. (E3-1,2,3,4) |
| | | | Torriorthents (shallow)-Torriorthents that are shallower than 51 cm (20 in.) to bedrock. (E4-1,2,4,5) |
| | | | Ustorthents (shallow)-Orthents that during the warm season of the year are intermittently dry for long periods and that are shallower than 51 cm (20 in.) to bedrock. (E6-2,3) |

Table 2.1. (continued)

| Map | Orders/definitions | Suborders with definitions | Great groups[a,b] |
|---|---|---|---|
| E | ENTISOLS (Cont.) | | Xerorthents-Orthents that are in climates with rainy winters but dry summers; during the warm season of the year, they are continually dry for a long period. (E7-1,2) |
| | | | Xerorthents (shallow)-Xerorthents that are shallower than 51 cm (20 in.) to bedrock. (E8-1) |
| | | PSAMMENTS-Entisols that have textures of loamy fine sand or coarser; used for woodland and small grains where warm and moist, and range and irrigated crops where warm and dry. | Torripsamments-Psamments that contain easily weatherable minerals; they are never moist as long as 3 consecutive months. (E11-2) |
| | | | Ustipsamments-Psamments that contain easily weatherable minerals; during the warm season of the year, they are intermittently dry for long periods. (E13-1) |

Table 2.1. (continued)

| Map | Orders/definitions | Suborders with definitions | Great groups[a,b] |
|---|---|---|---|
| M | MOLLISOLS: Soils that have nearly black friable organic-rich surface horizons high in bases; formed mostly in subhumid and semiarid warm to cold climates. | BOROLLS-Mollisols of cool and cold regions. Most Borolls have a black surface horizon; used for range, woodland, and some small grains in western states. | Argiborolls-Borolls of cool regions; they have a subsurface horizon in which clay has accumulated. (M3-5,10) |
| | | | Cryoborolls-Borolls of cold regions. (M4-1,2) |
| | | USTOLLS-Mollisols that are mostly in semiarid regions. During the warm season of the year, these soils are intermittently dry for a long period or have subsurface horizons in which salts or carbonates have accumulated; used for wheat or small grains and some irrigated crops. | Argiustolls-Ustolls that have a subsurface horizon of clay accumulation that is relatively thin or is brownish. (M9-2 through 9, 11,14,15,17,18,19) |
| | | | Calciustolls-Ustolls that are calcareous throughout and have either an indurated (petrocalcic) horizon cemented by carbonates or a horizon in which calcium carbonate or gypsum has accumulated. (M10-1) |
| | | | Calciustolls (shallow)-Calciustolls that are shallower than 51 cm (20 in.) to bedrock. (M11-1,2) |

Table 2.1. (continued)

| Map | Orders/definitions | Suborders with definitions | Great groups[a,b] |
|---|---|---|---|
| M | MOLLISOLS (Cont.) | | Haplustolls-Ustolls that have a subsurface horizon high in bases but without large accumulations of clay, calcium carbonate, or gypsum. (M12-1,3) |
| | | | Haplustolls (shallow)-Haplustolls that are shallower than 51 cm (20 in.) to bedrock. (M13-1,2) |
| | | XEROLLS-Mollisols that are in climates with rainy winters but dry summers; during the warm season of the year, these soils are continually dry for a long period; used for wheat, range, and irrigated crops. | Argixerolls-Xerolls that have a subsurface horizon of clay accumulation that is relatively thin or is brownish. (M15-2,3, 5,8,9,11,12) |
| | | | Haploxerolls-Xerolls that have a subsurface horizon high in bases but without large accumulations of clay, calcium carbonate, or gypsum. (M16-1,4,6) |
| U | ULTISOLS: Soils that are low in bases and have subsurface horizons of clay accumulation; usually moist, but during the warm season of the year, some are dry part of the time. | XERULTS-Ultisols that are relatively low in organic matter in the subsurface horizons; they are in climates with rainy winters but dry summers; during the warm season of the year, these soils are continually dry for a long period; used for range and woodland. | Haploxerults-Xerults that either have a subsurface horizon of clay accumulation that is relatively thin, a subsurface horizon having appreciable weatherable minerals, or both. (U7-2) |

Table 2.1. (continued)

| Map | Orders/definitions | Suborders with definitions | Great groups[a,b] |
|---|---|---|---|
| V | VERTISOLS: Clayey soils that have wide, deep cracks when dry; most have distinct wet and dry periods throughout the year. | USTERTS-Vertisols that have wide, deep cracks that usually open and remain open intermittently for periods that total more than 3 months but do not remain open continuously throughout the year; used for general crops and range plus some irrigated cotton, corn, citrus, and truck crops in the Rio Grande valley. | Pelluserts-Usterts that have a black or dark gray surface horizon. (V4-2) |
| X | MISCELLANEOUS LAND TYPES-Barren or nearly barren areas that are mainly rock, ice, or salt and some included soils; mostly not used for crops, but some in warm, moist climates have vegetation. | | Salt flats and playas, gently sloping. (X5) |

Source: USGS, 1970, The National Atlas of the United States, U.S. Department of Interior, Geological Survey, Reston, Virginia.

[a]In addition, there are Great Groups that are not listed on the map because they are not the most extensive soil in any map unit.

[b]Letters and numbers after Great Groups correspond to symbols on Fig. 2.6.

argillia horizons, may occur as relics that originated under more humid conditions (Tucker and Fuller 1971).

In arid regions the major soil characteristics that affect plant growth are moisture availability, salinity, and nutrient availability. Soil type and topography modify the precipitation patterns by influencing runoff and infiltration, so that depressions and low-lying areas typically receive more water than the amount of precipitation. Coarse-textured soils generally provide the most favorable moisture conditions for plant growth due to their greater capacity for infiltration and storage.

A climatic regime of low precipitation and high evaporation tends to cause accumulations in surface soil layers of soluble salts and other materials (Fuller 1974, Kovda et al. 1979). Such accumulations are commonly associated with poor drainage conditions when clay pans or hardened horizons are present, with migrating saline groundwater, or with poor irrigation practices. Under semiarid or steppe conditions with increased precipitation and greater density of vegetation, the geochemical processes that result in soil salinity and alkalinity tend to be eliminated. The effects of soil salinity on plant growth are varied and depend on the quantity and types of salts present and on the tolerances of the plant species. Salinity can effect plant growth through specific ion inhibition of nutrition, toxicity, and physiological dryness induced by various mechanisms, including osmotic pressure (Fuller 1974).

Arid soils have a relatively ample supply of plant nutrients if such nutrients are present in the parent materials (Smith 1968).

Nitrogen, however, is generally deficient due to a paucity of organic matter. The nitrogen that is present results from mineralization in response to repeated cycles of wetting and drying. Microorganisms can become active after a period of rain that is too slight to allow growth of higher plants. This microbial activity in the absence of nitrogen uptake by plants causes the accumulation of inorganic nitrogen that can be used by higher plants when rainfall sufficient for their growth occurs (Kovda et al. 1979).

Bajadas, alluvial fans or outwash slopes, are common characteristics in the basin and range physiographic region (Fig. 2.2). Drainage from mountains carries eroded material that is deposited in progressively finer sequences from the mouths of canyons or arroyos. Relatively stable bajadas may exhibit advanced soil formation (MacMahon 1979). The coarser-grained soils and underlying deposits on the upper slopes of bajadas tend to support a rich flora due to infiltration of runoff water (Benson and Darrow 1981).

## 2.4 VEGETATION

### 2.4.1 Ecology

Marked variations in elevation, physiography, topography, drainage, temperature, precipitation, evaporation, and soil type are responsible for the pronounced diversity in the vegetation of the Southwest. Plant communities in the region include chaparral, cold desert and semidesert, hot desert, bushland, ecotone woodland, montane forest, alpine, and northern and southern temperate grassland (Shelford 1974). Küchler's potential natural vegetation types in the study region are shown in Fig. 2.7 (with a key in Table 2.2).

R. G. Bailey has developed an ecological classification and characterization of natural regions based on regional climate, zonal soils, and climatic climax vegetation (Bailey 1976, 1980). His purpose was to identify areas for which ecological relationships between plant species, soil, and climate were essentially similar and for which similar management treatments would, therefore, produce comparable results. Thus, all the land in one natural region would have a similar biological productivity and a specific potential that is characteristic of that area. The ecoregions are classified in a hierarchy, from the most to the least inclusive, as domains, divisions, provinces, and section. Bailey's sections correspond closely with the potential natural vegetation types of Küchler (1964). In the publication to accompany the map (Bailey 1980), each province is described according to land-surface form, climate, soils, vegetation, and fauna. The study region section of the ecoregion map is included as Fig. 2.8, with the map codes identified in Table 2.3.

The percent of natural vegetation remaining in each state in the study region varies from a high of 96% for Nevada to a low of 56% for Oklahoma (Table 2.4) (Klopatek et al. 1979). These values are much higher, in general, than in other sections of the country and suggest that much of the land in the Southwest still supports natural plant communities. Therefore, Fig. 2.7 can be used as a general

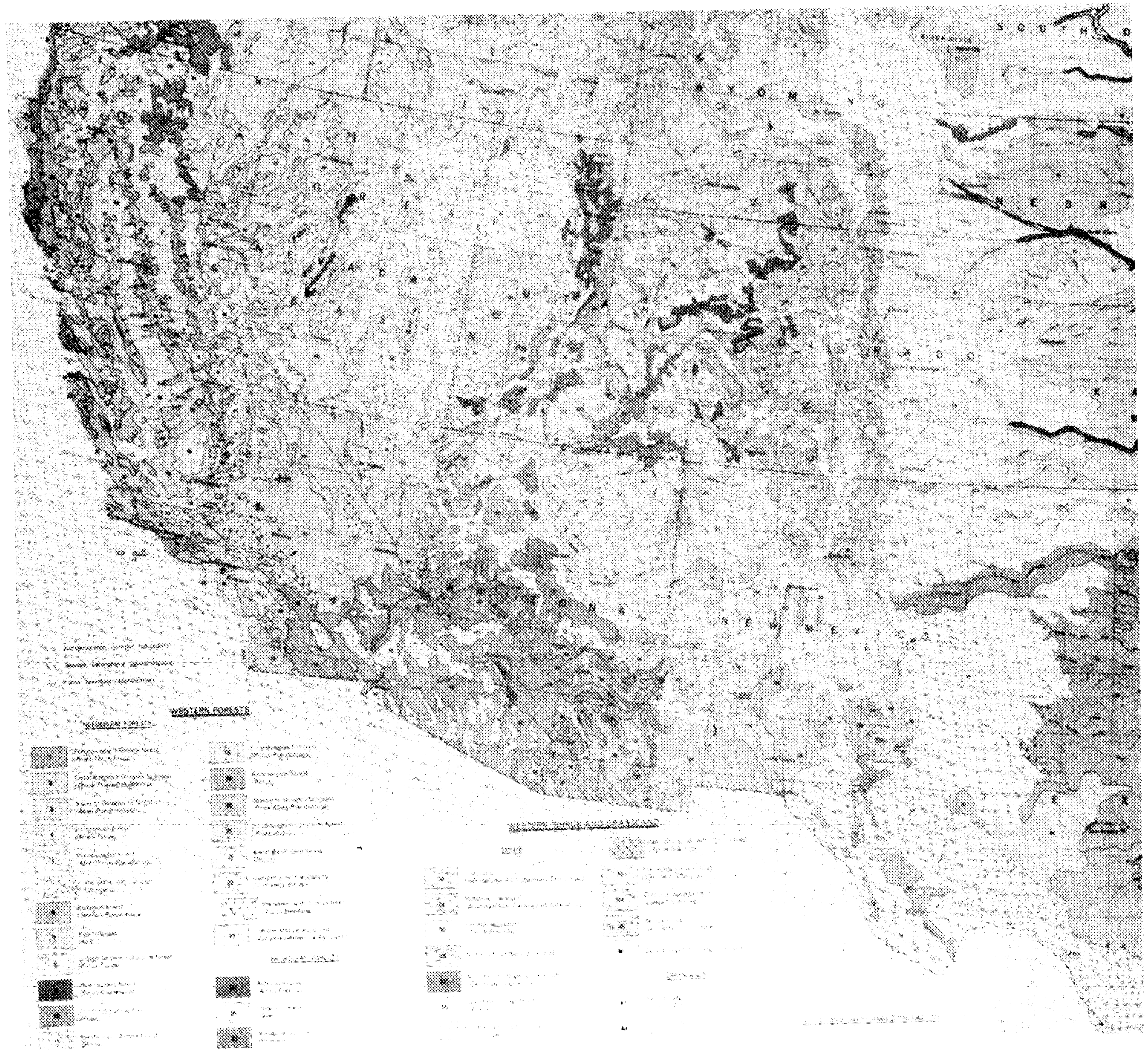


Fig. 2.7. Küchler map of potential natural vegetation in the study region. <u>Source</u>: A. W. Küchler, 1966, Potential natural vegetation (Map), Scale 1:7,500,000, Sheet no. 90, IN USGS 1970, The National Atlas of the United States, U.S. Department of the Interior, Geological Survey, Reston, Virginia.

Table 2.2. Küchler vegetation types occurring in the study region

| Group of types | Map unit number | Map unit name |
|---|---|---|
| Western forests | 5 | Mixed conifer forest (*Abies-Pinus-Pseudotsuga*) |
| | 7 | Red fir forest (*Abies*) |
| | 8 | Lodgepole pine-subalpine forest (*Pinus-Tsuga*) |
| | 10 | Western ponderosa forest (*Pinus*) |
| | 11 | Douglas-fir forest (*Pseudotsuga*) |
| | 14 | Western spruce-fir forest (*Picea-Abies*) |
| | 17 | Pine-Douglas-fir forest (*Pinus-Pseudotsuga*) |
| | 18 | Arizona pine forest (*Pinus*) |
| | 19 | Spruce-fir-Douglas-fir forest (*Picea-Abies-Pseudotsuga*) |
| | 20 | Southwestern spruce-fir forest (*Picea-Abies*) |
| | 21 | Juniper-pinyon woodland (*Juniperus-Pinus*) |
| | 26 | California oakwoods (*Quercus*) |
| | 27 | Oak-juniper woodland (*Quercus-Juniperus*) |
| | 28 | Transition between 27 and 31 |
| Western shrub | 29 | Chaparral (*Adenostoma-Arctostaphylos-Ceanothus*) |
| | 30 | Coastal sagebrush (*Salvia-Eriogonum*) |
| | 31 | Mountain mahogany-oak scrub (*Cercocarpus-Quercus*) |
| | 32 | Great Basin sagebrush (*Artemisia*) |
| | 33 | Blackbrush (*Coleogyne*) |
| | 34 | Saltbush-greasewood (*Atriplex-Sarcobatus*) |
| | 35 | Creosote bush (*Larrea*) |
| | 36 | Creosote bush-bur sage (*Larrea-Franseria*) |
| | 37 | Paloverde-cactus shrub (*Cercidium-Opuntia*) |
| | 38 | Ceniza shrub (*Leucophyllum-Larrea-Prosopis*) |
| Desert | 39 | Desert: vegetation largely absent |
| Western grassland | 41 | California steppe (*Stipa*) |
| | 42 | Tule marshes (*Scirpus-Typha*) |
| | 44 | Wheatgrass-bluegrass (*Agropyron-Poa*) |
| | 45 | Alpine meadows & barren (*Agrostis, Carex, Festuca, Poa*) |
| | 46 | Fescue-mountain muhly prairie (*Festuca-Muhlenbergia*) |
| | 47 | Grama-galleta steppe (*Bouteloua-Hilaria*) |
| | 48 | Grama-tobosa prairie (*Bouteloua-Hilaria*) |
| Western shrub and grassland | 49 | Sagebrush steppe (*Artemisia-Agropyron*) |
| | 51 | Galleta-three awn shrubsteppe (*Hilaria-Aristida*) |
| | 52 | Grama-tobosa shrubsteppe (*Bouteloua-Hilaria-Larrea*) |
| | 53 | Trans-Pecos shrub savanna (*Flourensia-Larrea*) |
| | 54 | Mesquite-acacia-savanna (*Andropogon*) |

Table 2.2. (continued)

| Group of types | Map unit number | Map unit name |
| --- | --- | --- |
| Central grassland | 58 | Grama-buffalo grass (Bouteloua-Buchlöe) |
| | 62 | Bluestem-grama prairie (Andropogon-Bouteloua) |
| | 63 | Sandsage-bluestem prairie (Artemisia-Andropogon) |
| | 64 | Shinnery (Quercus-Andropogon) |
| Central grassland and forest | 76 | Mesquite-buffalo grass (Boueloua-Buchlöe-Prosopis) |
| | 77 | Juniper-oak savanna (Andropogon-Quercus-Juniperus) |

Source: A. W. Küchler, 1966, Potential natural vegetation (Map), Scale 1:7,500,000, Sheet number 90, IN USGS 1970, The National Atlas of the United States, U.S. Department of Interior, Geological Survey, Reston, Virginia

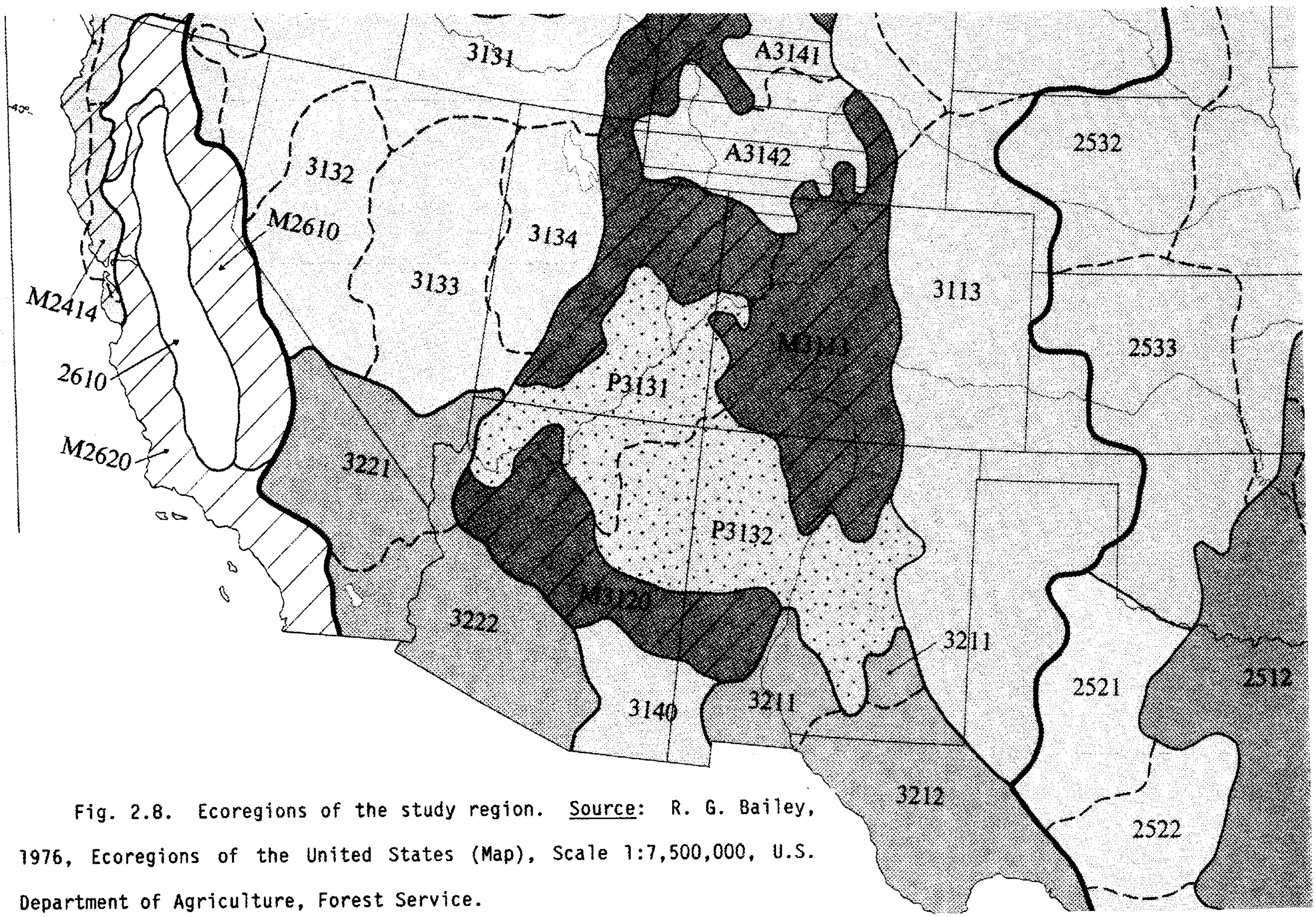


Fig. 2.8. Ecoregions of the study region. <u>Source</u>: R. G. Bailey, 1976, Ecoregions of the United States (Map), Scale 1:7,500,000, U.S. Department of Agriculture, Forest Service.

Table 2.3. Ecoregions included in the study region

| | | Lowland ecoregions | | Highland ecoregions[a] | |
|---|---|---|---|---|---|
| Domain | Division | Province | Section | Province | Section |
| 2000 Humid Temperate | 2500 Prairie | 2520 Prairie brushland | 2521 Mesquite-buffalo grass<br>2522 Juniper-oak-mesquite | | |
| | | 2530 Tall-grass prairie | 2523 Mesquite-acacia<br>2533 Bluestem-grama prairie | | |
| | 2600 Mediterranean (dry-summer subtropical) | 2610 California grassland | | M2610 Sierran forest<br>M2620 California chaparral | |
| 3000 Dry | 3100 Steppe | 3110 Great Plains short-grass prairie | 3113 Grama-buffalo grass | M3110 Rocky Mountain forest<br>M3120 Upper Gila Mountains forest | M3112 Douglas-fir forest<br>M3113 Ponderosa pine-Douglas-fir forest |
| | | 3130 Intermountain sage-brush | 3131 Sagebrush-wheatgrass<br>3132 Lahontan saltbush-greasewood<br>3133 Great Basin sage-brush<br>3134 Bonneville saltbush-greasewood<br>3135 Ponderosa shrub forest | P3130 Colorado plateau | P3131 Juniper-pinyon wood-land + sagebrush-saltbush mosaic<br>P3132 Grama-galleta steppe + juniper-pinyon woodland mosaic |
| | | 3140 Mexican highlands shrub steppe | | A3140 Wyoming basin | A3142 Sagebrush-wheatgrass |
| | 3200 Desert | 3210 Chihuahuan desert | 3211 Grama-tobosa<br>3212 Tarbush-creosote bush | | |
| | | 3220 American desert (Mojave-Colorado-Sonoran) | 3221 Creosote bush<br>3222 Creosote bush-bur sage | | |

[a]Key to letter symbols: M, mountains; P, plateau; A, altiplano.

Table 2.4. Percent of natural vegetation remaining in each state in the study region

| State | Natural vegetation remaining (%) |
|---|---|
| Nevada | 96 |
| New Mexico | 95 |
| Arizona | 93 |
| Utah | 93 |
| California | 78 |
| Colorado | 77 |
| Texas | 66 |
| Oklahoma | 56 |

Source: J. M. Klopatek, R. J. Olson, C. J. Emerson, and J. L. Jones, 1979, Table 3 IN Land-use conflicts with natural vegetation in the United States, ORNL/TM-6814, Oak Ridge National Laboratory, Oak Ridge, Tennessee.

approximation of the existing vegetation there. However, many specific types of natural vegetation are uncommon in the study region. For example, in the grassland area of eastern Colorado, predisturbance plant communities are rare, although some unplowed mesa tops, steep hillsides, and floodplains retain native grasses (Mutel and Emerick 1984).

Plant communities in the region exhibit pronounced patterns of zonation along elevational gradients as a result of moisture and temperature changes related to altitude (Mutel and Emerick 1984). These life zones are modified or influenced by aspect, soils, and latitude. Boundaries between adjacent plant zones, however, are rarely distinct. The transitional areas, or ecotones, are characterized by a mixture of plant species from two or more ecosystems.

The highest and lowest elevations are typically dominated by herbs and grasses (Mutel and Emerick 1984). In general, trees are excluded from the highest elevations by cold, drought, and wind and from the lowest elevations by drought. Most of the mountain forests are dominated by needle-leaved conifers, with the specific dominants changing as altitude changes. Most broad-leaved deciduous trees are limited to sites next to bodies of water.

In addition to altitudinal differences, the composition and productivity of plant communities in arid regions vary temporally and spatially with patterns of both climate and soil. The vegetation in the Southwest may change perceptibly as a result of natural climatic variation and change (Hastings and Turner 1965, Johnson 1968). For example, recent droughts have resulted in widespread death of major dominants in the oak-juniper woodland type in Texas and in the pinyon pine-juniper woodlands in New Mexico and Arizona (Darrow 1958).

Grasses and/or shrubs are the prominent life forms in much of the study region. In relatively undisturbed grasslands, most species are perennials and typically have most of their structure underground (Mutel and Emerick 1984), because extensive root systems are essential for vigorous growth. Most grassland species are either drought tolerant or avoid drought altogether by becoming dormant. Perennial shrubs often have massive, deep root systems that use moisture from a greater volume of soil than most grass species (Goodin and McKell 1971).

Fires were once an important component of grassland ecosystems. Extensive areas of the Southwest that were apparently dominated by grasses in prehistoric times today support shrubs or low-growing trees (Humphrey 1958, Cox et al. 1983, Herbel 1979). Since fires have been controlled, plant competition, rodents, rabbits, and the introduction of domestic livestock have favored woody plants at the expense of grasses. Had fires continued to occur with their former frequency, the desert grassland would probably be similar today to what it was in prehistoric times, that is, a subclimax maintained by fire (Humphrey 1958).

### 2.4.2 Physiology

The vegetation of arid regions throughout the world tends to be different in taxonomic composition yet similar in form and function.

Certain families (e.g., Chenopodiaceae) and genera (e.g., Acacia) are represented in most desert regions; many others are more restricted. However, similar features of physiology, anatomy, and behavior have developed in parallel. For example, the adaptation of succulence for water storage is similar in the Euphorbiaceae in Africa and the Cactaceae in America (McGinnies 1979).

Net primary plant production in arid regions is generally low. Noy-Meir (1973) reports average annual net aboveground primary production in arid and semiarid regions of 30-200 and 100-600 $g/m^2$, respectively. Belowground production is estimated at 100-400 and 250-1000 $g/m^2$ in arid and semiarid communities. At the other extreme, aboveground net primary production of 2400 $g/m^2$ was reported for a tulip tree forest in the Appalachians (Whittaker 1966).

Shoot biomass varies from year to year at the same site (Sims and Coupland 1979). In areas with low rainfall, year-to-year variations in biomass production depend more on amount of precipitation during the growing season than on any other environmental factor. The effectiveness of precipitation for plant productivity is related to the seasonality, regularity, intensity, and duration of its occurrence and to the slope, aspect, surface texture, soil depth, and ionic composition of the receiving surface. In general, as precipitation increases, the relative importance of these site-specific factors also increases (Lauenroth 1979).

Vegetation of arid regions has been categorized as drought-evading, drought-escaping, drought-resistant, and drought-enduring in recognition of numerous mechanisms to effectively utilize available water (McCleary 1968). These mechanisms include brief life cycles, restriction to moist sites, enhanced water uptake and translocation, regulatory controls on water loss, water storage organs, extensive root systems, shedding of leaves and stems, tolerance of dehydration, and reduced photosynthesis rates during dry periods.

Ephemeral annual plants in deserts exhibit phenological, physiological, and morphological adaptations depending upon the seasonal regimes of moisture and temperature (Mulroy and Rundel 1977). Because the rainy seasons tend to be short and somewhat unpredictable, most grasses and forbs tend to grow and set seed rapidly. In the Mojave and western Sonoran deserts, where maximum precipitation occurs in the winter and late fall, winter annuals that germinate and complete their life cycles during the winter and spring predominate. In the eastern and southern Sonoran desert, where there is significant and predictable summer precipitation, a diverse flora of summer annual species is found. Also, as latitude (degrees north) increases, more of the plant species are of the cool-season type (French 1979).

Winter and summer annuals tend to have different photosynthetic pathways, the winter annuals usually being Calvin or $C_3$ cycle species, while the summer annuals typically have the $C_4$-dicarboxylic acid pathway. The maximum photosynthetic rate is achieved at a temperature range of 10-25°C for $C_3$ plants and 30-45°C for $C_4$ plants (French 1979). The $C_4$ pathway for photosynthesis allows plants to fix high rates of $CO_2$ with a much lower internal concentration of $CO_2$ and a relatively restricted stomatal opening

Arnon 1975). Hence, $C_4$ species require about half as much water per unit of biomass produced (French 1979). A number of succulent plants keep their stomata closed during most of the day and use a third photosynthetic method, Crassulacean acid metabolism (CAM), that enables them to fix large amounts of $CO_2$ as organic acids at night and convert them into carbohydrates during the day (Arnon 1975). The lower temperatures that occur at night when the primary assimilation of $CO_2$ occurs allow CAM plants to limit the amount of water transpired for a given stomatal opening. Thus, both $C_4$ and CAM species are very efficient in their water use.

Plants have also been classified according to their tolerance to both drought and salts (Walter and Stadelmann 1974). Mesophytes include those plants with niches in which drought and salt stress are largely absent (e.g., phreatopytes and drought-evading ephemerals). Xerophytes include nonhalophytic, drought-enduring plants, such as succulents with water storage organs. Halopytes are distinctively salt-tolerant plants that absorb and accumulate salts in the cell sap, particularly in transpiring tissues (e.g., leaves), thereby compensating for the osmotic potential of the soil solution (Reimold and Queen 1974). True halophytes grow best in salt solutions, whereas salt-tolerant plants grow best on nonsaline soils. A distinction is made between halophytes that grow in locations of more or less continuously wet salt soils (hygro-halophytes) and those that grow on more well-drained sites (xerohalophytes). Further distinctions are made for chloride halopytes, sulfate halophytes, alkaline halophytes, and desalting halophytes.

## 2.5 LAND USE AND MANAGEMENT: PAST AND PRESENT

Land use during historic time has resulted in drastic changes in the patterns of biotic communities in the Southwest. Original plant productivity has been reduced over large areas by grazing abuses, brush invasion, droughts, and attempts to cultivate nonarable land (Herbel 1979). Natural succession is being prevented in many places by current land uses (Mutel and Emerick 1984). Climatic fluctuations that produce wind and drought cannot be prevented, but short-sighted grazing and agricultural practices can (Mutel and Emerick 1984). Each site has different characteristics and objectives and must be managed accordingly (Herbel 1979). Long-term productive cultivation is possible in some areas of the Southwest if farming practices are carefully matched to soil and climatic conditions. Most of the severe damage to croplands and to rangelands occurs during droughts, and farming and grazing systems must be highly flexible to adjust to yearly fluctuations in weather and plant growth. The challenge for the manager is to find the proper balance between the biological realities of the site and the demand for food and other products by the rapidly growing world population (Herbel 1979).

Figure 2.9 is a map of the Major Land Resource Areas (MLRAs) within the study region as delineated by the SCS (USDA/SCS 1981). Table 2.5 identifies the map units. The land resource regions within the study area are quite variable. They include the California subtropical fruit, truck, and specialty crop region, various regions where irrigated farming occurs, desert areas, and places where cotton is grown (Table 2.5).

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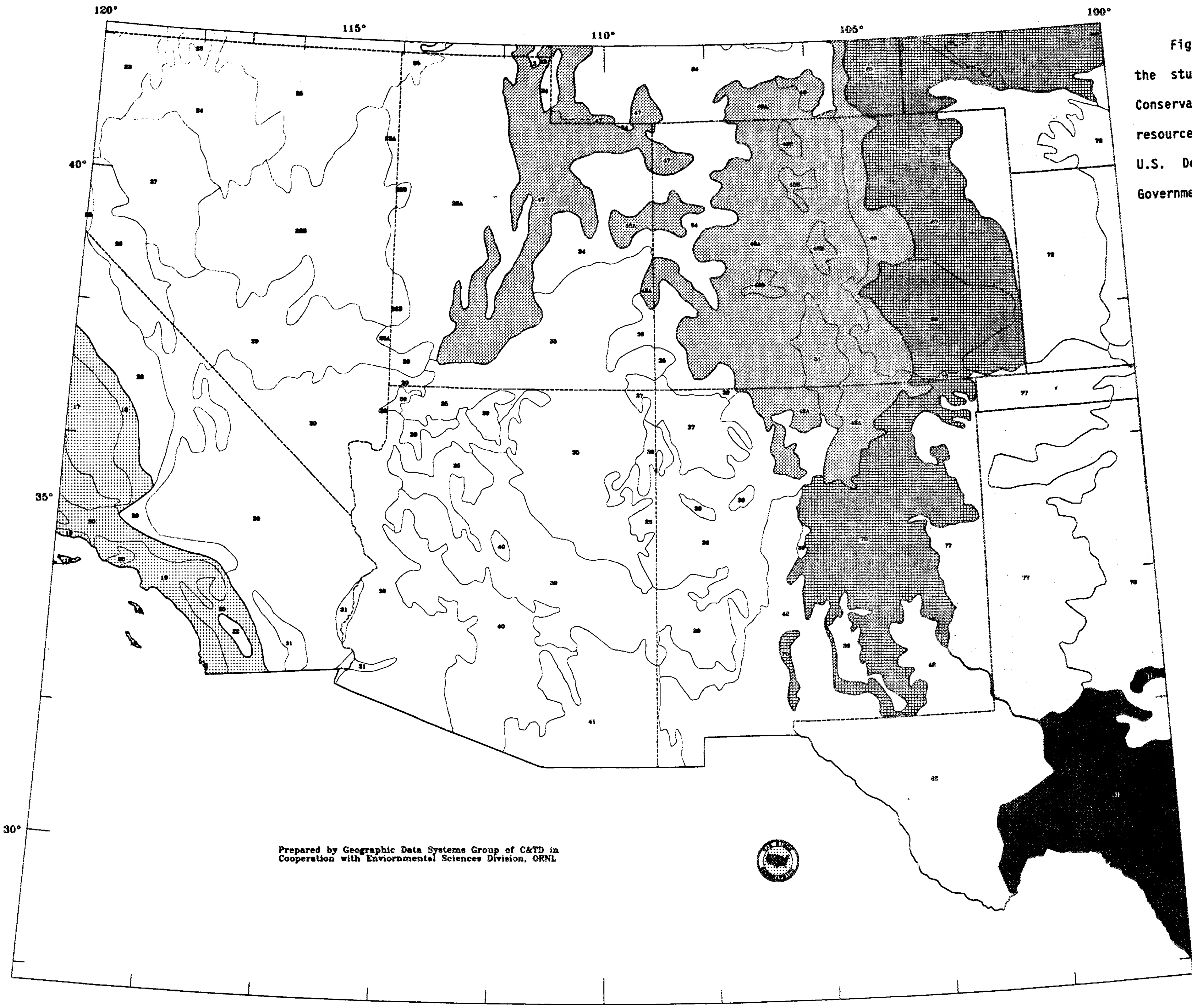


Fig. 2.9. Land resource regions and major land resource areas in the study region. Source: U.S. Department of Agriculture, Soil Conservation Service, 1981, Land resource regions and major land resource areas of the United States, rev., Agriculture Handbook 296, U.S. Department of Agriculture, Soil Conservation Service, U.S. Government Printing Office, Washington, D.C.

Table 2.5. Land resource regions and major land resource areas (MLRAs) included in the study region

| Map | Code | Region and area |
|---|---|---|
| C | | California subtropical fruit, truck, and specialty crop region |
| | 15 | Central California coast range |
| | 17 | Sacramento and San Joaquin valleys |
| | 18 | Sierra Nevada foothills |
| | 19 | Southern California coastal plain |
| | 20 | Southern California mountains |
| D | | Western range and irrigated region |
| | 22 | Sierra Nevada Range |
| | 23 | Malheur High Plateau |
| | 24 | Humboldt Area |
| | 25 | Owyhee High Plateau |
| | 26 | Carson basin and mountains |
| | 27 | Fallon-Lovelock Area |
| | 28A | Great Salt Lake Area |
| | 28B | Central Nevada basin and range |
| | 29 | Southern Nevada basin and range |
| | 30 | Sonoran basin and range |
| | 31 | Imperial Valley |
| | 34 | Central Desertic basin, mountains, and plateaus |
| | 35 | Colorado and Green river plateaus |
| | 36 | New Mexico and Arizona plateaus and mesas |
| | 37 | San Juan River Valley mesas and plateaus |
| | 39 | Arizona and New Mexico mountains |
| | 40 | Central Arizona basin and range |
| | 41 | Southeastern Arizona basin and range |
| | 42 | Southern Desertic basins, plains, and mountains |
| E | | Rocky Mountain range and forest region |
| | 47 | Wasatch and Uinta mountains |
| | 48A | Southern Rocky Mountains |
| | 48B | Southern Rocky Mountain parks |
| | 49 | Southern Rocky Mountain foothills |
| | 51 | High intermountain valleys |
| G | | Western Great Plains range and irrigated region |
| | 67 | Central High Plains |
| | 69 | Upper Arkansas Valley rolling plains |
| | 70 | Pecos-Canadian plains and valleys |

Table 2.5. (continued)

| Map | Code | Region and area |
| --- | --- | --- |
| H | | Central Great Plains range and irrigated region |
| | 72 | Central high tableland |
| | 77 | Southern High Plains |
| | 78 | Central rolling red plains |
| I | | Southwest Plateaus and plains range and cotton region |
| | 81 | Edwards Plateau |
| | 83B | Western Rio Grande Plain |

Vegetation management requires detailed and accurate information obtained from natural resource inventories. Integrated information on climatic and edaphic variables affecting plant growth and composition of plant communities is especially important for managing arid and semiarid ecosystems. In particular, information both on precipitation variability and water catchment characteristics and on practical methods of inventorying and monitoring vegetation dynamics of arid lands are needed (Lund et al. 1981). The challenge is enhanced by the fact that, in such regions, vegetation floristics and productivity can change seasonally and annually in response to variations in the amount and distribution of available moisture.

### 2.5.1 Livestock Grazing

Before 1600, bison were common in all the grasslands of North America except in California (Herbel 1979). Although they devastated much of the aboveground vegetation in their path, the herds would eventually move on. The grassland ecosystems were adapted to this form of grazing, and plant recovery was relatively rapid. Since the root systems were left intact, the grasses quickly resprouted, and little soil damage occurred (Mutel and Emerick 1984).

Many of these grassland areas are still grazed, but cattle have replaced bison (Mutel and Emerick 1984). Domestic livestock raising in the Southwest dates back to about 1500 (Humphrey 1958). From 1890 to 1980, wet periods with abundant forage were followed by overstocking, while drought periods were followed by livestock reductions (Herbel 1979, Cox et al. 1983). With each successive cycle, perennial grass productivity declined, and the rangeland supported fewer livestock.

Where grazing is not too intense, plant cover remains, but species composition is altered dramatically because cattle preferentially remove tall grasses and native forbs. With overgrazing, root development is severely retarded, leading to lower forage production and a decreased ability to withstand harsh climatic conditions. Further grazing pressures cause an increase in the numbers of weedy and drought-resistant species such as cacti and yucca and also decrease the incidence of prairie fires. Intensive grazing can eventually remove the protective grass cover and expose soils to wind and water erosion. Recovery following drought is much lower and slower on ranges that are consistently heavily utilized than on those that are used moderately (Cable and Martin 1975). Even with moderate use, it takes two years for perennial grass production in semidesert grass-shrub lands to recover from a one-year drought. However, when properly managed, grazing is the only major land use that permits some native plant species to remain, thus protecting soil from wind and water erosion and feeding and sheltering native wildlife as these ecosystems have done for centuries (Mutel and Emerick 1984).

The vegetation on some rangelands has improved since the early 1900s (Herbel 1979), after cooperative research was begun in the 1890s to determine the feasibility of reseeding native and introduced forage species to restore rangelands. Such revegetation is difficult and costly, but not impossible. In general, successful plantings are limited to irrigated plots (Cox et al. 1982). Most sites will show substantial increases in native forage production if plant competition is reduced, dead standing litter remains in place after treatment, and grazing is excluded or reduced, but no single seedbed treatment has been shown to be superior to any other at all locations and in all years. Some recommendations for seeding rangelands are based on premature results, infrequent observations, poorly conducted experiments, and data collected at atypical sites or in atypical years. Data integration to determine the number of days when air temperature exceeds 21°C and soil moisture is available may be more useful in selecting species for seeding rangelands than the commonly used parameters of elevation, precipitation, frost-free days, and season of precipitation (Cox et al. 1982).

Livestock raising in the Southwest is not restricted to the grasslands. Domestic livestock have been grazed in pinyon-juniper woodlands for more than 200 years (Springfield 1976, Mutel and Emerick 1984). While these woodland areas can offer excellent long-term grazing, livestock must be managed properly to prevent damage from overgrazing. Many woodlands overgrazed half a century ago still have not recovered.

### 2.5.2 Farming

Farming in arid and semiarid areas can lead to much damage because the land is often unsuited for crop production (Mutel and Emerick 1984). When the natural plant cover is destroyed, the land becomes subject to erosion that can be so severe as to interfere seriously with revegetation after farming is abandoned (Herbel 1979). Removal of the grass cover and excessive cropping can also result in reduction of water quality and flow stability and in increased aridness of sites.

Irrigated agriculture expanded rapidly in much of the Southwest in this century. From 1930 to 1960, irrigated farmland in southeastern Arizona rose from 353,703 to 954,508 ha (874,000 to 2,358,590 acres) (Cox et al. 1983). However, by 1980 the total had dropped to 164,869 ha (407,390 acres). During periods of maximum cultivation in each of the five counties in southeastern Arizona, about 1.05 million ha (2.6 million acres) were cultivated with irrigation. It is estimated that 890,000 ha (2.2 million acres) of irrigated farmland have been abandoned there in the past 40 years.

Some of the farmland in southern Arizona was abandoned because of urban growth (Cox et al. 1983). Other irrigated land was abandoned because of urban water demands. As urban demand for water increases, water will continue to be diverted from agricultural uses and more farmland will be abandoned (Cox et al. 1983). This abandoned farmland might be able to support nonirrigated biomass energy crops.

### 2.5.3 Other Land Uses

Land in the Southwest has been put to many uses, both by Indians in prehistoric times and by non-Indian settlers in recent times. Trees have been used for building houses and other structures, for charcoal, for fence posts, for firewood, for Christmas trees, and for furniture

(Arnold et al. 1964, Martin 1975, Springfield 1976, Mutel and Emerick 1984). Pitch from pinyon pine trees was used for glue, waterproofing, cooking, and many medicinal purposes. Many plants were gathered for food. The southwestern Indians depended on pinyon nuts as an important part of their diet; often a successful harvest was a matter of life or death.

Mesquite had widespread importance as a diverse resource for the native Americans in the Southwest. It was used for food, fuel, shelter, weapons, tools, fiber, dye, cosmetics, medicine, and many other practical as well as aesthetic purposes (Felger 1977). Creosote bush (_Larrea_ spp.) has also been used in many ways: as a medicinal plant, as firewood, and as a roofing material for adobe houses (Timmermann 1977).

Much of the Southwest is esthetically pleasing, both for recreation and for living purposes (Springfield 1976). Many state and national parks in the region provide spectacular scenery and opportunities to escape to a wilderness setting. Dude ranches, off-road vehicle excursions, and outings during the wild flower season are popular recreation activities in the Southwest. Such recreational uses are beginning to become an important land use in much of the Southwest (Martin 1975).

# 3. METHODS AND RESULTS

## 3.1 THE REGIONAL STRATIFICATION AND CHARACTERIZATION PROCESS

### 3.1.1 Introduction

This study is patterned after an earlier investigation (Maxwell et al. 1985) whose purpose was to evaluate the potential resources of the southwestern United States for the production of microalgae. The process used in both projects is termed "stratification" because the objective is to "stratify" or rank the region into general zones of relative resource and environmental suitability (McHarg 1969). By selecting and overlaying relevant mapped data, the areas with the most favorable conditions for biomass production should become apparent. Such a reduction of the study region into smaller areas provides a preliminary basis for estimating the resource potential and allows a determination of whether further studies of the region for biomass production are warranted. In addition, it identifies the parts of the study region where field experiments and pilot studies could most profitably be conducted in light of the existing resource and environmental conditions.

### 3.1.2 Project Objectives

The objectives of this investigation with regard to mapping, are:

- To characterize and map regional data on pertinent climate and land resource parameters including:

| Climate | Land |
|---|---|
| Freeze-free period | Soils |
| Precipitation | Vegetation |
| Evaporation | Slope (> or <10%) |
| | Land use/cover |
| | Land ownership |

- To overlay and composite the mapped natural resource data to depict areas of relative resource suitability and availability for terrestrial energy crop production.

Computer map data were available (Maxwell et al. 1985) for all of the climate parameters and for slope, land use/cover, and ownership of the land parameters. Only mapped data for soils and vegetation needed to be selected, brought to scale, and digitized.

### 3.1.3 Map Data Selection and Map Production

The two additional data needs for this analysis were in the areas of vegetation and soils. The selections that were ultimately made, an SCS map for soils (USDA/SCS 1967) and Küchler's map of vegetation (1966), were influenced by the uniform coverage of the study region that the maps provided. The study region portions of these maps are reproduced in black and white as Figs. 2.6 and 2.7 (with legends provided in Tables 2.1 and 2.2, respectively). A source of raster-based digital data for these maps was located at the Environmental Research Laboratory of the U.S. Environmental Protection Agency in Corvallis, Oregon. Alterations were made to this data base to allow it to be used with the existing maps from the microalgae study.

The soils map is limited to the Great Group level, which is unfortunate since the lower Subgroup and Family levels provide useful information on soil depth. Also, although the soils map was determined to be the best available comprehensive national or regional source, it is about 20 years old and does not reflect information subsequently obtained from ongoing soil surveys.

The map of "potential natural vegetation" by Küchler (1964, revised for the National Atlas 1966) provides uniform and complete coverage of the region. Each ecosystem is characterized in terms of both life forms and taxa because the presence and proportions of each give plant communities their unique and unmistakable character. The manual accompanying the map further characterizes the types with descriptions of their geographic occurrence, physiognomy, and dominant and other component species.

A great deal of information is lost in the process of digitizing the parameter maps. For example, for land use/cover only a few selected categories were digitized from the relatively detailed maps and the delineations of agricultural, rangeland, and forest classes and subclasses were subject to inclusions and mosaics of types. Also, the slope map exaggerates the area of <10% slope because the 152-m (500-ft) contour intervals of the original sources tend to smooth minor relief features.

The procedure ultimately used for stratification and characterization of the region for terrestrial energy crops involves both compositing and masking. The intent is to reduce the area of consideration by a reasonable process of elimination and to classify the remaining area into general zones of relative quality with displays of single parameters and composites.

## 3.2 PRODUCT MAPS

Each of the product maps is briefly discussed below. The maps are presented with symbol codes selected so that, in most cases, the darker the shade, the more favorable the conditions of that particular parameter or composite of parameters for terrestrial energy crops. One exception is the map of land use/cover within the reduced area (Fig. 3.15), in which an area of no data in northeastern Colorado is indicated with a darker symbol. Because distinctions of contrast between symbols are not always apparent, it is necessary in some instances to examine individual symbols carefully.

The regional map data are structured on a matrix of 360 columns by 24 rows of rectangular grid cells. At the map scale of 1:2,500,000 each grid cell represents an area of approximately 5041 ha (12,455 acres).

### 3.2.1 Study Area Maps

Precipitation. The computer-generated map of precipitation is shown in Fig. 3.1. The map is derived from a simplified version of the

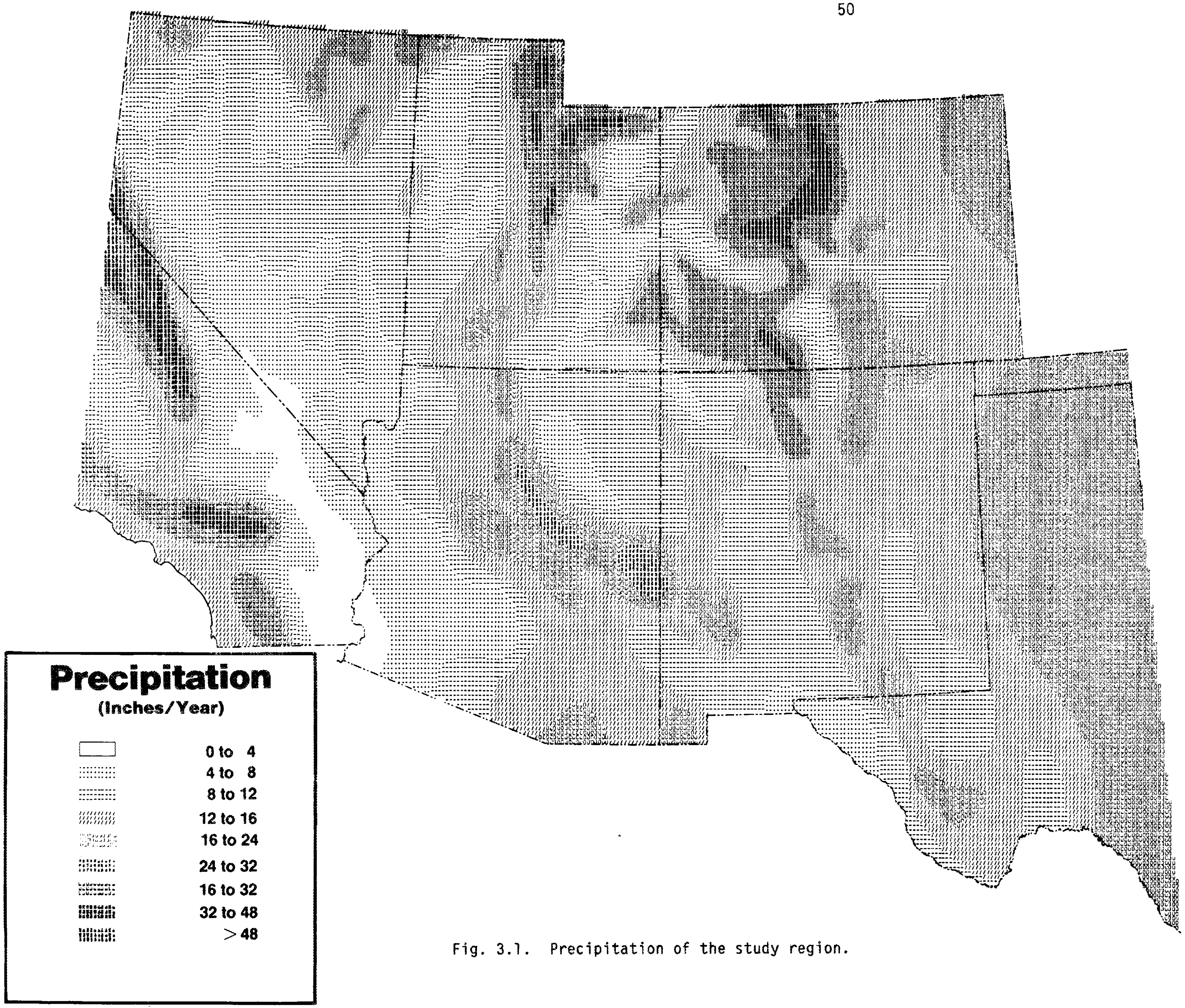


Fig. 3.1. Precipitation of the study region.

map of normal annual total precipitation, in inches, from the Climatic Atlas of the United States (USDC 1977) (Fig. 2.3). A peculiarity of the map, as reproduced and digitized, is that it includes some irregular and overlapping ranges of precipitation data values (e.g., 16-24 in., 16-32 in.) due to steep gradients of precipitation correlated with the steep topography.

Freeze-Free Period. The map of freeze-free-period is included as Fig. 3.2. This map is derived from a simplified version of the map of mean length of freeze-free period, in days, from the Climatic Atlas of the United States (USDC 1977) (Fig. 2.4). The data are presented in 60-day intervals between 120 and 300 days.

Area Reduction. The area reduction step is accomplished by logical compositing of the precipitation and freeze-free-period maps as indicated in Fig. 3.3. Areas of less than 30 cm (12 in.) precipitation and/or 120 days freeze-free period are eliminated from consideration on the basis that these criteria identify minimal moisture and growing season conditions for acceptable plant production. The remaining area, shown in Fig. 3.4, is approximately 40% of the study region or $7.725 \times 10^7$ ha ($1.908 \times 10^8$ acres).

Table 3.1 indicates the percent of the study region and of the reduced area that are included within each precipitation class. In the study region, 58.6% of the area has more than 30 cm (12 in.)/year precipitation. Almost one-third of this area (about 20% of the study region) is eliminated from the acceptable or reduced area because the freeze-free period there is less than 120 days/year.

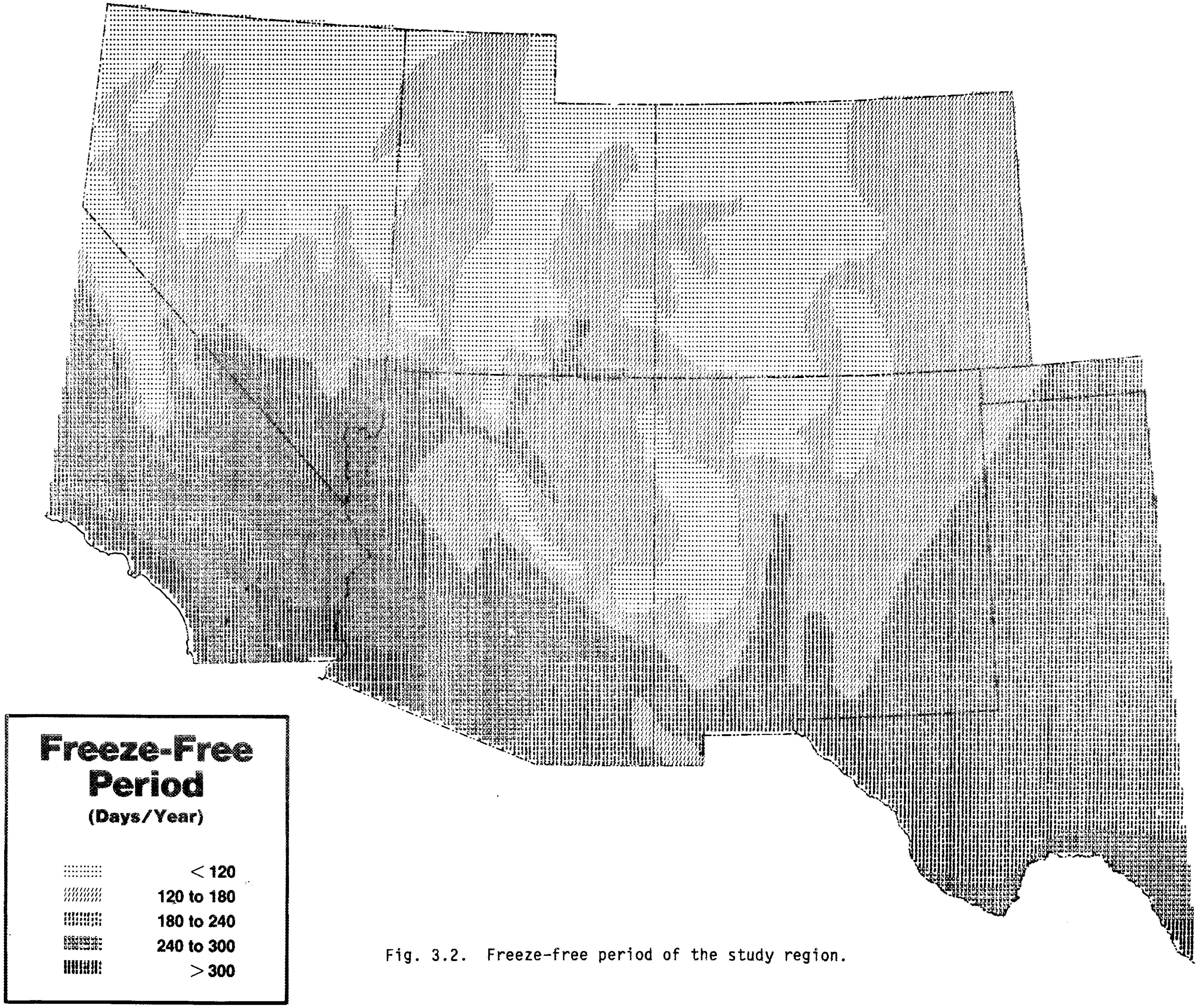


Fig. 3.2. Freeze-free period of the study region.

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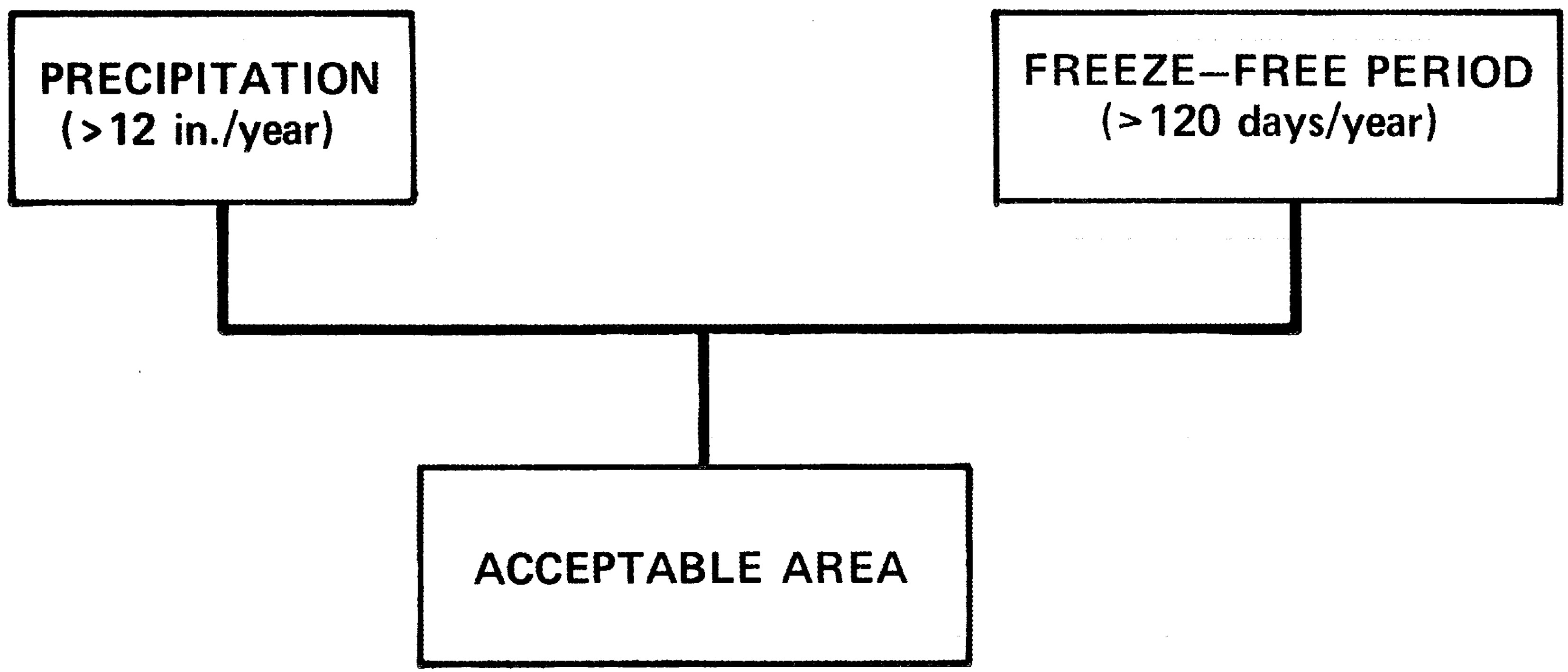


Fig. 3.3. The area reduction process.

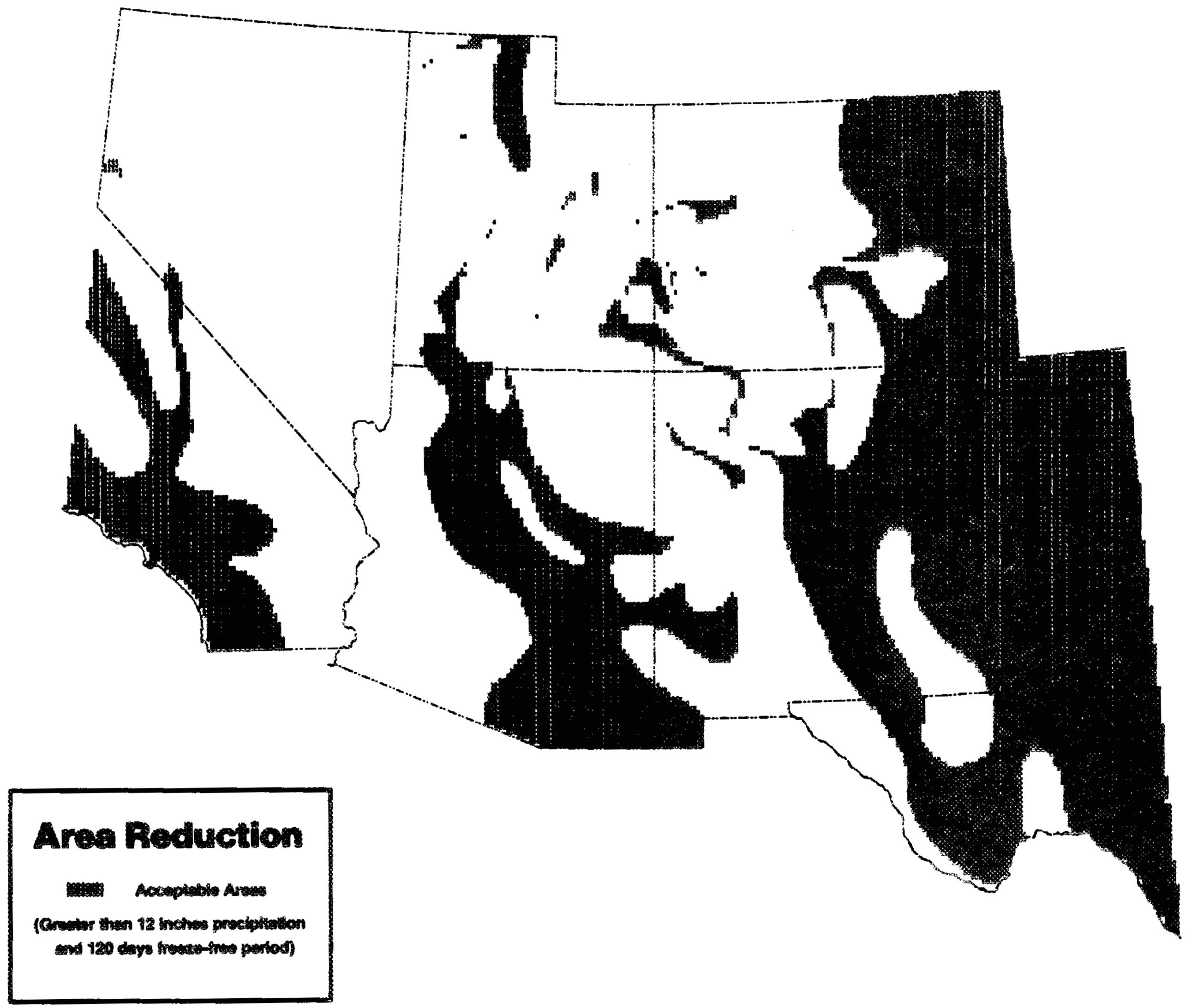


Fig. 3.4. Reduced, or acceptable, area of the study region.

Table 3.1. Comparative precipitation data for the study region and the reduced area

| Precipitation (cm/year) | Precipitation (in./year) | Percent of study region | Percent of reduced area |
|---|---|---|---|
| 0-30 | 0-12 | 41.4 | 0 |
| 30-41 | 12-16 | 29.5 | 54.8 |
| 41-51 | 16-20 | 7.4 | 18.2 |
| 41-61 | 16-24 | 7.1 | 10.3 |
| 51-61 | 20-24 | 4.2 | 10.3 |
| 61-81 | 24-32 | 0.5 | 0.2 |
| 41-81 | 16-32 | 7.6 | 5.4 |
| 81-122 | 32-48 | 2.0 | 1.0 |
| >122 | More than 48 | 0.3 | 0 |
| Total | | 100 | 100.2 |

Table 3.2. Comparative freeze-free period for the study region and the reduced area

| Period (days) | Percent of study region | Percent of reduced area |
|---|---|---|
| Less than 120 | 24.6 | 0 |
| 120-180 | 33.5 | 42.4 |
| 180-240 | 38.6 | 46.9 |
| 240-300 | 11.3 | 8.8 |
| More than 300 | 2.0 | 2.0 |
| Total | 100 | 99.9 |

Table 3.2 indicates the percent of the study region and the reduced area that are included in each class of freeze-free period. In the study region, 75.4% of the area has a freeze-free period greater than 120 days/year. Almost half of this area (about 35% of the study region) is eliminated from the acceptable area because it has precipitation of less than 30 cm (12 in.)/year.

3.2.2 Maps of the Reduced Area

Figure 3.5 indicates the compositing that was done with the various maps to determine the relative suitability of various parts of the reduced area for growing biomass energy crops.

Precipitation of the Reduced Area. Precipitation data within the acceptable area are mapped as two classes, as shown in Fig. 3.6. Only two classes were mapped because of the irregular nature of the precipitation data. Most of the precipitation occurring in amounts greater than 41 cm (16 in.)/year is in the range of 41 to 61 cm (16 to 24 in.)/year. This covers 38.8% of the reduced area.

Evaporation of the Reduced Area. Data for evaporation within the acceptable area are shown in three classes in Fig. 3.7. Table 3.3 provides comparative data on evaporation for the study region and the reduced area.

"Effective" Precipitation of the Reduced Area. Geographic definitions of arid regions are commonly based on the occurrence of a climate regime in which potential evaporation exceeds precipitation (Walter 1973, Trewartha and Horn 1980). Therefore, it is the relationship between potential evaporation and precipitation, rather

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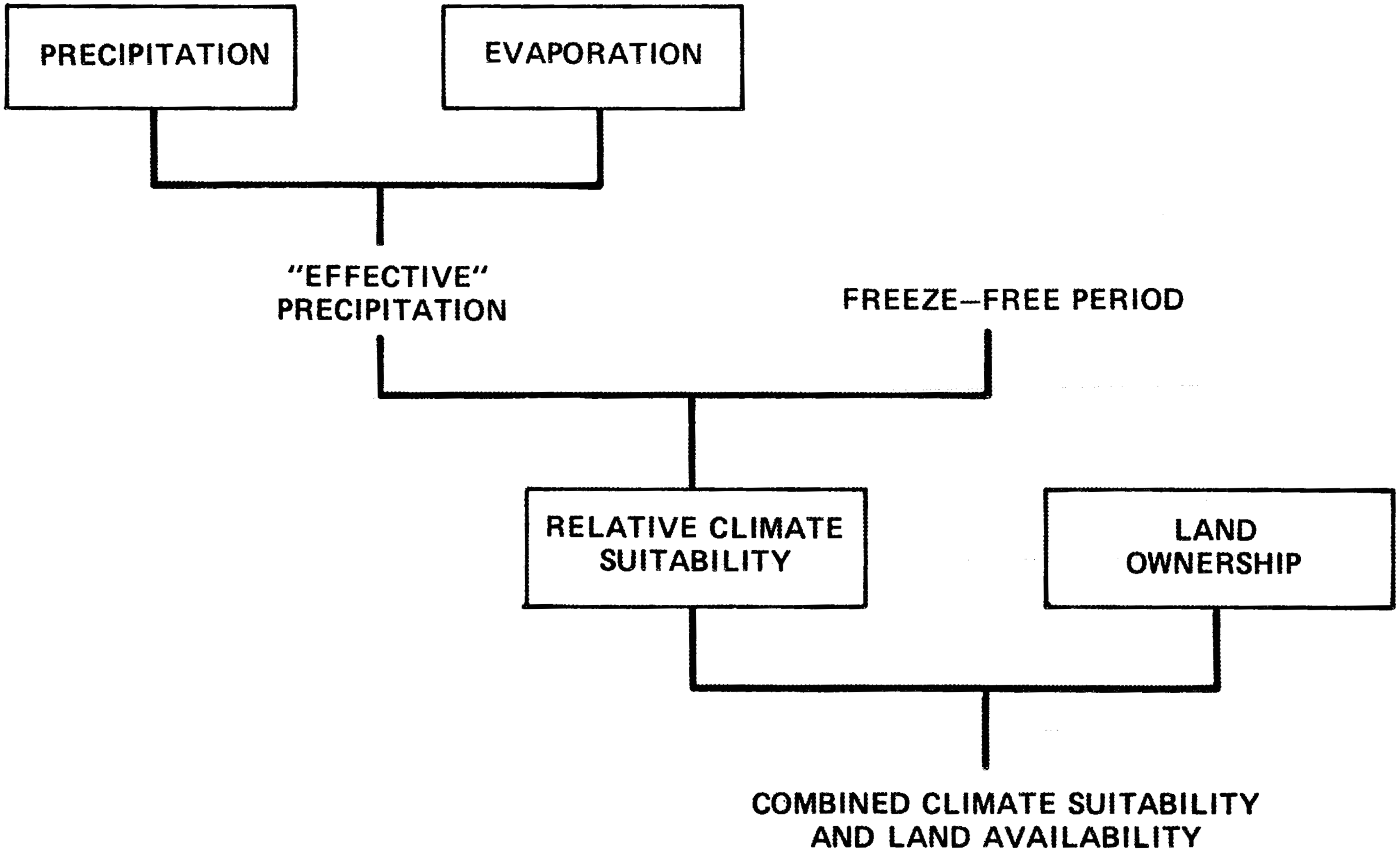


Fig. 3.5. The map compositing process.

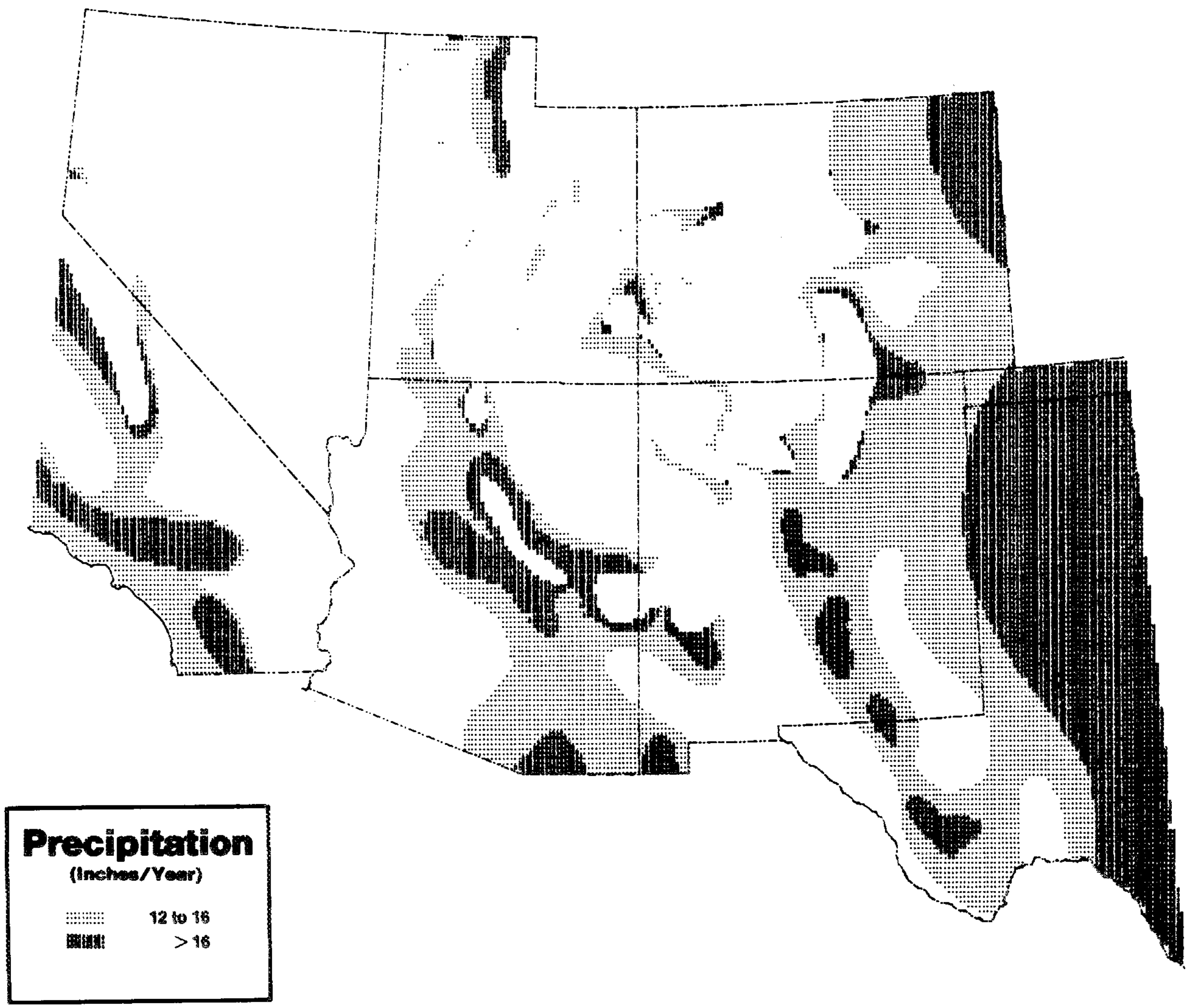


Fig. 3.6. Precipitation of the reduced area.

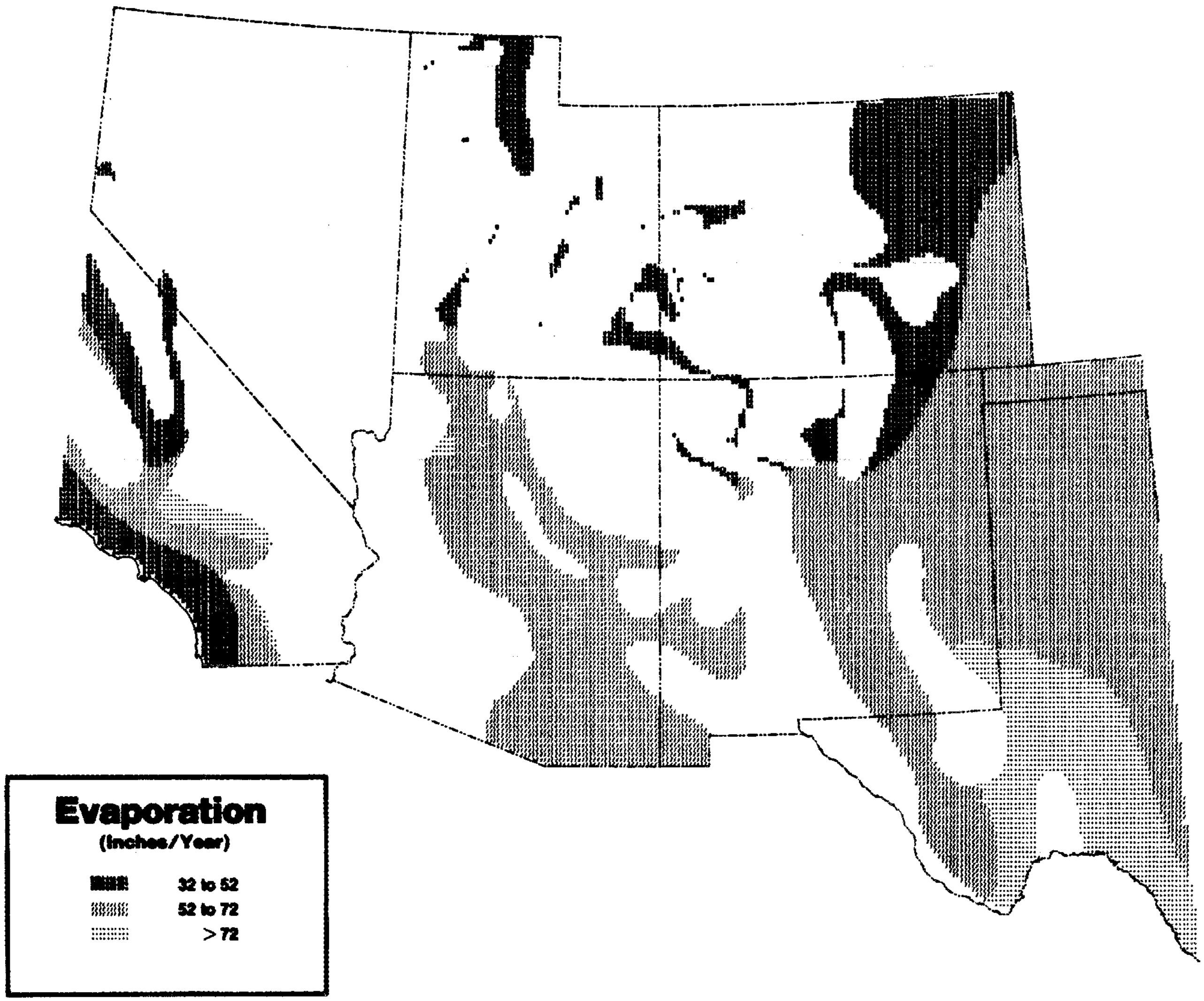


Fig. 3.7. Evaporation of the reduced area.

Table 3.3. Comparative evaporation data for the study region and the reduced area

| Evaporation (cm/year) | Evaporation (in./year) | Percent of study region | Percent of reduced area |
|---|---|---|---|
| <81 | Less than 32 | 1.5 | 0 |
| 81-107 | 32-42 | 13.8 | 5.7 |
| 107-132 | 42-52 | 24.6 | 16.5 |
| 132-157 | 52-62 | 19.7 | 21.1 |
| 157-183 | 62-72 | 24.8 | 44.5 |
| 183-208 | 72-82 | 12.5 | 12.0 |
| >208 | More than 82 | 2.9 | 0.2 |
| Total | | 99.8 | 100 |

Table 3.4. Comparative data of "effective" precipitation for the study region and the reduced area

| Deficit (cm/year) | Deficit (in./year) | Percent of study region | Percent of reduced area |
|---|---|---|---|
| >0 | More than 0 | 2.8 | 0.7 |
| 0 to -25 | 0 to -10 | 0.1 | 0 |
| -25 to -51 | -10 to -20 | 5.8 | 2.0 |
| -51 to -76 | -20 to -30 | 11.1 | 9.1 |
| -76 to -102 | -30 to -40 | 17.4 | 12.0 |
| -102 to -127 | -40 to -50 | 28.9 | 44.0 |
| -127 to -152 | -50 to -60 | 20.4 | 24.8 |
| -152 to -178 | -60 to -70 | 5.6 | 6.4 |
| <-178 | Less than | 7.4 | 0.2 |
| Total | | 99.5 | 99.2 |

than a simple threshold of precipitation, that defines and characterizes arid regions climatically.

"Effective" precipitation is determined in this study by subtracting the value for evaporation from that for precipitation, that is, the values in Fig. 3.7 are subtracted from those in Fig. 3.6. Data for effective precipitation within the acceptable area are aggregated into three classes, as illustrated in Fig. 3.8. There is only a relatively small proportion of the area in the upper two classes. Table 3.4 gives the comparative data for effective precipitation in the study region and the reduced area.

Freeze-Free Period of the Reduced Area. The data for freeze-free period within the acceptable area are grouped into three classes for the map shown in Fig. 3.9.

Relative Climate Suitability of the Reduced Area. The map of relative climate suitability illustrated by Fig. 3.10 is derived by compositing (by addition) the effective precipitation and freeze-free period maps. The three classes of effective precipitation shown in Fig. 3.8 are combined with two classes of freeze-free period (>180 days and 120-180 days). Numerical weights of 1 to 3 (1 being most desirable) are assigned to the two or three classes of the respective maps, resulting in four classes of relative suitability (Tables 3.5 and 3.6). The two lower suitability classes include almost 85% of the reduced area (Table 3.6).

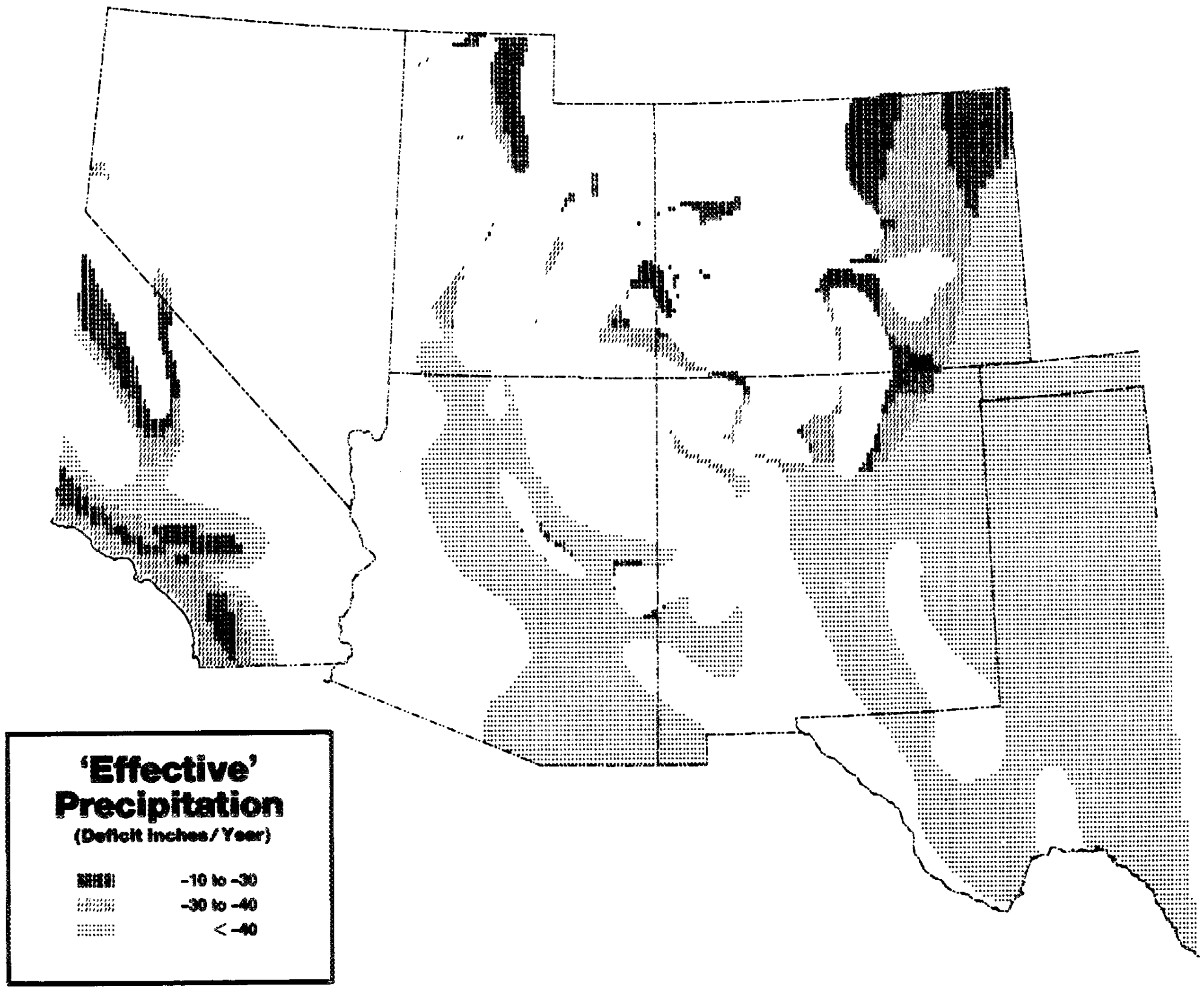


Fig. 3.8. "Effective" precipitation of the reduced area.

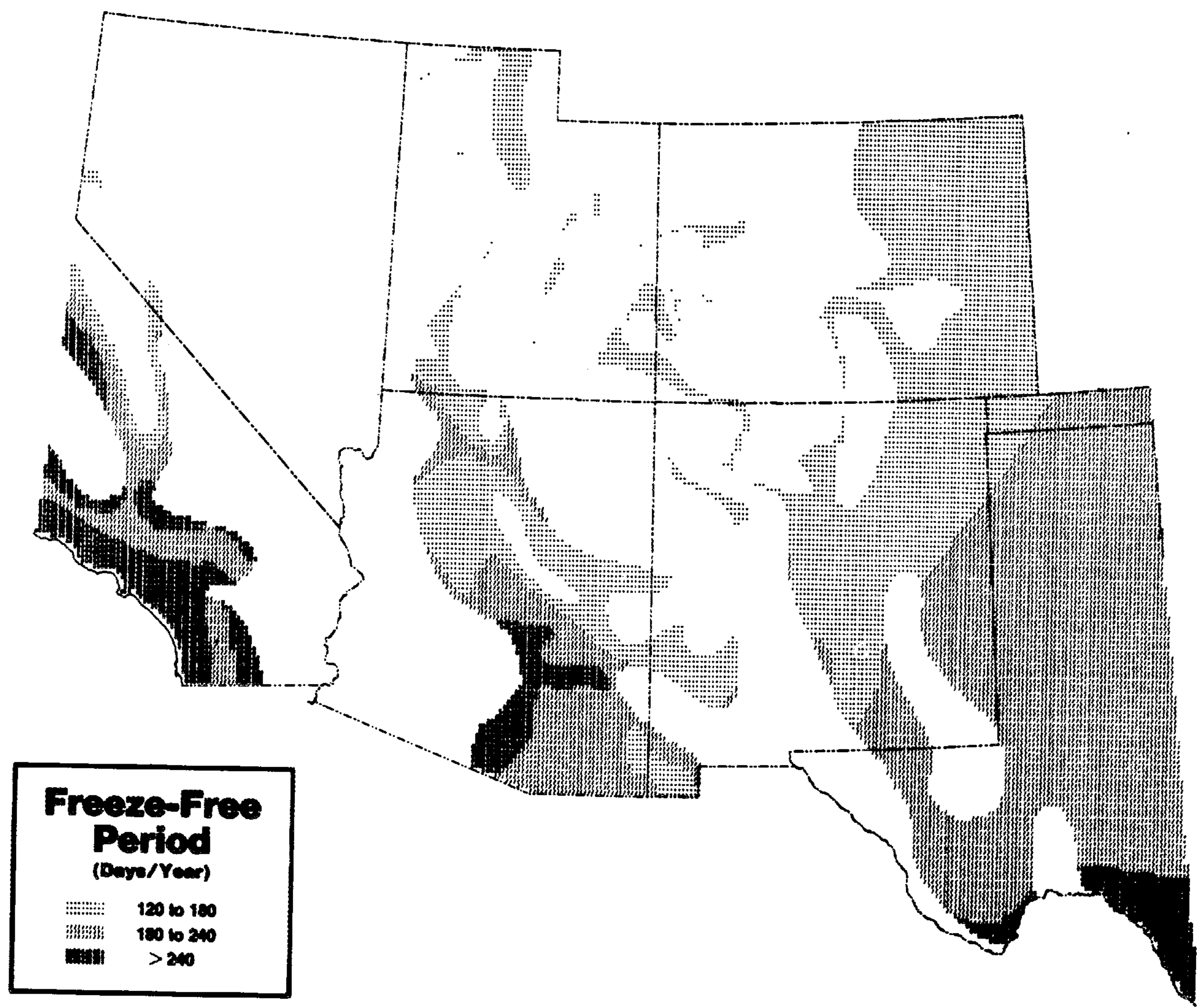


Fig. 3.9. Freeze-free period of the reduced area.

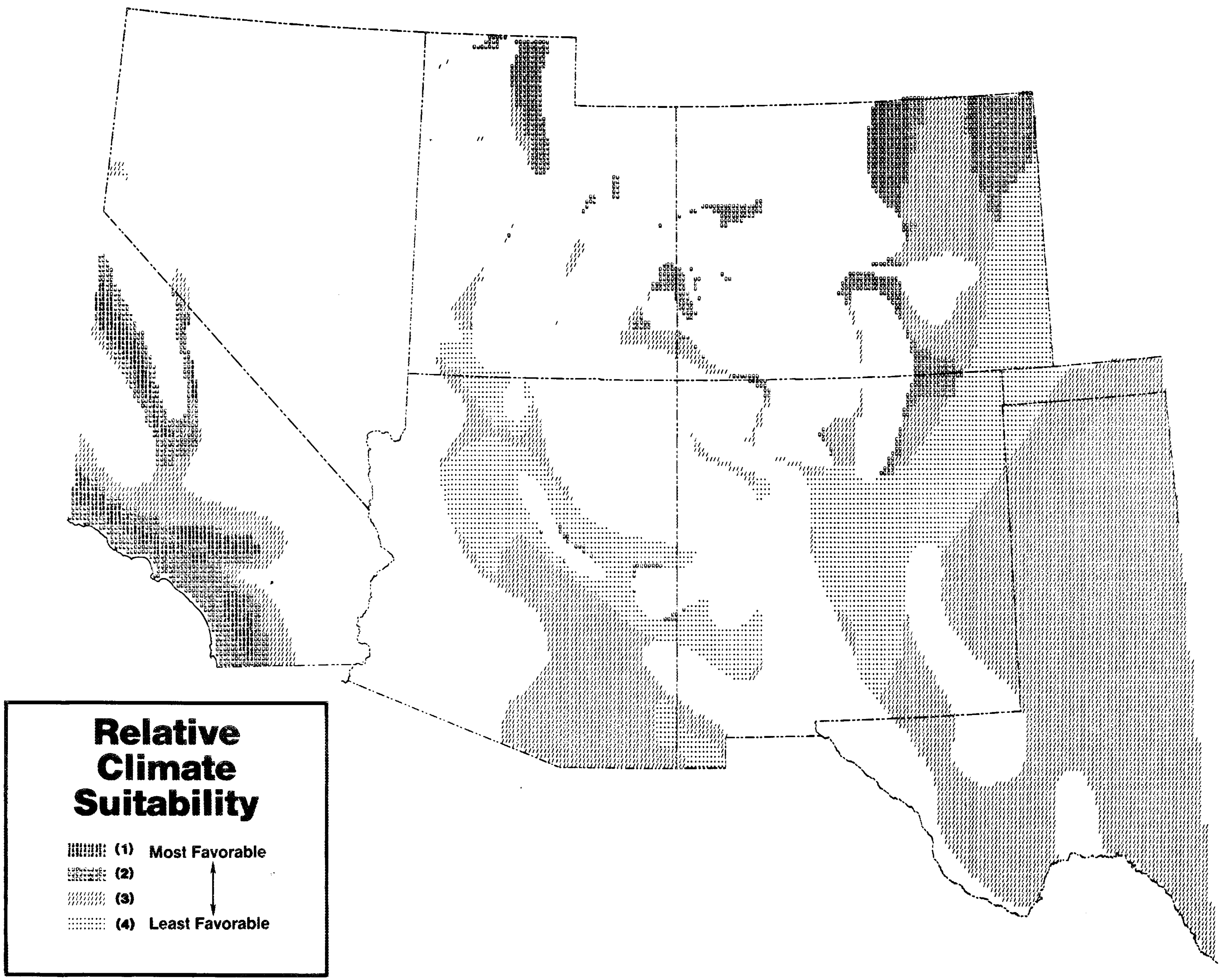


Fig. 3.10. Relative climate suitability of the reduced area.

Table 3.5. Matrix of relative climate suitability of the reduced area

| | Deficit (cm/year) | Freeze-free period (days) >180 (1) | 120-180 (2) |
|---|---|---|---|
| "Effective" precipitation | -26 to -76 (1) | 2 | 3 |
| | -76 to -102 (2) | 3 | 4 |
| | <-102 (3) | 4 | 5 |

NOTE: Values in parentheses are relative weights; the more favorable the conditions, the lower the number. Matrix values are sums of the relative weights.

Table 3.6. Relative climate suitability for the reduced area

| Composite weight[a] | Suitability class | Percent of reduced area |
|---|---|---|
| 2 | 1 (best) | 2.7 |
| 3 | 2 | 12.5 |
| 4 | 3 | 60.0 |
| 5 | 4 | 24.3 |
| Total | | 99.5 |

[a]Composite weights are matrix values from Table 3.5.

Land Ownership of the Reduced Area. Figure 3.11 is a map of land ownership for the reduced area. Table 3.7 indicates the percent of land in each ownership category. The third class of land ownership (parks, wilderness areas, and wildlife refuges) is not available for production of biomass and is a very small part of the reduced area, just over 2% of the land. The most available class [state, private, Bureau of Land Management (BLM), and mixed lands] includes 80% of the reduced area.

Combined Climate Suitability and Land Availability of the Reduced Area. The maps in Figs. 3.10 and 3.11 are composited by logical combination to produce the map of combined suitability and availability shown in Fig. 3.12. [Since category C lands (parks, wilderness, and wildlife refuges) are not available for biomass production, they are not included in these composites.] The logical combination approach was taken on the basis that land ownership is the dominant influence. Alternatively, arithmetic compositing would result in strata of mixed ownership classes. The maps, therefore, show areas that are most to least favorable climatically for the most available land ownership group (category A), followed by areas that are most to least favorable for the second land ownership class (category B). Table 3.8 indicates the percent of the land in the reduced area that is in each category on these maps.

Soils of the Reduced Area. In Fig. 3.13, soil orders represented in the acceptable area are aggregated into four categories and displayed according to a judgment of general relative quality for

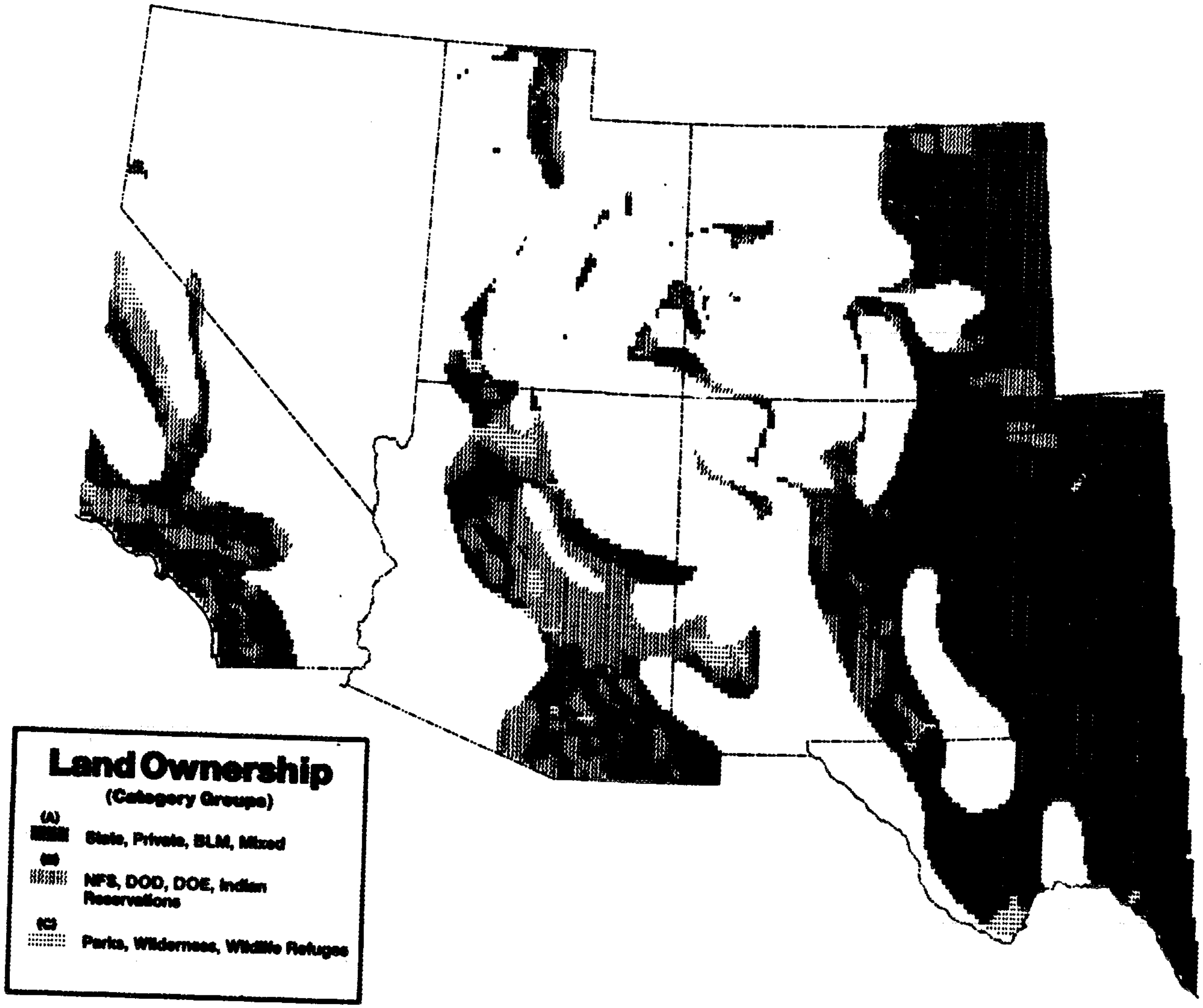


Fig. 3.11. Land ownership of the reduced area.

Table 3.7. Land ownership of the reduced area

| Category group[a] | Percent of reduced area |
|---|---|
| A: State, private, BLM, mixed lands | 80.0 |
| B: NFS, DOD, DOE, Indian lands | 16.7 |
| C: Parks, wilderness, wildlife refuges | 2.2 |
| Total | 99.7 |

[a]BLM = Bureau of Land Management, NFS = National Forest Service, DOD = Department of Defense, DOE = Department of Energy.

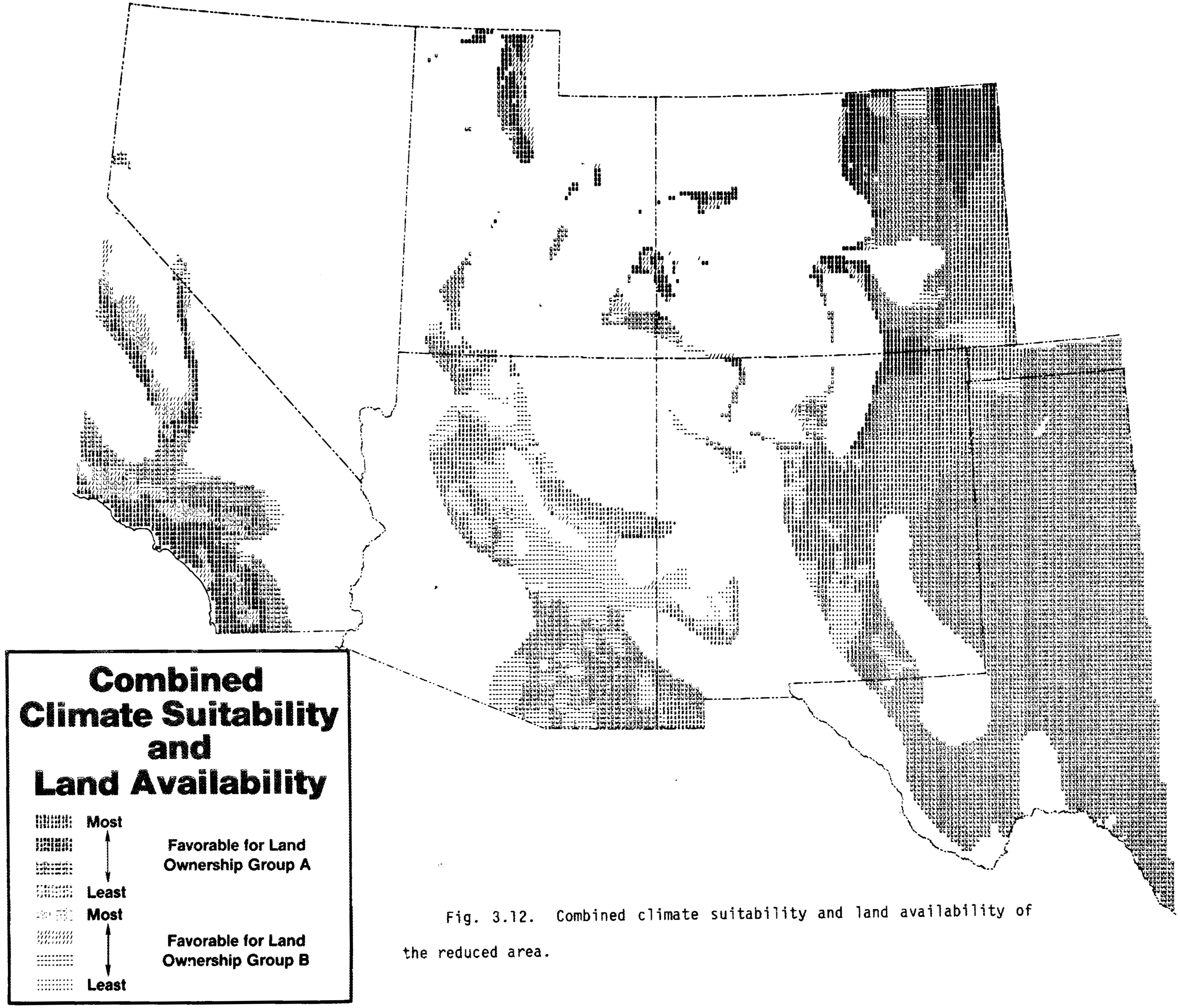


Fig. 3.12. Combined climate suitability and land availability of the reduced area.

Table 3.8. Composite suitability and availability data for the reduced area

| Favorability class[a] | Percent of reduced area |
|---|---|
| A-1 | 1.5 |
| A-2 | 9.6 |
| A-3 | 52.3 |
| A-4 | 17.2 |
| B-1 | 1.2 |
| B-2 | 2.7 |
| B-3 | 6.4 |
| B-4 | 6.4 |
| C | 2.2 |
| Total | 99.5 |

[a]Letter from land ownership classes, Fig. 3.11 and Table 3.7. Number from relative climate suitability classes, Fig. 3-10 and Table 3.6.

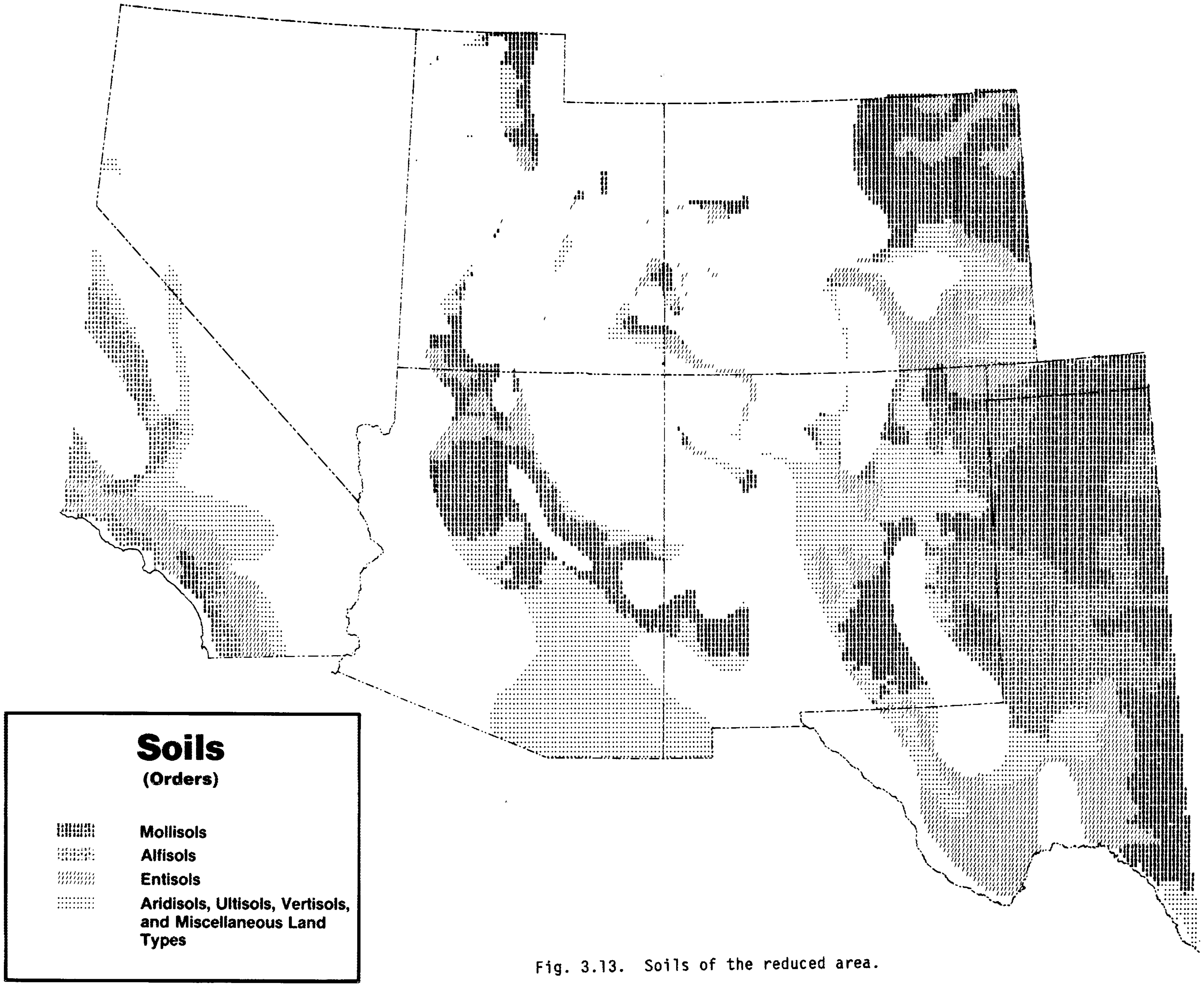


Fig. 3.13. Soils of the reduced area.

plant production. Mollisols are ranked highest based on their characteristic composition of organic matter. Alfisols are ranked as second most productive on the basis of moisture availability. Entisols are distinguished as the third quality class due to their association with watercourses and coarse-grained deposits. The remaining class is comprised primarily of Aridisols, which are characteristically dry. Table 3.9 indicates the relative percent of the study area and the reduced area that have each of these types of soils.

Vegetation of the Reduced Area. Groups of natural vegetation types within the acceptable area are represented in Fig. 3.14. Central grassland and western forest types cover the largest proportion of the area. A breakdown by Küchler types of the vegetation in the study region and in the reduced area is provided in Table 3.10. Table 3.11 gives the land area of the five most abundant Küchler vegetation types in the reduced area, and the Appendix provides descriptive information on those five vegetation types.

Land Use/Cover of the Reduced Area. The map of land use/cover presented as Fig. 3.15 was generated for this project by manually coding and digitizing the maps of interpreted Landsat imagery at a scale of 1:2,500,000. The coding procedure involved superimposing cellular coding sheets on a reduced and spliced set of the state land use/cover maps on a reverse-image computer map of the acceptable area (i.e., acceptable area blank). Nine codes were selected to represent the data. Table 3.12 indicates the part of the reduced area that is in each land use/cover category.

Table 3.9. Soils data for the study region and the reduced area

| Soil order | Percent of study region | Percent of reduced area |
|---|---|---|
| Mollisols | 22.5 | 34.9 |
| Alfisols | 12.5 | 17.4 |
| Entisols | 17.5 | 17.9 |
| Others: | | |
| Aridisols | 45.1 | 28.0 |
| Ultisols | 1.2 | 0.7 |
| Vertisols | 0.2 | 0.5 |
| Misc. types | 0.5 | 0.0 |
| Total | 99.5 | 99.4 |

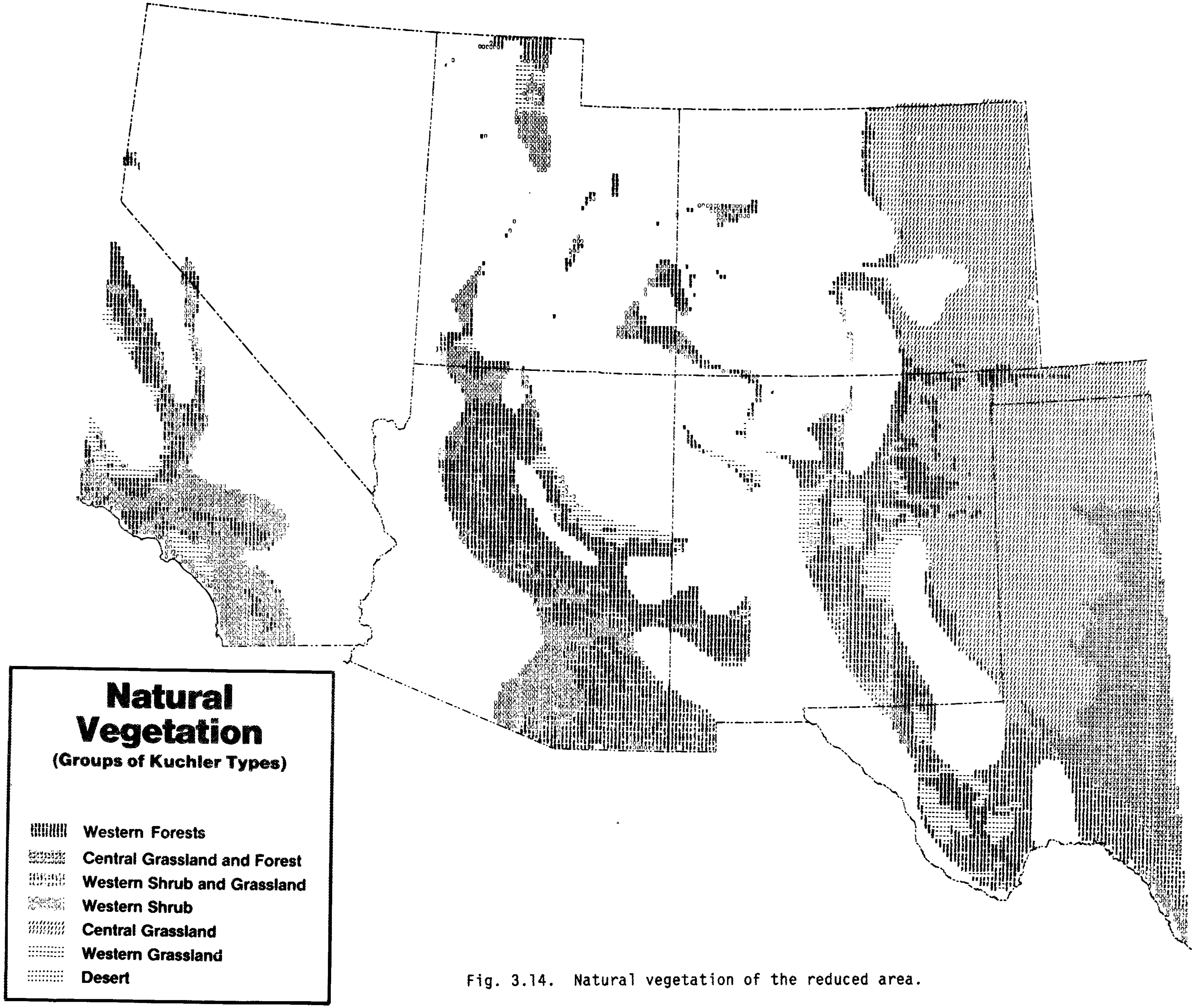


Fig. 3.14. Natural vegetation of the reduced area.

Table 3.10. Percent of potential natural vegetation ecosystems contained in the study region and the reduced area

| Group type | Map unit number | Map unit name[a] | Percent of study region | Percent of reduced area | Percent of each type in study region remaining in reduced area |
|---|---|---|---|---|---|
| Western forests | 5 | Mixed conifer forest (*Abies-Pinus-Pseudotsuga*) | 0.6 | 1.0 | 66.6 |
| | 7 | Red fir forest (*Abies*) | 0.2 | - | - |
| | 8 | Lodgepole pine-subalpine forest (*Pinus-Tsuga*) | 0.4 | - | - |
| | 10 | Western ponderosa forest (*Pinus*) | 0.3 | - | - |
| | 11 | Douglas fir forest (*Pseudotsuga*) | 0.6 | - | |
| | 14 | Western spruce-fir forest (*Pices-Abies*) | 1.8 | 0.2 | 5.5 |
| | 17 | Pine-Douglas fir forest (*Pinus-Pseudotsuga*) | 3.7 | 3.2 | 35.1 |
| | 18 | Arizona pine forest (*Pinus*) | 0.9 | 1.2 | 55.5 |
| | 19 | Spruce-fir-Douglas fir forest (*Picea-Abies-Pseudotsuga*) | 0.4 | - | - |
| | 20 | Southwestern spruce-fir forest (*Picea-Abies*) | 1.3 | 0.5 | 15.4 |
| | 21 | Juniper-pinyon woodland (*Juniperus-Pinus*) | 14.4 | 11.3 | 31.9 |
| | 26 | California oakwoods (*Quercus*) | 0.9 | 1.7 | 77.7 |
| | 27 | Oak-juniper woodland (*Quercus-Juniperus*) | 1.0 | 2.5 | 100.0 |
| | 28 | Transition between 27 and 31 | 0.8 | 2.0 | 100.0 |
| Group total | | | 27.3 | 23.6 | |
| Central grassland and forest | 76 | Mesquite-buffalo grass (*Bouteloua-Buchlöe-Prosopis*) | 3.2 | 7.9 | 100.0 |
| | 77 | Juniper-oak savanna (*Andropogon-Quercus-Juniperus*) | 0.6 | 1.5 | 100.0 |
| Group total | | | 3.8 | 9.4 | |

Table 3.10. (continued.)

| Group type | Map unit number | Map unit name[a] | Percent of study region | Percent of reduced area | Percent of each type in study region remaining in reduced area |
|---|---|---|---|---|---|
| Western shrub and grassland | 49 | Sagebrush steppe (Artemisia-Agropyron) | 3.6 | 0.5 | 5.5 |
| | 51 | Galleta-three awn shrubsteppe (Hilaria-Aristida) | 0.2 | - | - |
| | 52 | Grama-tobosa shrubsteppe (Bouteloua-Hilaria-Larrea) | 5.4 | 6.4 | 48.1 |
| | 53 | Trans-Pecos shrub savanna (Flourensia-Larrea) | 4.5 | 5.7 | 51.1 |
| | 54 | Mesquite-acacia-savanna (Andropogon) | 0.2 | 0.5 | 100.0 |
| Group total | | | 13.9 | 13.1 | |
| Western shrub | 29 | Chaparral (Adenostoma-Arctostaphylos-Ceanothus) | 1.2 | 2.7 | 91.6 |
| | 30 | Coastal sagebrush (Salvia-Eriogonum) | 0.4 | 1.0 | 100.0 |
| | 31 | Mountain mahogany-oak scrub (Cercocarpus-Quercus) | 1.2 | 0.5 | 16.6 |
| | 32 | Great Basin sagebrush (Artemisia) | 9.0 | 1.5 | 6.6 |
| | 33 | Blackbrush (Coleogyne) | 0.6 | 0.2 | 16.6 |
| | 34 | Saltbush-greasewood (Atriplex-Sarcobatus) | 7.0 | 1.2 | 7.1 |
| | 35 | Creosote bush (Larrea) | 5.3 | 1.7 | 13.2 |
| | 36 | Creosote bush-bur sage (Larrea-Franseria) | 4.5 | 2.7 | 24.4 |
| | 37 | Palo verde-cactus shrub (Cercidium-Opuntia) | 1.6 | 0.5 | 12.5 |
| | 38 | Ceniza shrub (Leucophyllum-Larrea-Prosopis) | 0.1 | 0.2 | 100.0 |
| Group total | | | 30.9 | 12.2 | |

Table 3.10. (continued.)

| Group type | Map unit number | Map unit name[a] | Percent of study region | Percent of reduced area | Percent of each type in study region remaining in reduced area |
|---|---|---|---|---|---|
| Central grassland | 58 | Grama-buffalo grass (Bouteloua-Buchloë) | 13.0 | 30.5 | 95.4 |
| | 62 | Bluestem-grama prairie (Andropogon-Bouteloua) | 0.2 | 0.5 | 100.0 |
| | 63 | Sandsage-bluestem prairie (Artemisia-Andropogon) | 0.6 | 1.5 | 100.0 |
| | 64 | Shinnery (Quercus-Andropogon) | 1.0 | 2.5 | 100.0 |
| Group total | | | 14.8 | 35.0 | |
| Western grassland | 41 | California steppe (Stipa) | 1.0 | 1.2 | 50.0 |
| | 42 | Tule marshes (Scirpus-Typha) | 0.3 | 0.2 | 33.3 |
| | 44 | Wheatgrass-bluegrass (Agropyron-Poa) | 0.1 | - | - |
| | 45 | Alpine meadows & barren (Argrostis, Carex, Festuca, Poa) | 1.1 | 0.2 | 9.1 |
| | 46 | Fescue-mountain muhly prairie (Festuca-Muhlenbergia) | 0.4 | - | - |
| | 47 | Grama-galleta steppe (Bouteloua-Hilaria) | 4.2 | 3.2 | 30.9 |
| | 48 | Grama-tobosa prairie (Bouteloua-Hilaria) | 0.8 | 1.2 | 62.5 |
| Group total | | | 7.9 | 6.0 | |
| Desert | 39 | Desert: vegetation largely absent | 1.1 | - | - |
| GRAND TOTAL | | | 99.7 | 99.3 | |

[a]From: A. W. Küchler, 1966, IN The National Atlas of the United States, U.S. Department of the Interior, Geological Survey, Reston, Virginia.

Table 3.11. Land area of most common Küchler vegetation types in the reduced area

| Map unit number | Map unit name | Percent of the reduced area[a] | Area[a] ($\times 10^6$) (ha) | Area[a] ($\times 10^6$) (acres) | Percent of each type in study region remaining in reduced area[b] |
|---|---|---|---|---|---|
| 58 | Grama-buffalo grass (*Bouteloua-Buchloë*) | 30.5 | 23.56 | 58.19 | 95.4 |
| 21 | Juniper-pinyon woodland (*Juniperus-Pinus*) | 11.3 | 8.73 | 21.56 | 31.9 |
| 76 | Mesquite-buffalo grass (*Bouteloua-Buchloë-Prosopis*) | 7.9 | 6.10 | 15.07 | 100.0 |
| 52 | Grama-tobosa shrubsteppe (*Bouteloua-Hilaria-Larrea*) | 6.4 | 4.94 | 12.21 | 48.1 |
| 53 | Trans-Pecos shrub savanna (*Flourensia-Larrea*) | 5.7 | 4.40 | 10.87 | 51.1 |
| | TOTAL | 61.8 | 47.73 | 117.90 | |

[a]Based on an area of $7.725 \times 10^7$ ha ($1.908 \times 10^8$ acres) in the reduced area.
[b]Values from Table 3.10.

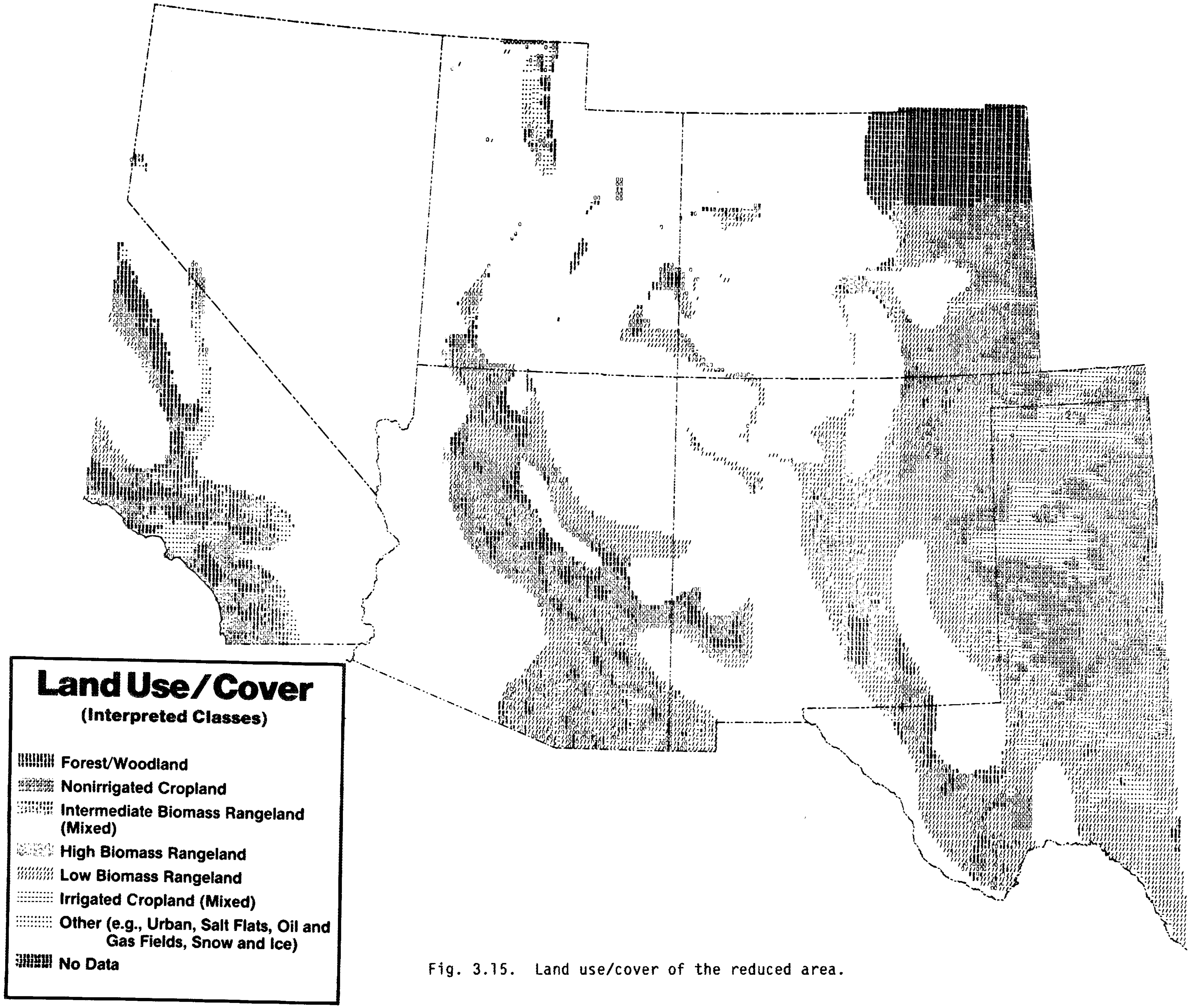


Fig. 3.15. Land use/cover of the reduced area.

Table 3.12. Land use/cover data for the reduced area

| Category | Percent of reduced area |
|---|---|
| Forest/woodland | 7.9 |
| Nonirrigated cropland | 10.3 |
| Irrigated cropland (mixed) | 6.9 |
| High biomass rangeland | 13.0 |
| Intermediate biomass rangeland (mixed) | 4.7 |
| Low biomass rangeland | 45.5 |
| Other (urban, salt flats, oil and gas fields, and snow and ice) | 5.7 |
| No data (northeast Colorado) | 5.9 |
| Total | 99.9 |

Slope. The principal limitation of slope for biomass energy production is during harvest, since it is difficult for harvesting equipment to operate on steep slopes. A map of areas of greater or less than 10% slope (Maxwell et al. 1985) was overlayed with an outline of the reduced area to produce Fig. 3.16, which shows the location and approximate extent of mountains and other complex terrain. About 42.6% of the study region has a slope greater than 10%, while the remaining 57.4% of the study region has a slope less than 10%. Because minor relief features were smoothed out in the preparation of the digital maps, it is estimated that the area designated as having a slope less than 10% is probably exaggerated by 30 to 40% (Maxwell et al. 1985).

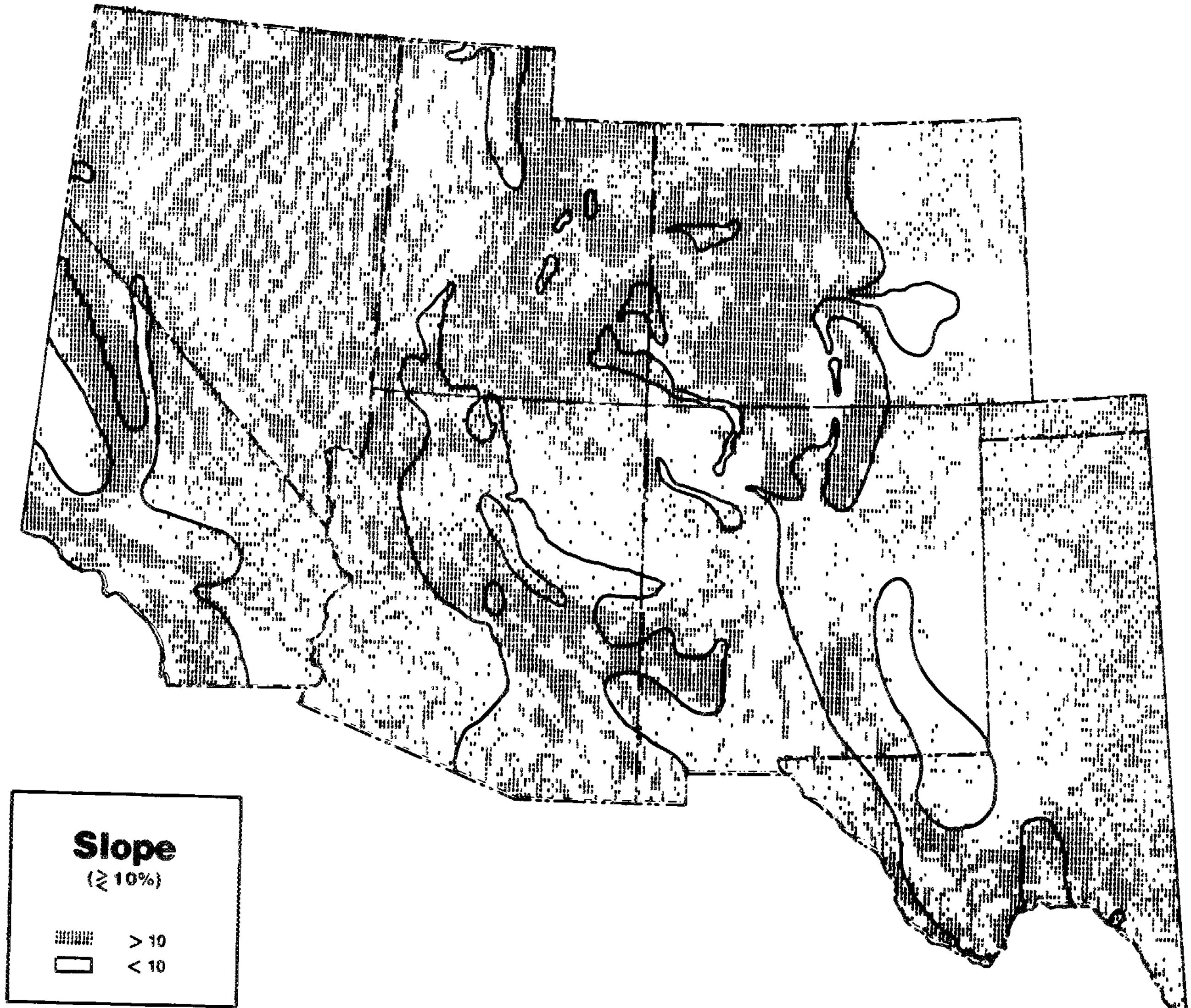


Fig. 3.16. Areas of greater or less than 10% slope in the study area. Dark lines indicate the reduced area.

# 4. DISCUSSION

The objective of this investigation is to relate the characteristics of apparent best land areas in the Southwest to the potential and needs of biomass energy production. Thus, the implications of the mapping process for biomass energy crops are discussed here. Emphasis is put on the composite maps and on the parameter maps that are most informative or that influenced the composite maps. The characteristics of prime areas and their implications for terrestrial energy crops are discussed, followed by an assessment of the productivity of various vegetation types in the reduced areas.

## 4.1 ASSESSMENT OF MAPS

The product maps in Sect. 3.2 illustrate general trends of climate, land use, and vegetation in the reduced area of the study region. Caution must be taken, however, in interpreting the maps too absolutely, because computer map registration error alone may account for precision within only about five miles on the land surface.

### 4.1.1 Composite Maps

Not all of the $7.725 \times 10^7$ ha ($1.908 \times 10^8$ acres) in the reduced area would be available for growing biomass energy crops. Parks, wilderness areas, and wildlife refuges (Fig. 3.11 and Table 3.7) cover 2.2% of the area. Additional land use/cover categories (Fig. 3.15 and Table 3.12) that would not be available for crops include the "other" category (urban areas, salt flats, oil and gas fields, and snow and ice) and "irrigated cropland." This reduces the possible biomass growing part of the reduced area by an additional 12.6%. Northeast Colorado, which is not included in the data in Fig. 3.15, includes the Denver metropolitan region and some irrigated cropland (USGS 1970). Conservatively, this would reduce the amount of land available in the reduced area for growing biomass crops by another 0.5%. Thus, at least 15.3% of the land in the reduced area, $1.18 \times 10^7$ ha ($2.92 \times 10^7$ acres), would not be available for growing biomass energy crops, leaving $6.54 \times 10^7$ ha ($1.62 \times 10^8$ acres) as potential land for biomass energy crops in the Southwest. Even this figure may be too high, since it does not take into consideration land that is too steep for harvesting, has soils that will not support crop production, is not productive enough for growing biomass energy crops, or is otherwise unsuitable for cultivation.

Maps were produced to obtain a view of (1) environmental suitability (Fig. 3.10) and (2) environmental suitability in conjunction with land availability (Fig. 3.12) in the reduced area. The environmental suitability composite, based on climate factors, represents a balance between opposite trends in the effective precipitation and freeze-free-period data. The most favorable moisture conditions correspond generally with areas of higher latitude and elevation or higher elevation areas near the Pacific Coast (Fig. 3.8). The freeze-free period shows an almost inverse pattern, with higher elevations and higher latitudes having shorter frost-free periods

(Figs. 3.2 and 3.9). As Fig. 3.10 indicates, the area in which both conditions are most favorable (i.e., suitability class 1) is very small, just 2.7% of the reduced area, and occurs only in California. In other parts of the reduced region, moister areas tend to have a shorter growing season, while areas with longer growing seasons are more arid. The potential natural vegetation found in suitability class 1 (comparing Fig. 3.10 with Fig. 3.14) is about equally divided between western forests (including juniper-pinyon, mixed conifers, and California oakwoods) and western shrublands (including chaparral and coastal sagebrush), with a small part being western grassland (primarily California steppe).

The most abundant suitability class (class 3) makes up 60% of the reduced area and is found throughout it. All potential natural vegetation groups, except desert, are included in this class. Class 3 is divided into northern and southern components reflecting opposing moisture and temperature trends (Fig. 3.10). The southern portion has more than 180 frost-free days/year but a lower effective precipitation, while the northern portion has a frost-free period of 120-180 days/year but a higher effective precipitation.

Interpreted in terms of crop types, these opposing trends suggest that two different types of plants are desirable for the more continental parts of the reduced area: (1) those that produce rapidly in a short growing season and (2) those that are capable of more or less continuous production under drier conditions. The conditions of the area under more Pacific maritime influence suggest a third type capable of utilizing a long growing season but with relatively less need for drought tolerance.

Figure 3.12 is a composite of climate suitability for the reduced area (Fig. 3.10) with land ownership for that area (Fig. 3.11). The 2.2% of the reduced area in ownership class C (parks, wilderness areas, and wildlife refuges) is not available for biomass production and is not included in this composite. The combination of ownership class A and environmental suitability class 3 is the most common one, covering 52.3% of the land in the reduced area. Land in suitability class 1 and ownership category A is most favorable in terms of both land ownership and climate.

### 4.1.2 Vegetation Types of the Reduced Area

Table 3.10 lists the 43 potential natural vegetation types found in the study region (Küchler 1964, 1966). Eight of these are not found in the reduced area of the study region, while ten occur entirely in the reduced area. Of the groups of types, the Central Grassland and Forest combination and the Central Grassland groups are found almost exclusively in the reduced area. The five most common types of natural vegetation in the study region cover 48.8% of the land area (juniper-pinyon woodland = 14.4%, grama-buffalo grass = 13%, Great Basin sagebrush = 9.0%, saltbush-greasewood = 7.0%, and grama-tobosa shrubsteppe = 5.4%). The five most common types in the reduced area make up 61.8% of that part of the study region (Table 3.11). Three types (grama-buffalo grass, juniper-pinyon woodland, and grama-tobosa shrubsteppe) are among the five most common vegetation types in both the entire study region and the reduced area. Great Basin sagebrush and saltbush-greasewood cover 16% of the study region, but account for only 2.7% of the land in the reduced area.

Of the five most common vegetation types in the reduced area, two, grama-buffalo grass and mesquite-buffalo grass, are found almost entirely there (respectively, 95.4% and 100% of the type in the study region occur in the reduced area). For the other three most common vegetation types in the reduced area, 31.9% of the juniper-pinyon in the study region occurs in the reduced area, 48.1% of the grama-tobosa shrubsteppe, and 51.1% of the trans-Pecos shrub savanna.

Shrub and grasslands. The grama-tobosa shrubsteppe and the trans-Pecos shrub savanna are both classified by Küchler (1964, 1966) as combination western shrub and grasslands, while Martin (1975) describes them as southwestern semidesert grass-shrub ranges. They are characterized by short grasses with dense-to-scattered shrubs and dwarf shrubs. The dominant plant species in the grama-tobosa shrubsteppe are black grama (*Bouteloua eripoda*), tobosa (*Hilaria mutica*), and creosote bush (*Larrea divaricata*). In the trans-Pecos shrub savanna the dominants are creosote bush and tarbush (*Flourensia cernua*). These ecosystems are scattered across the southern part of the study region, the former in southeastern Arizona and southern New Mexico and the latter in western Texas and adjacent New Mexico.

The part of the study region where these two vegetation types occur has over 120 frost-free days/year. Therefore, the parts of these vegetation types that are not included in the reduced area (51.9% of the grama-tobosa shrub-steppe and 48.9% of the trans-Pecos shrub savanna) are eliminated because the average annual precipitation where they are found is less than the 30 cm (12 in.)/year used in this study to define the acceptable region for biomass energy crop production. Since these vegetation types are found on both sides of the precipitation border that was used to define the acceptable region, they are likely to contain species that would be able to survive in those years in which the reduced area has less than average rainfall. In addition to the dominant plant species noted above, the Appendix lists other common species in these vegetation types.

Juniper-pinyon woodlands. The juniper-pinyon woodland type is found scattered throughout the study region (Fig. 2.7). It occurs from the western boundary in Nevada and California to the eastern point where Colorado, Oklahoma, and New Mexico meet and from the southcentral part of New Mexico to the northern border of Utah and Colorado. Although indicated by the same symbol, this type is not homogeneous in the study region. Differences in the type throughout its range are related to elevation, climate, and soil. Pinyon (*Pinus edulis*) is the dominant pine species in the eastern part of the range of the vegetation type, while oneleaf pine (*Pinus monophylla*) is more common in the western part of the range (see Appendix) (Küchler 1964, 1966). In the extreme south, Mexican pinyon (*Pinus cembroides*) replaces the pinyon pine (Springfield 1976). Various species of juniper are also found in different parts of the range, with oneseed juniper (*Juniperus* monosperma), Utah juniper (J. osteosperma), Rocky Mountain juniper (J. scopulorum), and alligator juniper (J. deppeana) being dominants or co-dominants in various places (Küchler 1964, 1966; Springfield 1976; Castetter 1956). This vegetation type is found on a variety of soils, but in general the soils are shallow and low in fertility (Mutel and Emerick 1984).

Juniper-pinyon woodlands are generally found at middle elevations in the mountains [e.g., in Arizona and New Mexico, it is found at elevations of 1372-2286 m (4,500-7,500 ft) (Springfield 1976)]. It occurs as a transition between the arid shrublands and grasslands of lower elevations and the mountain forests at higher elevations (Mutel and Emerick 1984). At the lower elevations, the vegetation appears as widely spaced and scattered trees, with much of the ground under them bare and rocky or with only a sparse covering of shrubs and grasses (Mutel and Emerick 1984). Grasslands surrounding the lower elevation pinyon-juniper woodlands may be invaded by junipers through pressures of grazing and reduction of fires (Arnold et al. 1964). Coarse-textured soils, in particular, favor the establishment of trees. Once established, trees usually become dominant.

Temperature and precipitation at the various elevations determine the relative numbers of pine and juniper in each woodland. Pinyon is more tolerant of the cold temperatures that are found at higher elevations, while the juniper is more tolerant of droughts that are more common at lower elevations (Mutel and Emerick 1984). At the lowest elevations junipers may form pure stands, but at higher elevations, the pinyon pine becomes dominant and the junipers decrease. At the higher elevations, the type mixes with Gambel oak, ponderosa pine, and Douglas fir, which are typical of the mountain forests (Springfield 1976, Mutel and Emerick 1984).

The juniper-pinyon ecosystem grows where precipitation is over 25 cm (10 in.)/year and where there are over 80 frost-free days/year (Springfield 1976, Mutel and Emerick 1984). Both of these lower extremes are below the acceptable range for biomass production set for this study, which explains why almost 70% of the type does not occur in the reduced area. Therefore, like the grama-tobosa shrubsteppe and the trans-Pecos shrub savanna, the type contains species that can survive those years in which the precipitation and frost-free period are less than average. However, extreme droughts will cause much plant death. A drought in 1949-56 resulted in widespread death of major *Juniperus* dominants in the Texas oak-juniper woodland type of the Edwards Plateau, and similar reductions in pinyon pine and juniper took place during the same drought period in the woodlands of New Mexico and Arizona (Darrow 1958).

Although the juniper-pinyon ecosystem has been used for many purposes (Sects. 2.5.1 and 2.5.3), the high costs of harvesting and the slow growth rates of pinyon and juniper trees have discouraged their management for the production of wood products (Arnold et al. 1964). The demand for forage products is greater than the demand for tree products obtained from this type, and trees are being removed in an attempt to increase forage production for livestock and big game.

Other ecosystems. Of the 14 western forest ecosystems that occur in the study region (Table 3.10), five have over 50% of their study region area in the reduced area. These include the mixed conifer forest, Arizona pine forest, California oakwoods, oak-juniper woodland, and a transition community between the oak-juniper woodland and the mountain mahogany-oak scrubland.

None of the shrublands found in the Southwest is among the five most common ecosystem types in the reduced area (Table 3.11). However, three of them, chaparral, coastal sagebrush, and ceniza shrub, have over 90% of their area in the reduced area (Table 3.10).

Two categories of grasslands are included in the study area: western and central grasslands. Of the seven western grasslands in the study area, only two of them, California steppe and grama-tobosa prairie, have 50% or more of their study region area within the reduced area. However, of the four central grassland ecosystems, three are found at 100% of their study region area in the reduced area and the other at 95.4%. One of these, the grama-buffalo grass ecosystem, is the most common ecosystem in the reduced area (Table 3.11), covering over 30% of the area.

## 4.2 CHARACTERISTICS OF PRIME AREAS IN THE REDUCED REGION

The dark area in Fig. 3.4 indicates the parts of the Southwest with the best potential for biomass energy production [i.e., those areas with greater than 30 cm (12 in.) precipitation and at least a 120-day freeze-free period each year]. There are three major subregions in the acceptable area:

1. a western area almost exclusively in California,
2. a central area primarily in Arizona, and
3. an eastern area in Colorado, New Mexico, Oklahoma, and Texas.

In addition, there are small scattered areas in Nevada, Utah, southwestern Colorado, and northwestern New Mexico. Each of the major subregions is discussed in detail below, followed by comments about the small scattered areas.

### 4.2.1 California

Although almost half of the part of California in the study region is included in the reduced area (Fig. 3.4), little of the land is available for biomass plantations. In terms of precipitation, the acceptable area in this subregion is about equally divided between areas with 30-41 cm (12-16 in.)/year and those with more than 41 cm (16 in.)/year (Fig. 3.6). In the area with more than 41 cm (16 in.)/year, most receives 41-81 cm (16-32 in.), with a small section having 81-122 cm (32-48 in.), and a very small area in the northwest part having more than 122 cm (48 in.)/year (Fig. 3.1). Winter is the season of primary precipitation maximum for this subregion, except for a small part at the eastern edge of the subregion that has a late fall maximum and a secondary maximum in winter (Fig. 2.5). In this subregion, effective precipitation is about equally divided among the three classes (Fig. 3.8).

Only in a narrow segment along the northern border of the acceptable region is the frost-free period <180 days/year (Figs. 3.2

and 3.9). A strip along the Pacific Ocean and a narrow strip on the southeast edge of the acceptable region have more than 300 frost-free days/year (Fig. 3.2).

The only part of the entire reduced region that falls in the most favorable climate suitability class is found in the California subregion (Fig. 3.10). The rest of this subregion is about evenly divided between climate favorability classes 2 and 3. None of this area falls in the least favorable category for relative climate suitability.

The largest part of this subregion falls into land ownership class A (i.e., state, private, BLM, and mixed lands, see Fig. 3.11). Only a small part is in class C (i.e., parks, wilderness, and wildlife refuges), which is not available for biomass production. These excluded areas include segments of Yosemite, Kings Canyon, and Sequoia national parks and a wilderness area.

A major part of this subregion (Fig. 3.15) is not available for biomass production because it includes the Los Angeles and San Diego metropolitan regions and their associated highlands. There are, however, other suitable lands available. Forest and woodlands are scattered throughout the subregion. Cropland in the subregion is primarily irrigated and, therefore, not suitable for biomass production according to the basic assumptions of this study, but some is nonirrigated. Rangelands are most commonly of the intermediate biomass type but also include both high- and low-biomass types.

All four soil types are found in the acceptable region in California (Fig. 3.13). The highest ranked soils for biomass production, the mollisols, are the smallest area in this subregion, being found only in a small area near the Pacific Ocean. The fourth class, dry soils and miscellaneous land types that would be poorest for growing biomass energy crops, are found along the eastern edge of the acceptable area.

Western shrub lands are the most common potential natural vegetation group in the region (Fig. 3.14), followed by western forests and western grasslands. None of the other groups is found in this subregion. Because winter is the season of major precipitation (Fig. 2.5), much of the vegetation is winter-active and summer-dormant. Much of it, especially the chaparral, is evergreen (Hanes 1981).

California chaparral is a complex and distinctive shrub formation that occurs on the hills and lower mountain slopes in much of the state (Hanes 1981). Most of the fires that occur in California natural areas occur in chaparral, so that fire suppression is a major concern, particularly near urban areas. During the June-to-December dry season, the chaparral is less than 10% moisture on a dry weight basis. Thus, harvesting during that period for use as a fuel would reduce the need for subsequent drying of the biomass and would also remove the chaparral during the season when it is most susceptible to fire. The chaparral regenerates after fires. Over half of the species that grow there sprout from stumps, independent of available water (Hanes 1981).

Thus, harvesting during the early part of the dry season might allow sprouters to begin to regenerate before the rainy season could cause severe erosion. Other species produce refractory seeds that germinate after fire, some due to scarification by heat, others due to destruction by heat of the phytotoxins produced by shrubs and found in the soil. How many of these species would germinate after harvesting rather than fire is uncertain, but at least some should.

Much of the acceptable area in California has a slope greater than 10% (Fig. 3.16), which would make harvesting biomass crops in those areas difficult. Steep land near the ocean is part of the coastal ranges that circle Los Angeles and San Diego, while steep land in the north is part of the Sierra Nevada Mountain Range.

Because of the long freeze-free period, combined with the relatively high effective precipitation, this subregion is appropriate for biomass energy crops that could not be grown in other drier, colder parts of the reduced area.

### 4.2.2 Arizona

This subregion runs from southwestern Utah through central Arizona and extends in three projections into southwestern New Mexico (Fig. 3.4).

More than half of this subregion falls into the 30-41 cm (12-16 in.)/year precipitation category (Fig. 3.6). Only a small part of east-central Arizona has more than 61 cm (24 in.)/year (Fig. 3.1). Most of the precipitation occurs in the summer, with a secondary maximum in winter (Fig. 2.5).

Evaporation for most of this subregion (Fig. 3.7) is 132-183 cm (52-72 in.)/year. As a result, the subregion is almost exclusively in the <-102 cm (<40 in.)/year effective precipitation category and quite dry (Fig. 3.6).

The most common range for frost-free days in the subregion is 180-240 days (Fig. 3.9), followed by the 120-180 range. None of the area in southern Arizona has more than 300 frost-free days/year (Fig. 3.2).

This subregion falls almost exclusively in the lower two classes for relative climate suitability (Fig. 3.10). Only a small area in the central part of the region, where the effective precipitation is in a higher category, is in the second class. The third suitability class in this subregion is not uniform. The central and southern blocks in the third class (indicated by "/" in Fig. 3.10) correspond to areas with more than 180 frost-free days/year. The northern tip of the subregion has only 120-180 frost-free days/year, but is in the third suitability class because it falls in the middle range for effective precipitation. The shorter frost-free period there is balanced by the more favorable effective precipitation range.

A small part of this subregion falls in land ownership class C (Fig. 3.11). This area includes Grand Canyon and Zion national parks, Wupatki and Saguaro national monuments, and several wilderness areas. The remaining area is about evenly divided between land ownership class A (i.e., state, private, BLM, and mixed lands) and class B (i.e., NFS, DOD, DOE, and Indian reservations). This subregion has a larger percentage of the category B lands that are less likely to be available for biomass production than the other subregions of the acceptable area.

Over half of the soils in the Arizona subregion are very dry aridisols (Fig. 3.13) in keeping with the general dryness of the subregion. The second most common soils are the mollisols, which are better for growing crops since they contain more organic matter. The smallest category for soils is the entisols, intermediate between the aridisols and the mollisols in their potential for growing crops. They are found in northern Arizona and southern Utah.

Potential natural vegetation in this subregion is about equally divided among western forests, combination western shrub and grasslands, and western shrub lands, with a small part in western grasslands (Fig. 3.14). Western forests are found mainly at the higher elevations in the middle of the subregion and correlate with the areas of steep slope (Fig. 3.16). Western shrublands are common in the southwestern part of the subregion, the very northern part, and scattered throughout the middle. Combination western shrub and grasslands are common in the southeastern part of the subregion and scattered among the western forests in the central part. Western grasslands are most common along the central edge of the subregion and extend outside the acceptable region into northeastern Arizona, where average precipitation is less than 30 cm (12 in.)/year. Therefore, species from the western grasslands may be good candidates for biomass energy crops since they should be able to survive years in which the precipitation is less than normal.

The most common land use/cover types in the subregion (Fig. 3.15) are high-, intermediate-, and low-biomass rangelands that are found throughout it. Another common type is the forest and woodlands. Any nonirrigated cropland in the subregion is in parcels too small to appear in Fig. 3.15. Irrigated, mixed croplands are found primarily in the southern part of the subregion but also in a few other scattered areas. Urban areas in the subregion, such as the cities of Tucson and Phoenix, are not available for growing biomass energy crops.

Figure 3.16 indicates that about half of this subregion has a slope greater than 10%. Although the steep area is primarily located in a band through the middle of the subregion, it also occurs in a concentrated section in the north and scattered throughout the southern part. The band of steep slope in the central part corresponds to several national forests in the Upper Gila Mountains. A relief map of the subregion indicates its general mountainous nature with relatively flat, high-elevation plateaus (USGS 1970).

This subregion is drier than other parts of the reduced area, and therefore, plants that can tolerate low levels of rainfall that vary from year to year are the best candidates for biomass energy crops here.

### 4.2.3 Eastern Subregion

The eastern section of the acceptable area covers more area than the rest of the acceptable region, including most of eastern Colorado, much of the eastern half of New Mexico, and all of Oklahoma and most of

Texas that are in the study region. The boundaries of the southern half of the subregion are determined by precipitation values (Figs. 3.1 and 3.6). With minor exceptions, the boundaries of the northern half of the subregion correspond more closely with freeze-free period values (Figs. 3.2 and 3.9).

The subregion is about equally divided between the 30-41 cm (12-16 in.)/year and >41 cm (16 in.)/year precipitation categories (Fig. 3.6). Only a very small area in north-central New Mexico has more than 61 cm (24 in.)/year precipitation.

In general, the southeastern and south-central parts of this subregion have 180-240 frost-free days/year, while the northern half has 120-180 (Fig. 3.9). An area in southern Texas has more than 240 frost-free days/year, and a very small part at the southernmost tip of Texas has greater than 300 frost-free days/year (Fig. 3.2). Different biomass energy crops could be grown in the parts of the subregion with a longer frost-free period.

Evaporation in the subregion generally increases going from north to south (Fig. 3.8). This rate combined with precipitation (Fig. 3.6) results in most of the subregion having less than -102 cm (-40 in.)/year of effective precipitation (Fig. 3.8). An area in Colorado and north-central New Mexico has effective precipitation of -76 to -102 cm (-30 to -40 in.)/year and is bounded by several areas with -25 to -76 cm (-10 to -30 in.)/year. These areas are, therefore, better in terms of effective precipitation than the more southern areas for growing biomass energy crops.

In terms of relative climate suitability (Fig. 3.10), the third favorability category is the most common, occurring in most of the southern half and also in the north-central part of the subregion. Class 4, the least favorable class, occurs in a wide band, starting at the west in central New Mexico and going northeastward to the eastern border of Colorado. In addition, there are several areas of the second favorability class scattered in northeastern and central Colorado and in central New Mexico. None of the area is in the most suitable climate class.

The subregion falls almost entirely in land ownership category A (i.e., state, private, BLM, and mixed-land owners, see Fig. 3.11). A very small part of the subregion is in category C and thus not available for growing biomass. These areas include Big Bend and Guadalupe Mountains national parks in Texas, Carlsbad Caverns National Park in New Mexico, and Lake Meredith and Amstad national recreation areas in Texas. The rest of the subregion is in category B (i.e., NFS, DOD, DOE, or Indian reservations). Several national grasslands administered by NFS are included in this subregion.

The composite of climate suitability and land availability with category C lands omitted is shown in Fig. 3.12. Most of the land in ownership class A in this subregion is in climate suitability class 3, with smaller parts in classes 4 and 2. For land ownership class B, the most common climate suitability class is class 4 (the least favorable class), followed by class 3, and then class 2.

This subregion includes all the soil types found in the study region (Fig. 3.13). The most common soil type is the mollisols, which are the most favorable for biomass production, although alfisols and entisols are almost as common. The miscellaneous category shown on the map includes vertisols in the southern tip of Texas and aridisols elsewhere.

All potential natural vegetation types except desert are found in this subregion, the most common type being central grasslands (Fig. 3.14). The only area of combined central grasslands and forests in the study region occurs in Texas. Western forests and central grasslands are found in all of the states in this subregion, and western shrublands in every state except Oklahoma. Combined western shrub and grasslands occur in Texas and New Mexico.

The most common land use type in the subregion is low-biomass rangeland, with nonirrigated and mixed irrigated croplands also abundant (Fig. 3.15). Scattered areas are found in intermediate-(mixed) and high-biomass rangeland, forests and woodlands, and the miscellaneous category (urban, salt flats, oil and gas fields, and snow and ice). Major land uses in northeastern Colorado, which has no data in Fig. 3.15, are similar to those in southeastern and east-central Colorado but with more cropland and cropland mixed with grazing land and less subhumid grassland and semiarid grazing land (USGS 1970).

Of the three major subdivisions of the acceptable region, this subregion has the least amount of land with a slope greater than 10% (Fig. 3.16). Areas with steeper slopes are scattered throughout the subregion, not concentrated in one part. The eastern half of the subregion is in the Great Plains province (Fig. 2.2), while the southwestern part is in the Basin and Range province.

Since grasslands are the prevalent ecosystem type here, herbaceous crops are the best candidates for biomass energy crops in most of this subregion. However, where climatic extremes occur, various other crops might be suitable. For example, in southern Texas the frost-free period is long enough that subtropical species could be grown, while at the higher elevations, temperate woody plants are more appropriate.

### 4.2.4 Scattered Areas

Parts of the acceptable region also occur in several small scattered areas (Fig. 3.4). These areas are located in western Nevada, north-central and southeastern Utah, western Colorado, and northwestern New Mexico.

The freeze-free period in all of the scattered areas falls in the 120-180 days/year category (Fig. 3.9). The precipitation in most of the scattered areas is in the 30-41 cm (12-16 in.)/year range (Fig. 3.6). For the area in the greater than 41 cm (16 in.)/year category, almost all is in the 41-81 cm (16-32 in.)/year range (Fig. 3.1).

Evaporation in the scattered areas (Fig. 3.7) falls in the range of 81-132 cm (32-52 in.)/year except for a small area in northwestern New Mexico, which is in the 132-183 cm (52-72 in.)/year range. The most common range for effective precipitation in the scattered areas (Fig. 3.8) is the -25 to -76 cm (-10 to -30 in.)/year range. The -76 to -102 cm (-30 to -40 in.)/year range is found in Nevada and north-central Utah and in the Four Corners area. In addition, the area in northwestern New Mexico with the highest evaporation has effective precipitation of less than -102 cm (-40 in.)/year.

None of the scattered areas are in the most favorable relative climate suitability class (Fig. 3.10). The most common class in these areas is the second most favorable class, followed by the third most favorable class. Only a small area in northwestern New Mexico is found in the least favorable climate class.

The most common land ownership class (Fig. 3.11) in the scattered areas is class A (state, private, BLM, and mixed ownership), which is considered to be most favorable for biomass production. There are a few places in these areas that fall into class C (parks, wilderness, and wildlife refuges) and that are not available for growing biomass crops. These areas include Mesa Verde National Park in southwestern Colorado and Natural Bridges National Monument in southeastern Utah.

The land in the scattered regions in ownership category A (state, private, BLM, and mixed land owners) is about evenly divided between climate suitability classes 2 and 3 (Fig. 3.12). A small part of this land ownership class, in northwestern New Mexico, is in class 4, the least favorable climate suitability class. The land in ownership class B (NFS, DOD, DOE, and Indian reservations) is more common in climate suitability class 2 than class 3, and a small part in northwestern New Mexico is in class 4, the least suitable.

Mollisols, the best soils for growing biomass crops, are the most common soil type in the scattered areas (Fig. 3.13). Entisols are also common in the scattered areas, but alfisols do not occur. The miscellaneous soil category includes aridisols, except for the western half of the area in Nevada, which is ultisols.

The most common potential vegetation types in the scattered areas are western forests and western shrublands, although western grasslands and combination western shrub and grasslands are also found (Fig. 3.14).

The scattered areas have a complex of land use/cover classes (Fig. 3.15). Rangelands, including high biomass, intermediate (mixed) biomass, and low biomass, are common. Croplands, both irrigated and nonirrigated, are also found in the scattered areas, although not in abundance. In addition, part of the scattered areas is in forest and woodlands, and part falls into the miscellaneous category (urban, salt flats, oil and gas fields, and snow and ice).

Figure 3.16 shows that the slope in much of the scattered areas is greater than 10%. This is an indication of the mountainous nature of the areas that primarily occur in the Rocky Mountains.

## 4.3 PRODUCTIVITY OF VEGETATION TYPES IN THE REDUCED AREA

Net primary productivity (i.e., the net biomass increase per unit area per year) is an important value for determining the potential of any area for terrestrial energy crops. In any landscape, primary productivity can vary over short distances as the result of differences in topography, water availability, soil quality, and successional stage of the land (Lieth 1975). In addition, the productivity of any one area can be modified by both natural (e.g., climate) and man-made (e.g., irrigation, fertilization, or frequency of harvesting) factors. Local maps that treat the productivity of particular tracts of land as a guide to their use have not been developed, although some statewide maps attempt such distinctions (Lieth 1975). Unfortunately, none has been produced for any states in the study area.

One of the assumptions of this study was that productivity could not be enhanced by routine irrigation, fertilization, etc., since that could increase the cost of energy crops to a prohibitive level. Therefore, the emphasis in this discussion is on natural productivity.

Table 4.1 gives productivity values for selected ecosystems of the world that are similar to types found in the study region. Some of the values given in this table are averages of published values, but in other cases the compilers have subjectively chosen them as reasonable, intermediate values from a range indicated by a few field measurements (Whittaker and Likens 1975). The values for world ecosystems in Table 4.1 range over almost three orders of magnitude, from a low of 30 kg•ha$^{-1}$•year$^{-1}$ for sandy, hot, dry deserts to over 20,000 kg•ha$^{-1}$•year$^{-1}$ for temperate annuals and 15,000 kg•ha$^{-1}$•year$^{-1}$ for temperate perennials. The value of 8,000 to 9,000 kg•ha$^{-1}$•year$^{1}$ for short-rotation intensive-culture woody crops is an average for productivity levels in test plots (Ranney et al. 1985). Under optimum conditions the

Table 4.1. Estimated net primary productivity of various terrestrial ecosystems

| Ecosystem type | Net primary productivity, dry weight ($kg \bullet ha^{-1} \bullet year^{-1}$) Ajtay et al. 1979 | Lieth 1975 | Ranney et al. 1985 |
|---|---|---|---|
| Forests | | | |
| Temperate evergreen/conifers | 15,000 | | |
| Temperate deciduous/mixed | 13,000 | | |
| Warm temperate mixed forests | | 10,000 | |
| Summergreen forest | | 10,000 | |
| Temperate woodlands (various) | 15,000 | 6,000 | |
| Chaparral, maquis, brushland | 8,000 | 8,000 | |
| Savanna | | | |
| Low tree/shrub savanna | 21,000 | | |
| Grass-dominated savanna | 23,000 | | |
| Dry savanna thorn forest | 13,000 | | |
| Dry thorny shrubs | 12,000 | | |
| Temperate dry grassland | 5,000 | 5,000 | |
| Desert and semidesert scrub | | | |
| Scrub-dominated | 2,000 | 700 | |
| Irreversibly degraded | 1,000 | | |
| Extreme deserts | | | |
| Sandy hot and dry | 100 | 30 | |
| Sandy cold and dry | 500 | | |
| Cultivated land | | 6,500 | |
| Temperate annuals | 12,000 | | |
| Temperate perennials | 15,000 | | |
| Woody crops (short-rotation intensive-culture) | | | 8,000-9,000 |

productivity levels of the most promising woody biomass energy crops in test plots can reach 30,000 kg•ha$^{-1}$•year$^{-1}$ dry weight. However, it is uncertain if such high values can be achieved in larger plantings on a wide range of sites that are considered marginal for conventional agriculture and, therefore, more available for energy plantations.

Productivity values are given in Tables 4.2-4.5 for all ecosystems in the reduced area for which such figures could be found. These tables do not include all the vegetation types that occur in the reduced area because information was not found for all of them. Even for those values listed, the measures are not all comparable. Productivity estimates for terrestrial communities are difficult to compare due to the variety of measuring and harvesting techniques used (Goodin and McKell 1971). This fact is evident by examining the column that indicates the various values measured in the different studies. In instances where the investigators were interested in the amount of cattle browse an area could produce, the listed values are forage and do not include woody vegetation. Some of the results are air-dried weights, others oven-dried weights, and for others there is no indication whether the values are wet or dry weights. In many cases it is not possible to correlate the ecosystems listed with the Küchler vegetation types used in this study, although that has been indicated where possible. Thus, it is impossible to determine the productivity of all the ecosystems in the reduced area with existing information.

Table 4.2. Productivity values for forest ecosystems in the Southwest

| Vegetation type | Location | Values measured | Productivity ($kg \cdot ha^{-1} \cdot year^{-1}$ unless otherwise indicated) | Source |
|---|---|---|---|---|
| Pine-oak woodland | Santa Catalina Mountains, near Tucson, Arizona | Total aboveground ecosystem (oven-dried weight) | 4,460 | Whittaker and Niering 1975 |
| Pine-oak forest | " | " | 4,960 | " |
| Low elevation pine forest | " | " | 5,800 | " |
| High elevation pine forest | " | " | 6,180 | |
| North-slope montane fir forest | " | " | 11,460 | " |
| Mesic ravine fir forest | " | " | 11,230 | " |
| Open oak woodland | " | " | 1,490 | " |
| Mountain mahogany | " | " | 1,850 | " |
| Successional aspen forest | " | " | 10,510 | " |
| Drier montane fir forest | " | " | 8,400 | " |
| Pygmy conifer-oak scrub (similar to Küchler's juniper-pinyon) | " | " | 1,860 | " |
| *Pinus edulis-Juniper osteosperma* | Grand Canyon National Park, Arizona | Pinyon pine: biomass increase of shoots | 2,303 | Darling 1966 |
| | | Pinyon: aboveground biomass increase, including needles | 3,782 | " |
| | | Estimate: total forest, aboveground, shoots only | 3,392 | " |
| | | Estimate: aboveground, total forest trees, including needles | 5,570 | " |

Table 4.2. (continued)

| Vegetation type | Location | Values measured | Productivity ($kg{\cdot}ha^{-1}{\cdot}year^{-1}$ unless otherwise indicated) | Source |
|---|---|---|---|---|
| Juniper-pinyon with grassy understory | New Mexico | Herbage: grazed | 527 | Pieper 1968 |
| | | Herbage: ungrazed | 628 | |
| Utah juniper subtype of juniper-pinyon | Arizona | Understory vegetation (grasses, forbs, & shrubs) with overstory intact | 250 | Clary 1971 |
| | | Understory vegetation (grasses, forbs, & shrubs) with overstory removed | 1,100 | |
| Juniper-pinyon | North and central Arizona | Herbage (air-dried): protected or winter-grazed | | |
| | | Intercept of tree canopy = 0% | 695 | Arnold et al. 1964 |
| | | = 10% | 417 | |
| | | = 30% | 243 | |
| | | = 50% | 125 | |
| | | = 80% | less than 56 | |
| Juniper-pinyon | North and central Arizona | Herbage (air-dried): protected or winter grazed after full season of growth, cleared of overstory vegetation | | |
| | | Seasons after clearing = 0 | 222 | Arnold et al. 1964 |
| | | = 1 | 353 | |
| | | = 2 | 381 | |
| | | = 5 | 617 | |
| | | = 8 | 689 | |
| | | = 10 | 773 | |
| | | = 13 | 762 | |
| | | Maximum expected herbage after clearing | 785 | |
| Juniper-pinyon | North and central Arizona | Herbage (oven-dried): land burned in 1953, reseeded in 1954 | | |
| | | Production values for 1958: lowest | 150 | Arnold et al. 1964 |
| | | average | 437 | |
| | | highest | 900 | |

Table 4.2. (continued)

| Vegetation type | Location | Values measured | Productivity (kg•ha$^{-1}$•year$^{-1}$ unless otherwise indicated) | Source |
|---|---|---|---|---|
| Juniper-pinyon | Arizona (Hualapai Indian Reservation) | Total herbaceous forage: After burning 13-15 years previously<br>Unburned | 453<br>154 | McCulloch 1969 |
| Juniper-pinyon, east exposure | Arizona (Hualapai Indian Reservation) | Total herbaceous forage: Untreated<br>Cabled 12 years previously | 108<br>321 | McCulloch 1970 |
| Juniper-pinyon, north exposure | Arizona (Hualapai Indian Reservation) | Total herbaceous forage: Untreated<br>Cabled 12 years previously | 129<br>268 | McCulloch 1970 |
| Juniper-pinyon | South-central New Mexico | Grass production (6-year average)<br>No fertilizer<br>Fertilized with nitrogen: 45 kg/ha<br>67 kg/ha | <br>553<br>1,064<br>1,371 | Dwyer 1971 (reported in Springfield 1976) |
| Juniper-pinyon and ponderosa pine | Near Flagstaff, Arizona | All herbaceous material, tree overstory removed 3-4 years previously: lowest<br>average<br>highest | 265<br>815<br>2,133 | Clary 1964 |
| Juniper-pinyon | Arizona | Forage production: Before juniper pinyon removal<br>After juniper-pinyon removal | 224<br>729 | Arnold 1957 |
| Juniper-pinyon | Arizona | Herbage (primarily grasses)<br>When tree canopy = 0-3% (average of 3 soil types)<br>= 16-19% (average of 2 soil types)<br>= 29-31% (average of 2 soil types) | <br>577<br>105<br>100 | Jameson and Dodd 1969 |
| Juniper-pinyon | New Mexico or Arizona (?) | Average firewood yields | 11.4 cords/acre | Howell 1940 (reported in Springfield 1976) |

Table 4.3. Productivity values for shrublands in the Southwest

| Vegetation type | Location | Values measured | Productivity (kg·ha$^{-1}$·year$^{-1}$ unless otherwise indicated) | Source |
|---|---|---|---|---|
| Chaparral | California | Total ecosystem | 1,000 | Hanes 1981 |
| Creosote bush | Rock Valley, Nevada | Total ecosystem, precipitation = 9.1 cm<br>= 24.7 cm | 144.6<br>523.9 | Barbour et al. 1977 |
| Creosote bush desert | Santa Catalina Mountains, near Tucson, Arizona | Total aboveground biomass, oven-dried | 920 | Whittaker & Niering 1975 |
| Paloverde-bursage semidesert (similar to Küchler's paloverde-cactus shrub) | " | " | 1,050 | " |
| Spinose-suffrutescent Sonoran semidesert (similar to Küchler's paloverde-cactus shrub) | " | " | 1,290 | " |

Table 4.4. Productivity values for grasslands in the Southwest

| Vegetation type | Location | Values measured | Productivity (kg•ha$^{-1}$•year$^{-1}$ unless otherwise indicated) | Source |
|---|---|---|---|---|
| Bouteloua-Agropyron | Nea Mexico | Herbage: grazed | 331 | Pieper 1968 |
| | | ungrazed | 684 | |
| Bouteloua-Artemisia | New Mexico | Herbage: grazed | 617 | " |
| | | ungrazed | 729 | |
| Bouteloua | New Mexico | Total herbage (loamy upland sites): | | |
| | | Lowest value in either year | 549 | Grace & Pieper 1967 |
| | | Average of 5 sites in 2 years | 1,126 | |
| | | Highest value in either year | 1,889 | |
| Bouteloua-Muhlenbergia | New Mexico | Total herbage (shallow upland site): 1964 | 573 | " |
| | | 1965 | 1,004 | |
| Bouteloua | New Mexico | Total herbage (stony hills sites): | | " |
| | | Lowest value in either year | 423 | |
| | | Average of 3 sites in 2 years | 650 | |
| | | Highest value in either year | 829 | |
| | | (highest and lowest values were for the same site in different years) | | |
| Bulbilis(=Buchloë)-Bouteloua | Burlington, Colorado | Dry weight, average of 3 years | 1,500 | Weaver 1924 |
| Agropyrum (=Agropyron) | " | Dry weight, average of 2 years | 4,500 | " |
| Mixed short and tall grasses | " | " | 2,300 | " |
| Bouteloua-Buchloë | Nunn, Colorado | Dry weight, average of 9 estimates | 1,450 | Lauenroth 1979 |

Table 4.4. (continued)

| Vegetation type | Location | Values measured | Productivity (kg.ha$^{-1}$.year$^{-1}$ unless otherwise indicated) | Source |
|---|---|---|---|---|
| *Bouteloua-Buchloë* | Boulder, Colorado | Dry weight, average of 4 estimates | 2,980 | Moir 1969 (cited in Laurenroth 1979) |
| *Bouteloua-Buchloë* | Amarillo, Texas | Dry weight, average of 3 estimates | 2,570 | Lauenroth 1979 |
| *Bouteloua-Buchloë* | Pawnee, Colorado | Total aboveground ecosystem, dry weight | | |
| | | Lowest year | 600 | Dodd and Lauenroth 1979 |
| | | Average of 6 years | 1,230 | |
| | | Highest year | 1,800 | |
| *Hilaria-Bouteloua* (desert grassland) | SE Pima County, Arizona | Air-dried forage: | | |
| | | No fertilizer | 1,438 | Freeman and Humphrey 1956 |
| | | Fertilizer added: | | |
| | | Superphosphate (0-20-0) | | |
| | | 112 kg/ha | 1,518 | " |
| | | 224 kg/ha | 1,471 | |
| | | 448 kg/ha | 1,787 | |
| | | Ammonium phosphate (16-20-0) | | |
| | | 112 kg/ha | 1,762 | " |
| | | 224 kg/ha | 1,906 | |
| | | 448 kg/ha | 2,053 | |
| | | Ammonium nitrate (32-0-0) | | |
| | | 112 kg/ha | 1,914 | " |
| | | 224 kg/ha | 1,830 | |
| | | 448 kg/ha | 1,789 | |
| Desert grassland (*Bouteloua*) | Santa Catalina Mountains, near Tucson, Arizona | Total aboveground ecosystem, oven-dried | 1,390 | Whittaker and Niering 1975 |

Table 4.5. Productivity values for combination grass and shrublands in the Southwest

| Vegetation type | Location | Values measured | Productivity (kg•ha$^{-1}$•year$^{-1}$ unless otherwise indicated) | Source |
|---|---|---|---|---|
| Semidesert grass shrub with mesquite (*Bouteloua-Aristida-Prosopis*) | Santa Rita Mountains near Tucson, Arizona | Perennial grasses, 10-year average (range) | | Cable and Martin 1975 |
| | | Pasture #8 | 466 (221-832) | |
| | | Pasture #10 | 488 (213-961) | |
| | " | Annual grasses, 10-year average | | |
| | | First pasture | 98 | |
| | | Second pasture | 29 | |
| Semidesert grass shrub with mesquite killed (*Bouteloua-Aristida*) | " | Perennial grasses, 10-year average (range) | | |
| | | Pasture #1 | 587 (316-867) | " |
| | | Pasture #7 | 395 (130-645) | |
| | " | Annual grasses, 10-year average | | |
| | | First pasture | 233 | |
| | | Second pasture | 167 | |
| Semidesert grass-shrub, mesquite infested | Southern Arizona | Perennial and annual grasses over a 20-year period | | Martin 1975 |
| | | 30 cm (12 in.) annual rainfall | 45-280 | |
| | | 41 cm (16 in.) annual rainfall | 336-1345 | |
| Mixed brush community | Santa Rita Mountains near Tucson, Arizona | Perennial native forage | | Cox et al. 1982 |
| | | Before treatment | 250 kg/ha | |
| | | After shrub competition was removed: | | |
| | | 4 months and 5 cm of precipitation later | 800 kg/ha | |
| | | 16 months and 17 cm of precipitation later | 2500 kg/ha | |
| | | 28 months and 38 cm of precipitation later | 3200 kg/ha | |
| Desert-shrub (*Larrea tridentata-Flourensia*) (creosote bush-tarbush) | Southeastern Arizona | Net annual primary production, dry weight | 1,400 | Chew and Chew 1965 |

Some of the values in Tables 4.2-4.5 represent fertilization and/or irrigation studies. Although it is not the intention of the biomass program to include the extra costs of routine irrigation and/or fertilization in the production of biomass energy crops, these values are included to give an indication of the increases in productivity of these lands that could result from such additions.

The highest ecosystem productivity value found, 11,460 kg•$ha^{-1}$•$year^{-1}$, was for a north-slope montane fir forest in the Santa Catalina Mountains near Tucson, Arizona (Table 4.2). Values for other forest ecosystems ranged down almost an order of magnitude to a low of 1,490 kg•$ha^{-1}$•$year^{-1}$ for an open oak woodlands in the same area. The former value is comparable with the net primary productivity of forest ecosystems, and the latter value is in the range for desert regions (Table 4.1).

The juniper-pinyon woodland is one of the five most common vegetation types in the reduced area, but is also common outside the reduced area (Table 3.11). Several values for productivity were found for the juniper-pinyon type, although it is not certain if they were all located in the reduced area. Most of the productivity values for the ecosystem were only for herbage because the investigators were interested in the amount of food available for cattle. However, two investigations reported figures that included woody vegetation. Whittaker and Niering (1975) gave a total ecosystem figure of 1,860 kg•$ha^{-1}$•$year^{-1}$ for a pygmy conifer-oak scrub forest that is similar in species composition to Küchler's juniper-pinyon type.

Darling (1966) estimated a value of 5,570 kg•$ha^{-1}$•$year^{-1}$ for total aboveground tree biomass for a juniper-pinyon forest in Grand Canyon National Park in northern Arizona. The highest herbage value for the juniper-pinyon ecosystem, 2133 kg•$ha^{-1}$•$year^{-1}$, was reported for an area in which the overstory had been removed three to four years previously (Clary 1964). The two other forage values greater than 1,000 kg•$ha^{-1}$•$year^{-1}$ that were found (Dwyer 1971, reported in Springfield 1976) were the result of adding nitrogen fertilizer to increase production. Several studies (Clary 1964, 1971; Arnold et al. 1964; McCulloch 1969, 1970; and Arnold 1957) reported increases in forage or understory vegetation after removing the tree overstory by various methods, such as cabling and burning. In addition, Arnold et al. (1964) and Jameson and Dodd (1969) reported an inverse correlation between the amount of forage produced and the amount of tree canopy (i.e., forage was highest at the lowest values of tree canopy and was progressively lower as the tree canopy increased). Since the productivity values for the juniper-pinyon forest are higher for woody vegetation than for forage, this ecosystem is a better candidate for woody biomass energy crops than herbaceous ones. However, because of the variety of conditions under which the juniper-pinyon ecosystem can grow and the variation in the type itself throughout its range, it is difficult to predict the amount of biomass that could be produced at any particular site. Therefore, site-specific studies will be necessary to determine the amount of biomass energy that could be produced at various places within the juniper-pinyon forest.

Values for western shrub ecosystems (Table 4.3) range from a low of 144.6 kg•ha$^{-1}$•year$^{-1}$ (Barbour et al. 1977) for a creosote bush shrubland with only 9 cm (23 in.) precipitation per year to 1,290 kg•ha$^{-1}$•year$^{-1}$ for a Sonoran semidesert that is similar in species composition to Küchler's paloverde-cactus shrub (Whittaker and Niering 1975). Even the highest of these is less than 20% of the lowest value for cultivated land (Table 4.1).

Productivity values for grasslands (Table 4.4) ranged from 331 kg•ha$^{-1}$•year$^{-1}$ for a grazed Bouteloua-Agropyron grassland in New Mexico (Pieper 1968) to 4,500 kg•ha$^{-1}$•year$^{-1}$ for an Agropyrum (=Agropyron) grassland in Burlington, Colorado (Weaver 1924). Of the 32 values included in Table 4.4, only four others are higher than 2,000 kg•ha$^{-1}$•year$^{-1}$, and the median value is 1,460 kg•ha$^{-1}$•year$^{-1}$. The highest value is slightly lower than that included in Table 4.1 for temperate dry grasslands, and the median value is in the range reported for desert and semidesert scrub. The highest value is significantly below the productivity for cultivated land listed in Table 4.1.

Values for ecosystems of combination grass and woody vegetation (either shrubs or forests) (Table 4.5) ranged from a low of 45 kg•ha$^{-1}$•year$^{-1}$ for just the annual and perennial grasses in a semidesert grass-shrubland infested with mesquite (Martin 1975) to a total ecosystem value of 1,400 kg•ha$^{-1}$•year$^{-1}$ for a creosote bush-tarbush desert shrub land in southeast Arizona (Chew and Chew 1965). The latter value is the only total ecosystem value found, the rest being only the perennial and/or annual grass production of the ecosystem. Even the total ecosystem value is low in comparison with the ecosystem productivity figures listed in Table 4.1. Ecosystem productivities may be higher for other types for which data was not available.

Productivity rates commonly seen for short-rotation woody biomass energy crops in test plots in mesic regions range from 4,000-15,000 $kg{\bullet}ha^{-1}{\bullet}year^{-1}$ dry weight with an average of 8,000-9,000 $kg{\bullet}ha^{-1}{\bullet}year^{-1}$ dry weight (Ranney et al. 1985). For the most promising species on good sites under optimum management strategies, productivity levels of 10,000-30,000 $kg{\bullet}ha^{-1}{\bullet}year^{-1}$ dry weight are achieved. The highest values for woody ecosystems reported in Tables 4.2-4.5 include several that fall within the ranges reported for short-rotation woody crops in test plots. However, those ecosystems with the highest productivity values are situated on steep slopes, so that harvesting and improving productivity through the use of superior trees or very intense management would be extremely difficult if not impossible. Thus, the best sites in the Southwest for woody biomass crops in terms of productivity are probably too steep for such uses.

## 4.4 POTENTIAL OF VARIOUS SPECIES AS BIOMASS ENERGY CROPS

Several recent symposia and investigations have focused on the energy potential of southwestern plants (Bender 1966, McGinnies et al. 1971, McKell et al. 1972, Goodin and Northington 1979). A technology assessment of the production and processing requirements needed to make 15 southwestern plant species useful to electric utilities is reported by Foster and Brooks (1981). Measurements of the growth characteristics and fuel qualities of selected individuals of several native species of shrubs in the basin and range region are described by Van Epps et al. (1982). After a literature screening of 2900 potential candidate species, Goodin and Newton (1983) report progress on plantings of four species in Texas. Felker et al. (1983) examined leguminous trees for use on hot, arid lands in California's Imperial Valley. The principal plant species considered in each of these studies are listed in Table 4.6. Most of the species considered in depth as possible energy crops were woody plants, either shrubs or small trees. However, a few herbs, both annuals and perennials, were also considered.

Mesquite (*Prosopis* spp.) and fourwing saltbush (*Atriplex canescens*) are considered to be promising biomass energy crop species in the semiarid Southwest based on preliminary species screening trials (Felker et al. 1983, Newton et al. 1982). The western edge of what is usually considered the Great Plains region includes the northern and central parts of the eastern subregion of the acceptable area in this study. Promising hardwood species in that area include black locust (*Robinia pseudoacacia*), Siberian elm (*Ulmus pumila*), and silver maple (*Acer saccharinum*) based on studies conducted in Kansas (Geyer 1985).

Table 4.7 gives estimated or measured yields for individual species that grow in the Southwest or elsewhere in the world under similar environmental conditions. The first four figures in Table 4.7

Table 4.6. Potential energy crop species for the Southwest

| Species (common name) | Foster & Brooks (1981) | Van Epps et al. (1982) | Goodin & Newton (1983) | Felker et al. (1983) |
|---|---|---|---|---|
| WOODY PLANTS (mainly shrubs or small trees) | | | | |
| *Acacia* spp. (acacia) | X | | | |
| *Artemisia tridentata* (big sagebrush) | X | X | | |
| *Atriplex canescens* (fourwing saltbush) | X | X | X | |
| *A. lentiformis* (big saltbush) | | X | | |
| *Casuarina equisetifolia* (she-oak) | X | | | |
| *Cercidium floridium* (paloverde) | | | | X |
| *Chrysothamnus linifolius* (spreading rabbitbrush) | | X | | |
| *C. nauseosus* (rubber rabbitbrush) | | X | | |
| *Eucalyptus* spp. (eucalyptus) | X | | | |
| *Larrea tridentata* (creosote bush) | X | | | |
| *Leucaena* spp. (lead-tree) | | | | X |

Table 4-6. (continued)

| Species (common name) | Foster & Brooks (1981) | Van Epps et al. (1982) | Goodin & Newton (1983) | Felker et al. (1983) |
|---|---|---|---|---|
| *Olneya tesota* (desert ironwood) | | | | X |
| *Parkinsonia aculeata* | | | | X |
| *Prosopis* spp. (mesquite) | X | | | X |
| *P. glandulosa* (mesquite) | | | X | X |
| *Sarcobatus vermiculatus* (greasewood) | | X | | |
| *Tamarix* spp. (salt cedar) | X | | | |
| HERBS | | | | |
| *Asclepias* spp. (Perennial) (milkweed) | X | | | |
| *Euphorbia lathyris* (Annual) (gopher plant) | X | | | |
| *Kochia scoparia* (Annual) (kochia) | | | X | |
| *Salsola kali* (Annual) (Russian thistle) | X | | | |
| *Sorghum halepense* (Perennial) (Johnson grass) | | | X | |

Table 4.7. Productivity of individual species

| Vegetation type | Location | Values measured | Productivity ($kg \cdot ha^{-1} \cdot year^{-1}$ unless otherwise indicated) | Source |
|---|---|---|---|---|
| Big sagebrush (*Artemisia tridentata*) | Wyoming (Buffalo Bill Reservoir) | Average plant biomass (oven-dry weight) of large individuals for highest yielding of 4-5 sites times plant density in nature | 20,924 kg/ha | Van Epps et al. 1982 |
| Fourwing saltbush (*Atriplex canescens*) | Utah (St. George) | " | 9,811 kg/ha | " |
| Greasewood (*Sarcobatus vermiculatus*) | Utah (Davis Spring Road) | " | 97,395 kg/ha | " |
| Rubber rabbitbrush (*Chrysothamnus nauseosus*) | Utah (?) | " | 76,328 kg/ha | " |
| Mesquite (*Prosopis* sp.) | Various | Pods from mature orchards, no irrigation or nitrogen after establishment, with groundwater or 25- to 50-cm annual rainfall | 4,000-10,000 | Felker 1979 |
| | Chile | Pod and foliage yields in salt desert with only ground water | 7,000 | Salinas and Sanchez 1971 (cited in Felker 1979) |
| | West Pakistan | Highest annual timber yield (clear bole) with 25 cm annual rainfall | 8,000 | Ahmed 1961 (cited in Felker 1979) |

Table 4.7. (continued)

| Vegetation type | Location | Values measured | Productivity ($kg \cdot ha^{-1} \cdot year^{-1}$ unless otherwise indicated) | Source |
|---|---|---|---|---|
| Saltbush (*Atriplex polycarpa*) | Southern California | Dry weight yields: | | |
| | | Irrigated (1968) | 3,805 | Goodin and McKell 1971 |
| | | Nonirrigated (1969) | 7,599 | |
| Saltbush (*A. lentiformis*) | " | Irrigated (1968) | 6,185 | " |
| | | Nonirrigated (1969) | 10,169 | |
| Saltbush (*A. canescens*) | " | Nonirrigated (1969) | 9,189 | " |
| *Opuntia* sp. | Northern Mexico | Average annual forage production, dry matter | 5,000 | Rojas et al. 1966 (cited in Goodin and McKell 1971) |

are standing biomass of large individuals of the listed species at the density that they occur in nature (Van Epps et al. 1982). No age was given for any of the shrubs, so these figures cannot be translated into productivity values. It was assumed that those large individuals have a genetic advantage for growing bigger and faster than average for the species and would produce offspring equally as large. Laboratory tests were also done on these species to determine their heat of combustion. The heat produced from the combustion of woody and annual material was about the same for each species except greasewood (Sarcobatus vermiculatus), for which the current year's growth produced less heat than the woody material. The estimated energy potential for these four species ranged over an order of magnitude from a high of 4.585 x $10^8$ kcal/ha (Van Epps et al. 1982) for greasewood to 4.44 x $10^7$ kcal/ha for big sagebrush (Artemisia tridentata). The potential for biomass energy production from these shrubs may be increased with minimal management. Van Epps et al. (1982) suggest that a possible strategy in planning for biomass production from shrubs in semiarid regions would be to grow genetically superior plants in spaced plantings to optimize the use of soil moisture. Research is currently underway to establish a tissue culture system to allow rapid, low-cost, high-volume propagation of the elite gigas biotype of Atriplex canescens for biomass production (McKell et al. 1985). Energy production of rangeland, thus, could be an additional multiple use, since grazing and recreation could still be possible during the periods between harvesting the plants for biomass energy.

The values in Table 4.7 for saltbush species (Atriplex sp.) in southern California present an interesting anomaly in that dry weight yields were higher in the year when they were not irrigated than in the year when they were (Goodin and McKell 1971). No reason is given in the report for this discrepancy, but it could be due to a difference in natural rainfall in the 2 years. This difference exemplifies one of the difficulties in growing biomass energy crops in a region in which the rainfall can be so variable from year to year. Even with this variation, Goodin and McKell conclude that harvesting saltbush as a forage crop has considerable potential in marginal lands subject to prolonged drought or excessive salinity. Production of such crops for biomass energy could also be possible, depending on the costs of harvesting and transporting them to a conversion site and on the energy value of the dried crop.

Several productivity values for mesquite species in dry areas around the world are given in Table 4.7. These values are within the range listed in Table 4.1 for cultivated crops. The values for three species of saltbush in Table 4.7 range from just under 4,000 $kg \bullet ha^{-1} \bullet year^{-1}$ to just over 10,000 $kg \bullet ha^{-1} \bullet year^{-1}$ which is the low part of the range of current productivity levels of biomass hardwood energy crops (Ranney et al. 1985). On the basis of their productivity levels in nature, therefore, these genera have promise as biomass energy crops in the Southwest.

The last entry in Table 4.7 is Opuntia spp., commonly called prickly pear or cholla, a member of the cactus family. Many species occur in the western hemisphere, but the exact number is uncertain (Correll and Johnston 1970). Some species in the genus have characteristics that increase their potential as biomass energy crops. For example, some species and varieties are spineless, making handling during harvesting and conversion easier. Although most species are shrubs or bushes, others are small trees. Hybrids occur naturally, so genetic manipulations to enhance desired characteristics are feasible. Cultivation requirements are already known for species grown as ornamentals. Some of these escape and become pests, indicating their adaptability to the prevailing climate conditions. Thus, some species in the genus may have potential as biomass energy crops, but economic analysis and further research is needed to determine the feasibility of such use.

## 4.5 OTHER CONSIDERATIONS

### 4.5.1 Economic Viability

A major question that is not considered in this investigation is whether terrestrial energy crops can be economically produced in the Southwest. Economic evaluations to address the trade-offs among productivity; rotation length/number (for woody species); and costs of harvest, transportation, storage, conversion, etc., need to be undertaken before a decision can be reached on the suitability of the Southwest for commercial production of biomass energy crops. In other words, can enough biomass be produced to justify the research and investment costs that are needed to establish and run a biomass energy project?

Economic considerations should include an investigation of the competition with other land uses, such as food crops, grazing, and recreation. Land that is marginal for conventional agriculture for various reasons might be able to grow crops solely for their energy content (Slesser and Lewis 1979). Land that has a high salt content could grow native species that can survive in conditions where most food crops cannot (Goodin 1979). Also, some of the abandoned farmland in the Southwest has irrigation systems in place that could be used for crop establishment. For example, in five counties in southeastern Arizona, it is estimated that over $9 \times 10^5$ ha ($2 \times 10^6$ acres) of irrigated farmland were abandoned between 1900 and 1980 (Cox et al. 1983). In cases where irrigation water is too salty for use on food crops, it may even be possible to use it on energy crops if the delivery costs are not too high. The low population density in most of the region, coupled with the distance between major population centers, must also be considered in an analysis of the ability of the region to economically produce energy crops.

Production of biomass energy crops could be an additional use of national forest lands. These lands are common in the Southwest and have a legislative mandate to be managed for multiple purposes. Grazing and recreational use might be able to continue on rangelands during the periods between harvests of woody vegetation, which would only occur every few years (Van Epps et al. 1982). Thus, the costs of growing energy crops could be spread over multiple uses instead of being exclusively assigned to energy production.

Species that contain valuable constituents that can be separated as by-products during the processing of biomass for energy are more likely to be profitable energy crops. Thus, a species that cannot currently be grown profitably solely for its energy content might be profitable if it contains sufficient quantities of valuable nonfuel co-products, such as natural rubber, hard vegetable waxes, edible vegetable oils, specialty and medicinal chemicals, or textile fibers (Lipinsky and Kresovich 1979). Then, if energy costs rise to levels that justify the production of crops simply for their energy content, projects would be in place that could take advantage of the price increases.

Biomass energy production may be viable if coupled to other programs in a multipurpose project that has more than one end product. For example, removing the California chaparral might provide an energy source while reducing a fire hazard. [The Pacific Southwest Forest and Range Experiment Station sponsored a seminar in 1976 to investigate the feasibility of doing that (cited in Van Epps et al. 1982).] Mesquite removal on rangelands could not only provide a fuel but also increase the amount of forage available for cattle (Sects. 2.5.1 and 4.3). Energy crops could be a source of jobs for native Americans whose reservations are common in isolated parts of the Southwest where jobs are often scarce.

All these and other economic trade-offs need to be considered before the Southwest can be finally accepted or rejected as a region for commercial-scale biomass energy crop production. While the region as a whole may not be fit for such production, there may yet be places within the region where biomass energy crops would be viable.

4.5.2 Factors to Consider in Identifying Biomass Energy Crop Species

The vegetation of arid regions throughout the world tends to be generally similar in form and function as a result of similar conditions of scanty and irregular moisture supply. Thus, the search for biomass energy crops for the Southwest should not be restricted entirely to native species; there are many plants adapted to similar environmental conditions in other arid and semiarid regions of the world. However, care must be taken if exotic species are used because it is possible for them to escape and become weeds.

Because of the variability of the climate in the Southwest, biomass energy crops must be species that can survive during years when the climate is significantly drier and/or colder than normal. Species that can survive severe moisture limitations are, thus, good biomass energy candidates. Under such conditions, deep-rooted, perennial shrubs offer a better potential than do grasses for improved productivity on the harsh sites found in much of the Southwest (Goodin and McKell 1971). For example, mesquite (*Prosopis* sp.) roots can reach almost 50 m below the ground and extend outward for 18 m (Mooney et al. 1977). They can tap both groundwater and water in the upper soil horizon and thus survive when precipitation is low.

Three of the five most common vegetation types in the reduced area (Table 3.11) are grassland and woody vegetation combinations: mesquite-buffalo grass, grama-tobosa shrubsteppe, and trans-Pecos shrub savanna. For the first of these, all of it that occurs in the study area is found in the reduced area. For the latter two, about 50% of their area in the Southwest is found in the study area. These two can survive in conditions drier and/or cooler than those found in the reduced area and, therefore, could survive during years when climate conditions there are below average. Thus, the species in these two vegetation types (see Appendix) should be screened to select those with the highest productivity, since they are the most likely candidates for biomass energy crops.

Species that use the $C_4$ or CAM pathway of carbon metabolism are good candidates for biomass energy crops on marginal lands, particularly in the arid or semiarid environments common in the Southwest. Their photosynthesis process is highly efficient at high temperatures, and they efficiently utilize water during their growth, both characteristics that increase growth in the climate in the Southwest (Slesser and Lewis 1979) (Sect. 2.4).

Species that sprout from their stumps or roots after cutting or burning are also good candidates for biomass energy crops because they need to be planted only once to produce multiple crops. This characteristic reduces both the costs and the environmental problems associated with crop establishment (Ranney et al. 1985). Many species native to the Southwest have such a capacity. Half of the species in the California chaparral stump sprout as an adaptation to the fires that occur every 10-40 years there (Hanes 1981). Alligator juniper (Juniper deppeana) is the only juniper in the Arizona pinyon-juniper forest that stump sprouts. Almost all young trees of that species sprout when cut, but trees with trunks 0.6 m (2 ft) or more in diameter are unlikely to do so (Arnold et al. 1964). Spreading rabbitbush (Chrysothamnus linifolius) and mesquite (Prosopis sp.) are other species that stump sprout (Van Epps et al. 1982, Felger 1977).

Other considerations involve the microorganisms that grow as symbionts on or in the roots of many plant species. Many woody plants have ectomycorrhizal fungi as symbionts on their roots, which substantially increase the growth of the plants (Abelson 1985). Investigations into ways to enhance their functioning on species in the Southwest might lead to increased productivity of biomass energy crops there. Also, since it was assumed that routine application of fertilizers would not be cost-effective in growing biomass energy crops in the Southwest, those species that have symbiotic relationships with nitrogen-fixing bacteria are good candidates for biomass energy crops (Slesser and Lewis 1979).

Species that contain valuable constituents that can be extracted as co-products or by-products (e.g., natural rubber, hard vegetable waxes, edible vegetable oil, or textile fibers) are good energy crop candidates until fuel prices rise to levels that justify growing crops solely for their energy content (Lipinsky and Kresovich 1979).

Thus, investigations of native ecosystems should be directed at identifying species that tolerate climatic conditions drier and/or colder than normal, that have the $C_4$ or CAM carbon metabolism, that sprout from their stumps or roots when cut or burnt, that produce valuable by-products, and that have bacterial symbionts that fix nitrogen.

4.5.3 Matching Site-Specific Conditions and Potential Species

Using the data set prepared for this study, the climate and land characteristics (precipitation, soils, evaporation, land use, etc.) of each ecosystem can be summarized. Of the 43 vegetation types in the study region, 34 are found in the reduced area (Table 3.10). For these 34, two have only 5.5% of their area in the reduced area, while ten are located entirely in the reduced area. For those 24 ecosystems that occur both within and outside of the reduced area, two lists could be prepared to indicate what conditions, other than freeze-free period or precipitation limits, differ in the places where the ecosystem grows in the reduced area and in the rest of the Southwest. There would, of course, be just one list for those ecosystems that occur only in the reduced area. These compilations may indicate subgroups of some ecosystems, such as juniper-pinyon forests, that are not uniform over the wide area where they occur in the Southwest. Thus, for each ecosystem in the reduced area, the climatic conditions under which it grows and the land characteristics where it is located can be identified.

When the data are tabulated, species that have the potential to grow on a particular site could be identified. The simplest way to do this is to determine which of Küchler's potential natural vegetation types occurs at that site. However, by using the data base summary of ecosystem climatic and land characteristics, the features of the site could be matched with those of other potential natural vegetation types to identify ecosystems that grow under similar conditions. Then the species in these ecosystems could be screened to select those that are potential biomass energy crops at a particular site in the Southwest. In this way, the data base could be searched to identify species that could tolerate the natural conditions that occur at a particular site and to identify species to screen as potential biomass energy crops.

The data base could also be used to identify areas where species that have been identified as potential biomass energy crops could be grown. For native species, the natural conditions under which they grow could be identified from the data base, and then areas with similar climatic conditions could be located. For non-native species, this could also be done if the conditions that are required for their growth have been characterized, either under cultivation or natural conditions. Thus, if the conditions under which these potential energy crops can grow are known, areas that have these conditions could be identified from the data base, and the search for sites to grow energy crops narrowed to those areas.

Using the data base developed for this study in the manner described above follows the approach advocated by Lipinsky and Kresovich (1979):

> One must first determine which species of plants grow naturally in the given or similar environment, and then attempt to exploit them rather than introducing a plant with different environmental adaptations and attempting to alter the environment to the plant. . . . From these regional efforts, candidates can be pooled to determine which species will perform best in a given set of environmental conditions.

### 4.5.4 Additional Questions

Because of the variation in the climate in the Southwest, the weather in any year can be colder and/or drier than the minimum used to define the reduced area (i.e., 120 days/year frost-free period and 30-cm average annual precipitation). Since minimum values for average precipitation and frost-free period are so low in much of the area, a variation that is minor in an area with higher precipitation or longer frost-free period could be significant in the Southwest (e.g., if rainfall is 15 cm below average, it is a 50% reduction where average precipitation is 30 cm/year, but only a 12% reduction in an area that has annual precipitation of 125 cm/year). Thus, within the reduced area, those parts that have higher average rainfall and/or longer frost-free periods (Figs. 3.6 and 3.9) or in which the variance from the average is lowest would be the best areas for initial investigation of biomass energy crop production because the weather should be less extreme in those areas.

Additional productivity studies of natural ecosystems could provide useful information on possible biomass energy crop production levels. The values listed in Tables 4.2-4.5 do not include all of the ecosystems that are found in the reduced area. Thus, productivity information is not available on many species that are adapted to the local climate. Since all the values reported in those tables are not comparable, it is difficult to predict which ecosystems are the best ones for further investigations as crop lands.

Many plants and animals listed as threatened or endangered by the U.S. Fish and Wildlife Service (USFWS 1986) are found in the Southwest. The possible occurrence of these species must be considered in assessing the potential of an area in the Southwest for biomass energy crop production (DOE 1983).

There are numerous other federal and state laws and regulations that must be complied with by DOE when undertaking major activities such as demonstration projects. Some of these that might be applicable to biomass energy crop production in the Southwest, in addition to the Endangered Species Act, include the Fish and Wildlife Coordination Act, the American Indian Religious Freedom Act, the National Historic Preservation Act, and the National Environmental Policy Act.

# 5. CONCLUSIONS

The southwest United States is an area of diverse climate, vegetation, soils, topography, and terrain. It is not surprising that the potential for growing terrestrial energy crops also varies throughout the region. Natural productivity of much of the land in the Southwest is low. Even in years when weather is best for plant growth, it may still be difficult to grow an economical crop on much of the land there. Thus, production of crops in the Southwest solely for their energy content may be difficult unless energy prices rise significantly. However, multipurpose projects in which energy production is one aspect may be feasible and should be considered.

Use and management of arid and semiarid ecosystems by man must consider the limitations of the environment. Overuse of vegetation can result in increased susceptibility of the soil to wind and water erosion, since relatively long periods of time are required for regeneration and restoration of plants and soils. Prudent stewardship thus involves avoiding excessive risks by, for example, managing in accordance with the minimum annual precipitation. Because plant growth depends on the amount of soil moisture that is available, flexible management technologies are required that are capable of both maximizing production during particularly wet years and stabilizing production under drought conditions. Techniques to be considered include mixed species inter-cropping, water-harvesting, and efficient fertilizer application with provisions for midseason adjustments (Mann 1981).

This study shows that the potential for production of biomass energy crops in the Southwest is limited. Even in those parts of the region that have precipitation and a growing season adequate for crop production, other factors, such as soil, slope, or conflicting land uses, will limit the amount of biomass energy crops that can be grown there. Further site-specific research in the parts of the region that are best suited for plant growth is necessary to determine the contribution that the Southwest can make to the nation's energy supply through biomass energy crops.

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# APPENDIX

## CHARACTERISTIC SPECIES OF THE MOST COMMON NATURAL VEGETATION TYPES IN THE REDUCED AREA

APPENDIX

Characteristic species of the most common natural vegetation types in the reduced area

| Unit Number Atlas[a] | Orig.[b] | Name | Physiognomy | Occurrence | Dominants | Other components |
|---|---|---|---|---|---|---|
| 58 | 65 | Grama-buffalo grass (*Bouteloua-Buchloë*) | Fairly dense grassland of short grass with somewhat taller grasses in the eastern sections | Eastern parts of New Mexico and Colorado, southeastern Wyoming, western parts of Nebraska, Kansas, Oklahoma, and Texas | Blue grama (*Bouteloua gracilis*)<br>Buffalo grass (*Buchloë dactyloides*) | *Agropyron smithii*<br>*Aristida purpurea*<br>*Bouteloua curtipendula*<br>*B. hirsuta*<br>*Gaura coccinea*<br>*Grindelia squarrosa*<br>*Haplopappus spinulosus*<br>*Lycurus phleoides*<br>*Muhlenbergia torreyi*<br>*Opuntia* spp. (southern part)<br>*Plantago purshii*<br>*Psoralea tenuiflora*<br>*Raxibida columnifera*<br>*Senecio* spp.<br>*Sitanion hystrix*<br>*Sphaeralcea coccinea*<br>*Sporobolus cryptandrus*<br>*Yucca glauca*<br>*Zinnia grandiflora* |
| 21 | 23 | Juniper-pinyon woodland (*Juniperus-Pinus*) | Open groves of needleleaf evergreen low trees with varying admixtures of shrubs and herbaceous plants | California to Colorado; southward to Arizona and New Mexico | Oneseed juniper (*Juniperus monosperma*)<br>Utah juniper (*Juniperus osteosperma*) | *Agropyron smithii*<br>*Artemisia tridentata* (not in southern part)<br>*Bouteloua curtipendula*<br>*B. gracilis*<br>*Ceanothus* spp. |

APPENDIX (continued)

| Unit Number<br>Atlas[a] | <br>Orig.[b] | Name | Physiognomy | Occurrence | Dominants | Other components |
|---|---|---|---|---|---|---|
| 21 | 23 | Juniper-pinyon woodland (*Juniperus-Pinus*) | Open groves of needleleaf evergreen low trees with varying admixtures of shrubs and herbaceous plants | California to Colorado; southward to Arizona and New Mexico | Pinyon pine (*Pinus edulis*) (more in eastern part)<br>Oneleaf pine (*Pinus monophylla*) (more in western part) | *Cercocarpus* spp.<br>*Chrysothamnus* spp.<br>*Cowania mexicana*<br>*Fallugia paradoxa*<br>*Juniperus deppeana* (southern part)<br>*J. occidentalis*<br>*Oryzopsis hymenoides*<br>*Purshia tridentata*<br>*Quercus emoryi*<br>*Q. gambelii*<br>*Q. grisea*<br>*Q. undulata*<br>*Sporobolus cryptandrus* |
| 76 | 85 | Mesquite-buffalo grass (*Bouteloua-Buchloë-Prosopis*) | Short grass with scattered low broadleaf deciduous trees and shrubs and low needleleaf evergreen shrubs | Northwestern Texas, southwestern Oklahoma | Buffalo grass (*Buchloë dactyloides*)<br>Mesquite (*Prosopis juliflora* var. *glandulosa*) (not in northern part) | *Acacia greggii*<br>*Aristida purpurea*<br>*A. roemeriana*<br>*Bouteloua gracilia*<br>*B. hirsuta*<br>*B. trifida*<br>*Condalia obovata*<br>*Juniperus pinchotii*<br>*J. virginiana* (northeastern part)<br>*Quercus virginiana* var. *fusiformis*<br>*Schedonnardus paniculatus*<br>*Yucca galuca* |

APPENDIX (continued)

| Unit Number Atlas[a] | Orig.[b] | Name | Physiognomy | Occurrence | Dominants | Other components |
|---|---|---|---|---|---|---|
| 52 | 58 | Grama-tobosa shrubsteppe (*Bouteloua-Hilaria-Larrea*) | Short grasses with a shrub synusia varying from very open to dense | Southeastern Arizona, southern New Mexico | Black grama (*Bouteloua eriopoda*)<br>Tobosa (*Hilaria mutica*)<br>Creosote bush (*Larrea divaricata*) | *Acacia constricta*<br>*Andropogon barbinodis*<br>*Aristida divaricata*<br>*A. glabrata*<br>*A. hamulosa*<br>*A. longiseta*<br>*Astragalus* spp.<br>*Baileya multiradiata*<br>*Bouteloua curtipendula*<br>*B. gracilis*<br>*B.* spp.<br>*Gutierrezia sarothrae*<br>*Hilaria belangeri*<br>*H. jamessi*<br>*Mentzelia* spp.<br>*Muhlenbergia porteri*<br>*Opuntia* spp.<br>*Prosopis juliflora* var. *torreyana*<br>*Sphaeralcea* spp.<br>*Sporobolus airoides*<br>*S. cryptandrus*<br>*S. flexuosus*<br>*Yucca baccata*<br>*Y. elata*<br>*Zinnia grandiflora*<br>*Z. pumila* |

| Unit Number | | Name | Physiognomy | Occurrence | Dominants | Other components |
|---|---|---|---|---|---|---|
| Atlas[a] | Orig.[b] | | | | | |
| 53 | 59 | Trans-Pecos shrub savanna (*Flourensia-Larrea*) | Shrubs and dwarf shrubs, dense to scattered, with short grass | Western Texas and and adjacent New Mexico | Tarbush (*Flourensia cernua*)<br>Creosote bush (*Larrea divaricata*) | *Acacia constricta*<br>*A. greggii*<br>*Agave lechugilla*<br>*Aristida* spp.<br>*Bouteloua breviseta*<br>*B. trifida*<br>*Dasylirion leiophyllum*<br>*Fouquiera splendens*<br>*Hilaria mutica*<br>*Muhlenbergia porteri*<br>*M.* spp.<br>*Opuntia* spp.<br>*Prosopis juliflora* var. *glandulosa*<br>*Scleropogon brevifolius*<br>*Yucca* sp. |

[a]A. W. Küchler, 1966. Potential natural vegetation (Map), Scale 1:7,500,000, Sheet number 90, IN USGS 1970, The National Atlas of the United States, USDI Geological Survey, Reston, Virginia.

[b]A. W. Küchler, 1964, Potential natural vegetation of the conterminous United States, Special Publication No. 36, American Geographical Society, New York.

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