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Application of Biophysical Data to an Unsupervised Classification to Map Ecoregional Boundaries in the Desert Southwest

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APPLICATION OF BIOPHYSICAL DATA TO AN UNSUPERVISED CLASSIFICATION TO MAP ECOREGIONAL BOUNDARIES IN THE DESERT SOUTHWEST

by

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ABSTRACT

Application of Biophysical Data to an Unsupervised Classification to Map

Ecoregional Boundaries in the Desert Southwest

by

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Major Professor: Dr. R. Douglas Ramsey
Program: Geography

An unsupervised classification was applied to continuous biophysical variables in an attempt to delineate ecoregional boundaries in the desert southwest. Output was then compared with ecoregions delineated by the Natural Resources Conservation Service (NRCS), the Environmental Protection Agency (EPA), and the Forest Service at the national level. An attempt was made to use the same biophysical variables for input into the unsupervised classification as was emphasized by the various agencies with their ecoregional classifications at the desert level. Major constraints included data availability at such a large study area, data resolution, and data that were continuous. This eliminated categorical data such as vegetation type, geology type, or soil texture. The aim of the study was to develop a more objective and repeatable approach to identifying self-similar geographic regions.

(90 pages)

ACKNOWLEDGMENTS

I would like to thank my committee members, Neil West and Paul Box, for their patience and advice. I would like to especially thank my major professor, R. Douglas Ramsey, for his encouragement, patience, and advice, as I went through four different ideas for this thesis over a period of a few years. I would also like to thank Dr. David Roberts from Forestry and Dr. David Tarbotten from Environmental Engineering for their time and advice. And finally, I would like to thank Susan Durham, statistical advisor for the College of Natural Resources, who spent a lot of time helping me understand what was statistically feasible and infeasible about my thesis subject.

I also want to thank all my friends I made at Utah State, especially the "Geoslackers," the Maranatha Baptist Church family, and the Utah State FOCUS group (Fellowship of Christian University Students) with whom I worshiped and praised God in His beautiful creation, the Rocky Mountains. Over this period of time and thesis research, I came to a realization that nature is too complex for us to ever perfectly model and understand. This reinforced my belief that the universe was created by God, and yet at the same time motivated me more than ever to continue researching my thesis topic. I concluded that there was no reason for my belief in God and my pursuit of science to clash.

"For since the creation of the world God's invisible qualities--his eternal power and divine nature--have been clearly seen, being understood from what has been made, so that men are without excuse" -- Paul's letter to the Romans, 1:20.

Paxton R. McClurg

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INTRODUCTION

The Mojave Desert Ecosystem Program (MDEP) is a multi-agency cooperative project primarily overseen by the Department of Defense. The program goal is the development and implementation of a database to facilitate collection, storage, transfer, sharing, and analysis of information regarding inventories, resource assessments, scientific documentation, and land management by federal, state, regional, and local agencies and other interested parties (MDEP, 1998). A main objective is to provide land managers and resource specialists accurate and standardized data that can be used as a tool for informed decision making within the Mojave Desert ecosystem.

The Mojave Desert Ecosystem Program uses the boundary defined by Bailey (1994) and labeled the "Mojave Desert Section" (Section 322A) as the best approximation of the area covered by the Mojave Desert. This boundary was identified at a scale of 1:7 million as part of a national ecoregion mapping effort. Because of scale disparities, it was evident to MDEP managers that section 322A of Bailey's map did not adequately cover what was considered to be the entirety of the desert. An arbitrary 50-km buffer was added to the boundary to increase the size of the study area and therefore err on the side of commission.

The question that I address in this thesis deals with the issue of scale and ecoregion definition. More specifically I deal with the process by which ecoregion boundaries can be detected by various definitions and made repeatable. Ecoregion boundaries are normally defined using criteria that support various research and management agendas, supporting end-user requirements. However, the artistic and scale-dependent nature of boundary delineation needs a more objective evaluation and process.

Defining an ecoregion boundary that different government agencies and scientific disciplines can agree on has proven to be a difficult task. Many issues come into question, such as what mapping criteria should be considered for boundary delineation and at which scale? Is it possible to acquire these data? Can the method of boundary delineation be duplicated with similar results?

Over the past two decades, the National Resources Conservation Service (NRCS), the Environmental Protection Agency (EPA), and the U.S. Forest Service have developed methods to classify ecoregions across the United States. Different criteria and combinations of criteria are considered at different levels on a nested hierarchy that range from broad scale (only a few regions across the continental U.S.) to fine scale (several subregions within one region). In other words, the relationships between biophysical criteria (i.e., topography, climate, vegetation, soils, geology) and the landscape vary with scale. The Mojave Desert Ecoregion can be defined at a certain level on these nested hierarchies and we can see which biophysical criteria were emphasized. The terms ecosystem and ecoregion will be used throughout this thesis. Ecosystem refers to the abstract, conceptual term that describes a complex of organisms and the biophysical environment functioning as a nonspatially defined unit, and ecoregion refers to a more concrete boundary identifying a specific geographic area that can include many ecosystems.

There is no overriding definitive solution when delineating ecological boundaries across a landscape. These boundaries depend on the objective and scale that a land manager or researcher is working. The existing classification schemes can only provide a guideline for recognizing ecological boundaries. Yet, in order to produce a map of ecoregions, specific boundary lines have to be drawn either by hand or by computer. This brings into question whether or not the map is an accurate (to scale) representation of the ecoregions' boundaries. Is it objective or subjective? Is the process repeatable? The definitions of these classification schemes provide the "ingredients," but do not provide a specific recipe.

Objectives

The overall objective of this thesis was to develop a quantitative approach for integrating spatial biophysical data to identify self similar geographic regions within the desert southwest, with a focus on the Mojave Desert. A second objective was to apply various combinations of input data to determine the sensitivity of ecoregion delineation given various input parameters, and determine if there are any data that play a key role in the identification of the ecoregion. A third objective was to test the effects of scale on ecoregion delineation.

Study Area

The study area for this thesis is confined to a rectangular area covering the southwestern portion of the U.S. It ranges from the Pacific Ocean off San Diego in the southwestern corner to central Utah in the northeastern corner and from near Lake Tahoe in the northwestern corner to near Phoenix in the southeastern corner. The total area is is just over 500,000 square kilometers.

The landscape ranges in elevation from -83 m to 4500 m and in major climate zones from subtropical desert to Mediterranean to various temperate areas at higher elevations and latitudes. Vegetation cover consists of barren terrain to sparse Creosote Bush to a mixed western Sierra forest. Landforms range from mesas to deep canyons to low flat valleys to steep, rugged mountains. Soil climate regimes range from aridic/hyperthermic to frigid/aquic (Miles and Goudey, 1997).

LITERATURE REVIEW

Defining Ecoregions

In the past, different government agencies and individuals have inventoried land resources based on their particular scientific discipline with a goal of answering specific functional questions (Bailey, 1996). For example, Hammond (1970) classified land forms, Hunt (1967) classified physiographic regions of the United States, Koppen (1931) classified climatic regions of the U.S., and Kuchler (1970) classified potential natural vegetation regions of the U.S. More specific to the desert west, Shreve (1942) first mapped the four North American deserts based on vegetation, Jaeger (1957) modified Shreve's boundaries, adding a fifth major desert (Benson and Darrow, 1944), and MacMahon (1979) modified these desert boundaries once again, adding animal distribution to vegetation (Trimble, 1989) (Figure 1).

Today, land managers acknowledge that such a singular or intuitively multivariate focus rarely works because ecoregions are complex integrated systems. Consequently, land management agencies are shifting to an integrated, multivariate-based approach. This philosophy involves resource users in implementing resource management practices and decisions, and in establishing objectives for an area and its associated scale (Smith et al., 1994). With this holistic management approach comes a need for classifying ecoregions that meet multipurpose needs of resource managers and at the same time allow enough flexibility to meet specific objectives.

An ecosystem is considered a localized group of interdependent organisms together with the physical environment that they depend on. Unique flows of energy and

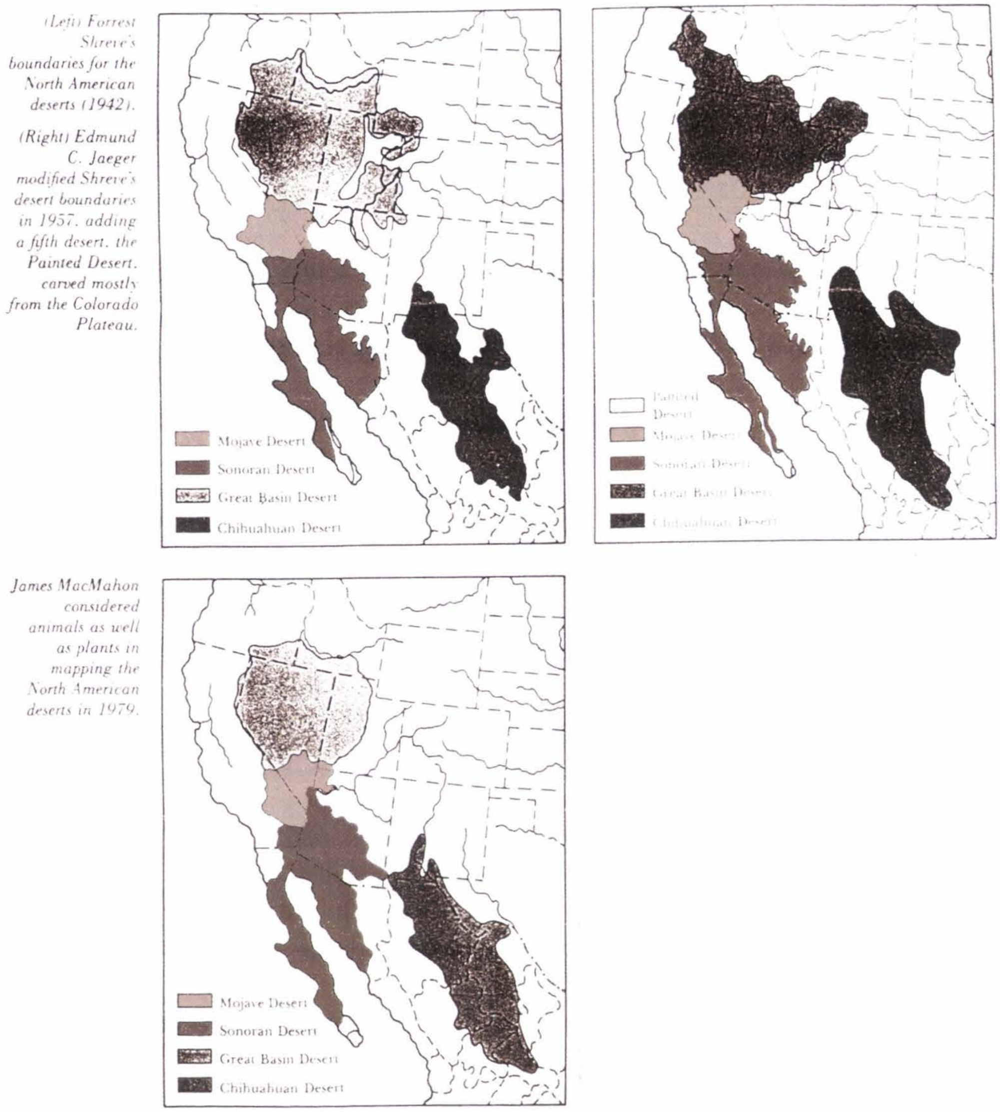


Figure 4. Regional Deserts according to Shreve, Jaeger, and MacMahon (Trimble, 1989).

cycling of materials (nutrients and water) and informational feedbacks and feed forwards characterize each ecosystem whose boundaries in space and time are at least partially arbitrary. There are many similar ecosystems located within an ecoregion, depending on definition and scale. The ecoregion concept brings the biological and physical worlds of a number of ecosystems together into a holistic framework within which lands and waters can be described, evaluated, and managed (Rowe, 1992). Other definitions for ecoregions include:

1) "A geographic unit of the landscape that includes all natural phenomena and that can be identified and surrounded by boundaries" (Bailey, 1996).
2) "Are based on the premise that relatively homogeneous areas exist and that these areas can be perceived by simultaneously analyzing a combination of causal and integrative factors including land surface form, soils, land use, and potential natural vegetation" (Omernik, 1987).
3) "An integrated ecological unit consisting of the living organisms and the physical environment (biotic and abiotic factors) in a particular area" (Morgan, 1995).
4) Any area where plants, animals, and other organisms interact with each other and their physical environment; boundaries are defined based on research or management objectives (Knight, 1994).

To properly identify ecoregions, Rowe (1992) tells us to take a step back, look at the "big picture" of the entire environment, and then simplify and organize it. Knight (1994) tells us that organization of ecoregions into a map is based on specific objectives. Bailey (1996) tells us that setting ecoregional boundaries involves dividing the landscape where the defined mapping criteria exhibit a consistent or significant degree of change when compared with adjacent areas. Rowe (1980) states that "the key criteria are not to be found simply in the vegetation, in the soil profile, in the topography and geology, in the rainfall and temperature regimes, but rather in the spatial coincidences, patterning and relationships of these functional components"

These descriptions lead us to the reality that mapping the earth's surface in a holistic sense is an art, not a science. There is no single correct way to delimit ecological units and no universal set of unit descriptions (Kaufman, 1997). Nor is there one scale with which these units can meet all management objectives.

What is needed is a classification and mapping system that captures the integrated nature of the land's resources (Bailey, 1996), and has the structure and flexibility for delineating ecological classes from a continental to a local scale (ECOMAP, 1996). This would require a hierarchical system, where one ecosystem may be broken down into multiple ecosystems that must fall within its boundaries. A nested hierarchy would allow land resources to be more easily managed from a broad scale to a fine scale and at the same time allow a better understanding of the relationship between the ecoregions and their subregions (ECOMAP, 1996).

Classification of Ecoregions

In the past few decades, several researchers have used an integrated, hierarchical approach to classify ecoregions for geographical scales ranging from global to local (ECOMAP, 1996). Three that have received considerable attention by the federal government are the Major Land Resource Areas of the United States (MLRA), the Ecoregion Framework, and the National Hierarchical Framework of Ecological Units (ECOMAP) (McMahon et al., 2001).

The MLRA was created by the USDA in 1981 and has broken the country into 204 regions. It is characterized by a particular pattern of soils, geology, climate, water resources, and land use (USDA, 1998). At a scale of 1:3,750,000, it is part of a hierarchy with a parent system that was originally developed for national and regional agricultural concerns at a broader scale called land resources regions. The finer scale units in this hierarchy are STATSGO (1:250,000) and SURGO (1:24,000) and are more soil specific. While MLRA's were created to meet requests for a more integrated resource classification scheme, there has been criticism that there is still bias toward agricultural applications and the scale is too broad for local land management decisions (Omernik, 1987). Figure 2 shows MLRA Regions 29 (Southern Nevada Basin and Range) and 30 (Sonoran Basin and Range) that comprise the general Mojave and Sonoran Desert areas.

Another classification was developed in 1987 by Jim Omernik for the EPA to assist managers with water quality decisions and to understand the relationships between watersheds and other land resources. Originally called Ecoregion Framework and then revised and renamed Ecoregions of the Conterminous United States, it combines many factors such as geology, physiography, vegetation, climate, soils, land use, wildlife, and hydrology. The classification is a hierarchical system consisting of four levels, level 1 being the coarsest and breaking North America into 15 ecological regions. The relative importance of each characteristic varies from one ecological region to another regardless of the hierarchical level (EPA, 1996). Level 3 (compiled at a scale of 1:2.5 million) identifies the Mojave area as region 14, Southern Basin and Range (Figure 3) . At this particular level, Omernik analyzed four "component" maps (Major Land Uses (Anderson, 1970), Classes of Land-Surface Form (Hammond, 1970), Potential Natural Vegetation (Kuchler, 1970), and soils maps from various sources) together to sketch out regions that

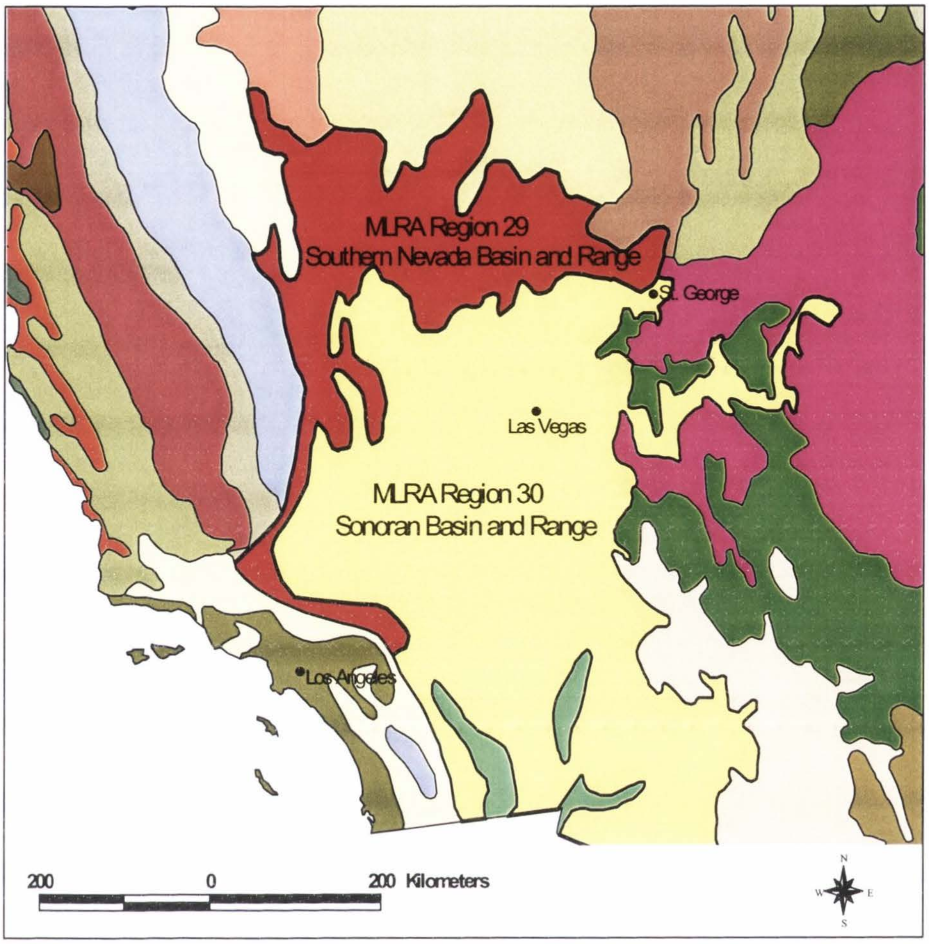


Figure 2. MLRA Region 30, Sonoran Basin and Range (Scale- 1:3,750,000).

were relatively homogenous and to tabulate the identified classes of each. Several other maps were used for verification of regional accuracy of the component maps and to further support ecoregion patterns (Omernik, 1987).

In 1993, Robert Bailey of the U.S. Forest Service led the development of ECOMAP, which states that the primary purpose for delineating "ecological units" is to identify land and water areas at different hierarchical levels that have similar capabilities

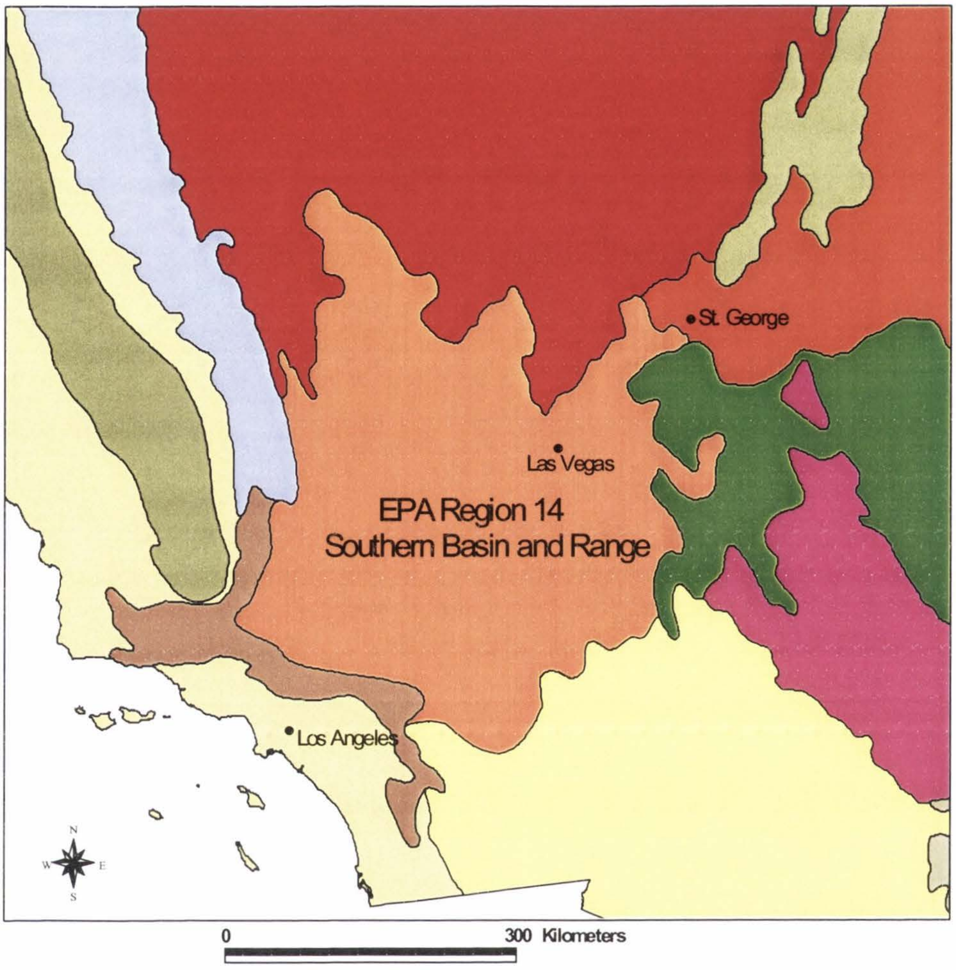


Figure 6. Ecoregions of the Conterminous U.S., Region 14 - Southern Basin and Range (Scale - 1:1,250,000).

and potentials for management. The units are developed at various scales by integrating multiple components such as climate, physiography, geology, soils, water, and potential vegetation (ECOMAP, 1996). ECOMAP states that all components are not equally important at all spatial scales. At coarse scales, the important components are largely abiotic, while at finer scales both biotic and abiotic components are important (ECOMAP, 1996). See Tables 1 and 2 for a guideline to these ecological units.

Table 1. Principal map unit design criteria of ecological units Adapted from ECOMAP, 1996.

Ecological Unit	Principal Map Unit Design Criteria **
Domain	-Broad climatic zones or groups (e.g., dry, humid, tropical)
Division	-Regional climatic types (Koppen 1931, Trewartha 1968). -Vegetational affinities (e.g., prairie or forest). -Soil order.
Province	-Dominant potential natural vegetation (Kuchler 1964). -Highlands or mountains with complex vertical climate-vegetation-soil zonation.
Section	-Geomorphic province, geologic age, stratigraphy, lithology. -Regional climatic data. -Phases of soil orders, suborders or great groups. -Potential natural vegetation.
Subsection	-Geomorphic process, geologic age, stratigraphy, lithology. -Phases of soil orders, suborders or great groups. -Subregional climatic data. -PNV- formation of series.
Landtype Association	-Geomorphic process, geologic formation, surficial geology, and elevation. -Phases of soil subgroups, families, or series. -Local climate. -PNV - series, subseries, plant associations.
Landtype	-Landform and topography (elevation, aspect, slope gradient and position). -Phases of soil subgroups, families, or series. -Rock type, geomorphic process. -PNV- plant associations..
Landtype Phase	-Phases of soil families or series. -Landform and slope position. -PNV- plant associations or phases.

*It should be noted that the criteria listed are broad categories of environmental and landscape components.

Table 2. Map scale and polygon size of ecological units.

Ecological Unit	**Map Scale Range**	**General Polygon Size**
Domain	1:30 million or smaller	1,000,000's of square miles
Division	1:30 million to 1:7.5 million	100,000's of square miles
Province	1:15 million to 1:5 million	10,000's of square miles
Section	1:7.5 million to 1:3.5 million	1,000's of square miles
Subsection	1:3.5 million to 1:250,000	10's to low 1000's of square miles
Landtype Association	1:250,000 to 1:60,000	high 100's to 1,000's of acres
Landtype	1:60,000 to 1:24,000	10's to 100's of acres
Landtype Phase	1:24,000 or larger	<100 acres

The ecoregions at the upper four levels (Table 3) of the nested hierarchy have been mapped in "Ecoregions of the United States" (Bailey, 1994). Climatic regimes and regional climates are an important boundary criteria at these broad scales. Other factors, such as geomorphic process, soils, and potential natural communities, take on equal or greater importance than climate at the lower four levels (ECOMAP, 1996). The latest sub-ecoregion in this hierarchy to have been mapped at a national level is the "section," which is described in "Ecological Subregions of the United States: Section Descriptions" (McNab and Avers, 1994) (Table 1).

What makes the ECOMAP classification scheme different from the others is the term "ecological units." Ecological units address the spatial distributions of relatively stable associations of potential conditions (ECOMAP, 1996). Classifying ecological units is only the first step to mapping ecoregions. The second step is to combine ecological units with maps of existing conditions (current vegetation, wildlife, water quality, land use) that change readily through time. This second step depends on management objectives. The combination provides a means of addressing spatial and temporal variations that affect the structural and functional attributes of ecosystems (ECOMAP, 1996).

As mentioned earlier, there is no exact science to defining and mapping ecosystems or ecoregions. It depends on the research or management objectives. Once these objectives are determined, the goal is to combine stable and dynamic biophysical conditions to meet the objectives. Ecosystem boundaries therefore vary according to objectives, but the boundaries of ECOMAP's ecological units are not meant to change. They are meant to be the permanent ingredient, or base, for ecoregion classification.

Ecoregions based on various objectives allow researchers to compare outcomes and come to an understanding of commonalities. To date, there is an ongoing effort under the Interagency Memorandum of Understanding (McMahon et al., 2001) to develop a common spatial framework of ecological units of the United States based on lessons learned from past ecoregion mapping efforts. The Interagency goal is to ease the exchange of spatial ecological data and information across agency boundaries for a common benefit (ECOMAP, 1996). This will significantly contribute to the understanding and refinement of each of the existing classifications. ECOMAP's ecological units, the EPA's Ecoregion Framework, and the USDA's Land Resource

Regions and MLRAs will be used as guides for this effort (McMahon et al., 2001).

The Mojave Desert Ecosystem Program (MDEP) defined the Mojave ecoregion according to Bailey's delineation of sectional ecological units. The "Mojave Desert Section," labeled 322A, is shown in Figure 4 and is compared to MLRA Region 30 in Figure 5 and Omernik's Region 14 in Figure 6. MDEP added a 50-kilometer buffer to Section 322A to include any areas omitted from Bailey's original 1:7.5 million scale map (Figure 7). This erred on the side of commission, but also had the added effect of including areas covered by MLRA and Omernik ecoregions which stretched outside Bailey's definition. All three Mojave ecoregions encompass four states: California, Nevada, Arizona, and Utah.

Biophysical Characteristics of the Mojave Desert Ecoregion

The following are general descriptions of stable/potential biophysical data across the Mojave Desert Ecoregion taken from Miles and Goudey (1997). The five types of data listed are considered to be key factors at the Section level in delineation of ecological units `ccording to Robert Bailey and ECOMAP (see Table 1). They were also used by the MLRA and Omernik/EPA Level 3 classifications.

Geomorphology/landform/topography: Extensive plains from which isolated mountains rise abruptly. Alluvial fans and bajadas surround the mountains, which terminate in dry washes and lakes in the basins. Also contains plateaus, playas, basins, and dunes. Elevation ranges from 280 feet below sea level to 7900 feet above.

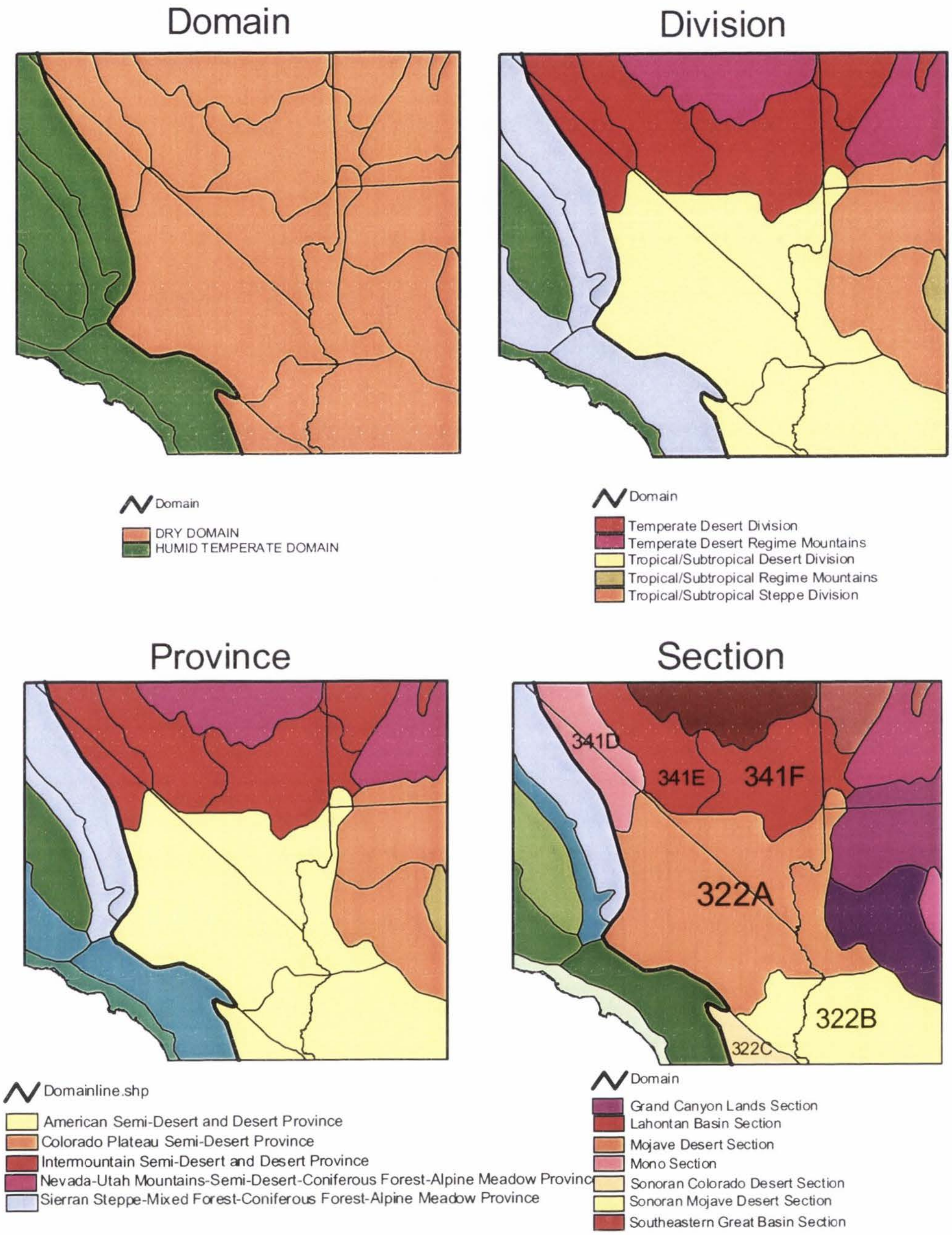


Figure 7. ECOMAP Nested Hierarchy in desert southwest. Scale - 1:7,500,000.

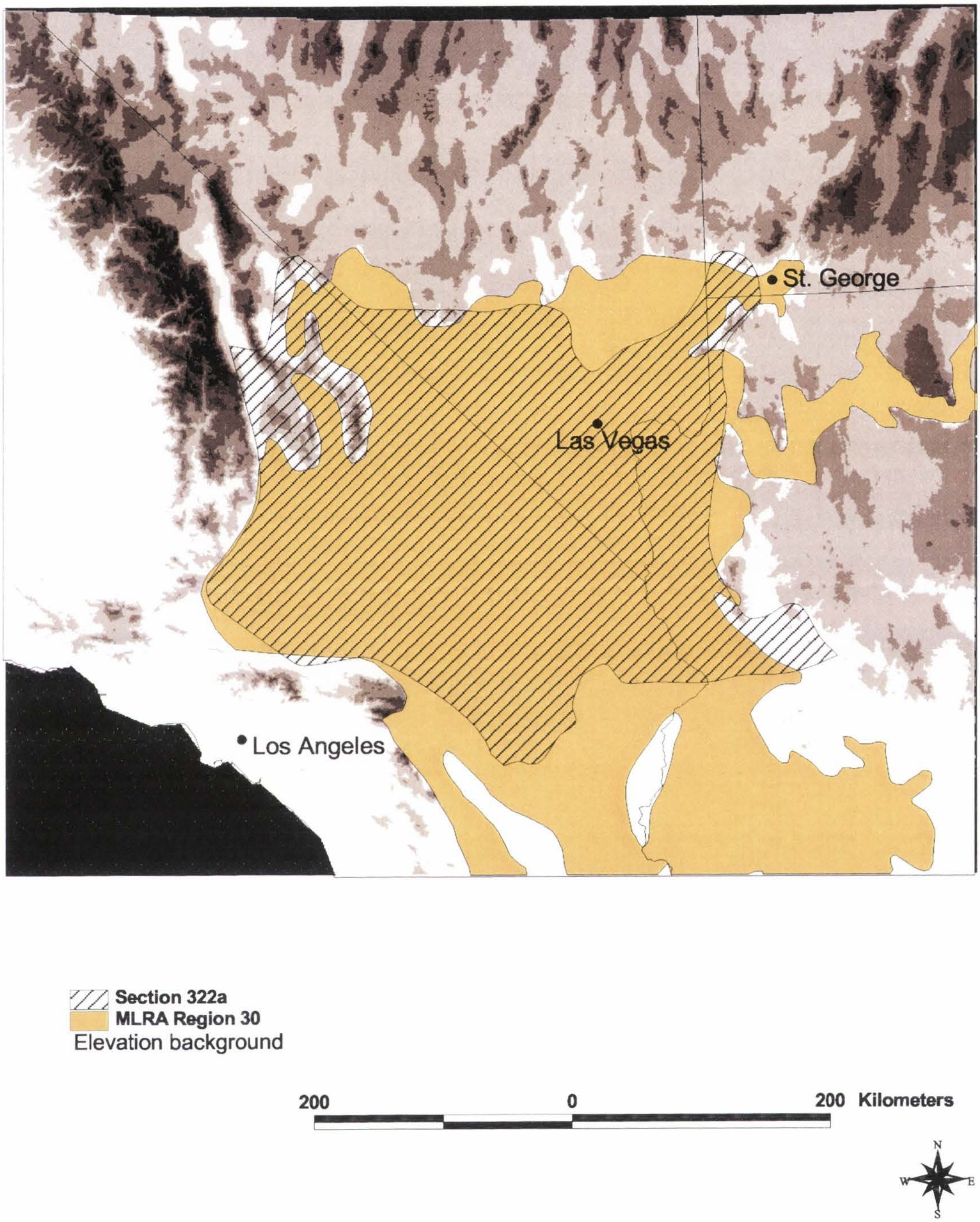


Figure 8. Section 322a and MLRA Region 30.

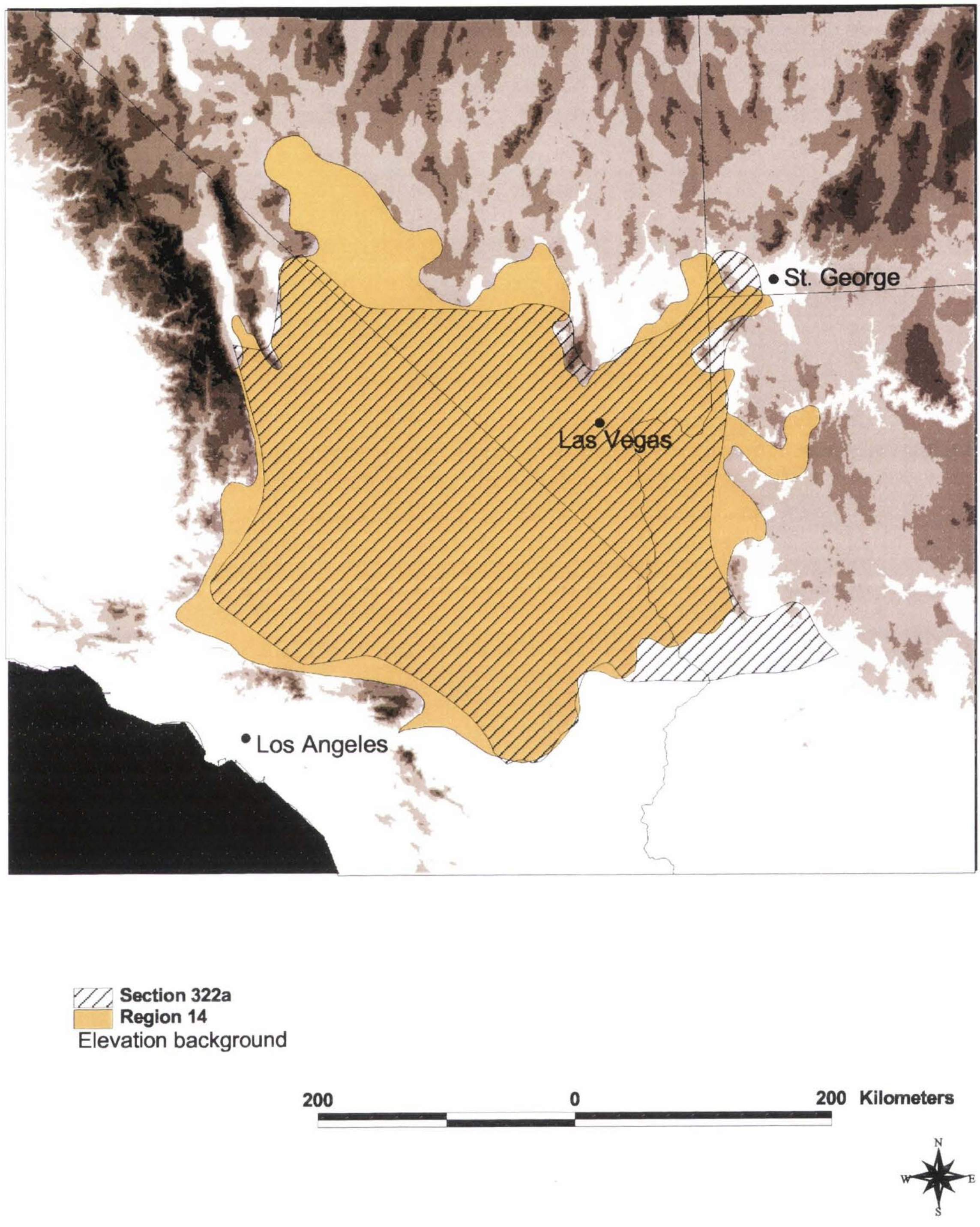


Figure 9. Section 322a and Region 14.

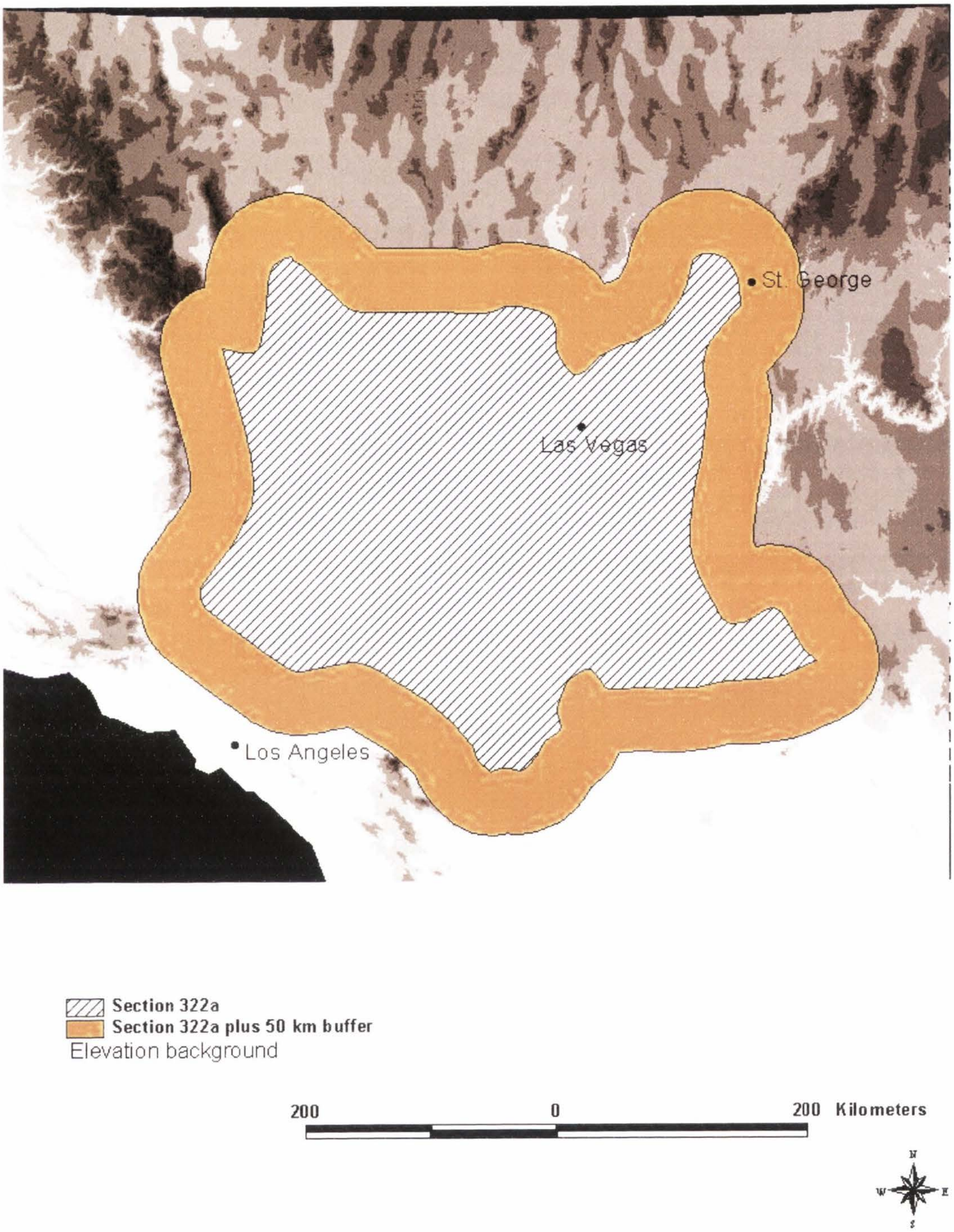


Figure 10. Section 322a plus 50 km buffer.

Climate: Long and extremely hot summers. Precipitation - 3 to 8 inches, mostly occuring as scattered high intesity storms of short duration. Average temperature range : 45 deg. F to 77 deg. F.

Potential natural vegetation: Predominant communities includes Creosote Bush (Larrea tridentata), Blackbrush, Greasewood and Saltbush series on basins, plains, and hills; Joshua Tree (Yucca brevifolia) series on plains and hills; and Basin Sagebrush, Western Juniper and Pinyon Pine (Juniperus-Pinus) series on mountains.

Soil taxa: Aridisols and Entisols in combination with thermic or hyperthermic soil temperature regimes and aridic soil moisture regimes on foothills and valleys. Contains areas with salt affected soils. Aridisols and Entisols in combination with thermic or mesic soil temperature regimes, and aridic and xeric soil moisture regimes on mountains.

Geology /lithology/stratigraphy: Cenozoic nonmarine sedimentary and granitic rocks and alluvial deposits, and precambrian rocks of all types.

Analysis of Section 322A Boundaries

Section 322A of Bailey's 1994 ecoregion map describes a commonly accepted boundary of the Mojave Desert ecosystem, which includes southeastern California, southern Nevada, northwestern Arizona, and extreme southwestern Utah (Figure 4). It is bounded by the San Andreas and Garlock faults and large mountain ranges to the west and southwest, by the Sonoran Desert to the south and southeast, the Colorado Plateau to the east, and the Great Basin to the northeast, north, and northwest. These boundaries coincide with changes in the various biophysical data mentioned in the previous section. Some boundaries are more evident than others because of dramatic changes in all biophysical factors over short distances. The San Andreas Fault and uplift of the San Gabriel Mountains is a good example. Other boundaries are not as obvious, such as the one between the Sonoran and Mojave Deserts, where both sides of the boundary line contain similar climate, topography, vegetation, and soils.

According to ECOMAP's classification, the biophysical changes that occur across various boundaries between the Mojave and other ecoregions do range in significance across the nested hierarchy. The division between the Mojave and the mountain ranges to the west is at the domain level (humid and dry) on the hierarchy (Table 2).

The separation between the Mojave ecoregion and the Great Basin and Colorado Plateau ecoregions is at the division level on the hierarchy, which is attributed to a shift in regional climate, vegetational affinities, and soil orders. Vegetation changes, coincidental with change in precipitation, are a good indicator of transition from the Great Basin to the Mojave. An example is on the Nevada Test Site north of Mercury, Nevada. Creosote Bush communities dominate where the annual rainfall is less than 7.25 inches, while Big Sagebrush and Shadscale are more abundant where rainfall is more than 7.25 inches (MacMahon, 1992). This abrupt change identifies the division between a temperate (Great Basin) and subtropical desert (Mojave). This boundary separates Divisions 320 (Tropical/Subtropical Desert) and 340 (Temperate Desert) in the hierarchy (Bailey, 1996).

The division between the Mojave and the Sonoran Deserts is at the section level on the hierarchy, which is attributed to changes in geomorphology, geology, regional climate, soil orders and suborders, and potential natural vegetation (ECOMAP, 1996). None of these changes are as evident as with the other boundaries. According to the descriptions of Section 322b (Sonoran Mojave Desert Section) by Miles and Goudey (1997), geomorphology, landforms, topography, geology, soil taxa, and precipitation are about the same as in Section 322a. The key difference is lower average elevation (250 - 4400 feet), resulting in higher average temperatures and longer growing seasons, which in turn result in greater vegetation species diversity among Creosote Bush communities, including several succulents.

Another subtropical desert region south of Section 322a and southwest of Section 322b is labeled Section 322c (Sonoran Colorado Desert Section) according to ECOMAP (1996), also called the Colorado Desert in other classification scheme according to Benson and Darrow (1944). On the average, it is characterized by lower elevations, higher average temperatures, and less precipitation than Sections 322a and 322b (Miles and Goudey, 1997).

Comparison of Section 322A with MLRA Region 30 and Omernik's Region 14

Topographically, the Mojave's landforms are similar to those of the Great Basin to the north and the Sonoran Desert to the south. Within another classification scheme, these three deserts fall within the larger Basin and Range Physiographic Province (Hunt, 1967), which consists of widely separated low mountain ranges and desert plains (Miles and Goudey, 1997). In the Great Basin, the mountain ranges tend to be higher, closer together, and mostly run north-south. Elevation generally decreases from the Great Basin in the north to the Sonoran in the south, with the Mojave in between.

As evident in Figure 5, Section 322A is divided by MLRA's 29 and 30. Number 29 is labeled "Southern Nevada Basin and Range" and falls in the northern part of Section 322A. Number 30 is labeled "Sonoran Basin and Range" and includes most of 322A. It also includes all of 322B, the Sonoran Section, meaning it combines the different characteristics of the Mojave and the Sonoran Deserts into one. This classification most closely resembles the American Semi-Desert and Desert Province (322), devised by Robert Bailey and used by ECOMAP (See Table 1).

With the exception of the northwestern boundary in Nevada and a small area to the east in extreme western Arizona, Omernik's Region 14 (Southern Basin and Range) closely resembles Section 322A (Figure 6). In addition to differences in biophysical criteria used for input, some discrepancies in delineated boundary lines between Omernik, Bailey, and MLRA may be due to difference in mapping scale. As mentioned previously, Omernik's classification was compiled for the entire U.S. at a scale of 1:2.5 million, Bailey's classification was at a scale of 1:7.5 million, and MLRA at a scale of 1:3.75 million. By using ECOMAP's biophysical criteria and hierarchical structure, another boundary definition was compiled for the state of California by the U.S. Forest Service and the Natural Resources Conservation Service (NRCS) at a scale of approximately 1:1 million (Figure 8). In order to refine the section lines at a finer scale, a "bottom-up" methodology was used. Subsections (see Table 1) were classified using STATSGO polygon boundaries along with the other biophysical criteria. The boundary lines at finer scales were then used up the hierarchy to refine the section, province, division, and domain boundaries.

Multivariate Clustering Techniques

While the concept of ecoregions existing in nested spatial hierarchies defined by factors operating at multiple scales has been well described by Bailey/ECOMAP and Omernik/EPA, the mechanisms and data for implementing these ideas have been less clear. These classifications generally require numerous, subjective decisions on the relative importance of different data layers, and often the boundaries have been defined by consensus. This approach is not necessarily repeatable, and the derived units may not relate mechanistically to the ecological processes that define and characterize ecoregions. The development of well-defined criteria, standardized data, and robust analytical methods can improve the repeatability and interpretability of ecological classifications, and remove much of the subjectivity involved in delineating ecoregion boundaries (Host and Polzer, 1996).

Image classification is a well known form of custom grouping, based on reflection characteristics, which results in the delineation of similar areas within an image (Hargrove and Luxmoore, 1997). The ArcInfo function ISOCLUSTER uses a clustering technique on sampled subsets of cells to develop reflectance signatures for subsequent

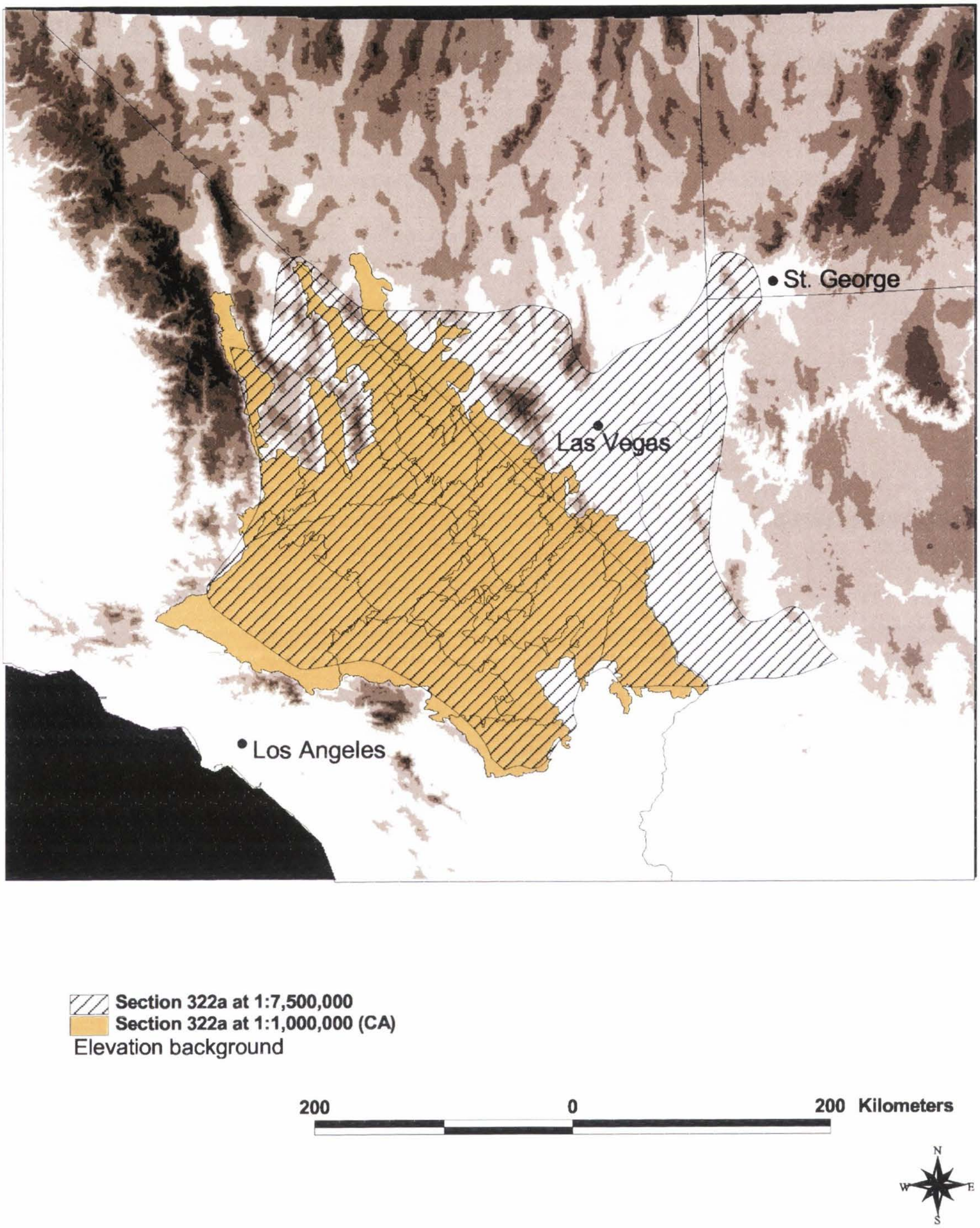


Figure 11. Section 322a at 1:7.5 million and 1:1 million (CA only)

image analysis and classification. However, the technique has rarely been applied to primary, non-spectral data outside traditional image classification (Hargrove and Luxmoore, 1997).

Omi et al. (1979) used multivariate map clustering on primary variables, including steepness, drainage, precipitation, and fault density to delineate fire management planning zones in the Angeles National Forest in California. Hargrove and Luxmoore (1997) used a spatial clustering technique to identify patches in the Southeast which are similar with regard to temperature, precipitation, elevation, and various soil characteristics. Host et. al (1996) combined GIS with multivariate statistical analyses to integrate climatic, physiographic, and edaphic databases and produce a classification of regional landscape ecoregions in northwestern Wisconsin. Both Host et al. (1996) and Hargrove (1997) used a principal component analysis to remove correlations among input variables, and standardized the data to reduce the dimensionality (Hargrove, 1997). Host et al. (1996) and Hargrove and Luxmoore (1997) both applied a K-means cluster analysis to identify the relationship among the clusters and to aggregate similar clusters (Host et al., 1996).

METHODS

The objectives of this thesis were met by applying an unsupervised classification to stable biophysical data that the USDA, Omernik, and Bailey used in their classifications. Arc Grid's Isocluster was used to generate biophysical clusters and a maximum likelihood classification algorithm was applied to the resulting biophysical signature file to produce a grid representing the spatial distribution of each cluster. A comparison of the frequency distribution of biophysical clusters within established Mojave ecoregion boundaries as defined by ECOMAP, EPA, and MLRA and the frequency of the same clusters falling outside these boundaries was made. Contiguity and homogeneity of the classes within each boundary was observed. A cluster analysis to identify biophysical cluster similarity was applied to the signature file, using a dendrogram tree for output.

The five types of data (geomorphology/landform/topography, climate, potential vegetation, soils, lithology/stratigraphy) mentioned in the literature review were not easily available for input. A significant limitation was that the Isocluster algorithm required continuous raster data. Since expressing soil type, geology, landform, and land cover as interval/ratio data was beyond the scope of this thesis, these data were not considered for input. As a surrogate to land cover, a normalized difference vegetation index (NDVI) generated from NOAA-AVHRR imagery was used. These data represent the "greenness" of the vegetation in quantitative terms, rather than the vegetation type itself. A 1-km resolution digital elevation model (DEM) was used as the elevation data source.

Climate was represented by annual temperature and precipitation data interpolated between weather stations.

A second limitation was that available data were restricted by the large size of the study area. High-resolution biophysical data covering the entire study area are not available. The minimum resolution available for NDVI, DEM, and the climate data was 1 km, which defined the output grid resolution.

When comparing this input data with the five stable biophysical characteristics in the literature review or with the map criteria for the Section in Table 1, it is obvious that only a small portion of relevant data for this study was used as input.

Data Sources

Elevation

Elevation data were acquired from NOAA's global land one-km base elevation (GLOBE) Project. DEM data representing a large portion of the western US and the eastern Pacific were downloaded from GLOBE's web site.

Vegetation

A normalized difference vegetation index (NDVI) calculated from NOAA's AVHRR satellite imagery, 1-km resolution, was extracted from the USGS AVHRR 10-day composite database collected between 1990 and 1994. These data consist of approximately 21 10-day periods for each year representing the amount of photosynthetically active vegetation for that period of time. Similar time periods for each year were averaged together to generate a yearly average NDVI response curve for each of the 21 periods. NDVI values were converted to a fractional index (0 - 100%) which represents the fraction of ground covered by vegetation. The following equation was used to make this conversion:

$$\textbf{Fractional Index (\%)} = ((\text{NDVI - Global Minimum}) / (\text{Global Maximum - Global Min.}))^2 * 100$$

The 21 10-day periods define the growth curve of vegetation within the study area. To reduce these data into meaningful parameters, this dataset was summarized by extracting maximum greenness and minimum greenness, which were chosen to show the maximum and minimum range of fractional vegetation for any given area.

Climate

Eighteen year normal annual precipitation and maximum temperature data, 1-km resolution, were acquired from University of Montana's Numerical Terradynamics Simulation Group. The method used to generate these data was based on the spatial convolution of a truncated Gaussian weighted filter, using inputs such as DEM's and observations of maximum temperature, minimum temperature, and precipitation from ground-based meteorological stations (Thornton et al., 1997). Minimum temperature was omitted because of its high correlation with maximum temperature when averaged over such a time period. All data were converted to Arc Grid format, clipped to the study area, and projected to UTM, zone 11, datum NAD83.

Standardization

Before the various biophysical grids could be combined for a multivariate analysis, their data ranges were standardized. Differences in grid values between layers were due to different units of measurement. For example, measurement units of elevation (meters), NDVI (index), and climate (degrees celsius or millimeters) cannot be directly compared. All grids were standardized to a scale of 0 - 100 (floating value carried to three places) using the following matrix algebraic equation in ArcGrid:

$$Z = (X - oldmin) * (newmax - newmin) / (oldmax - oldmin) + newmin$$

where:
Z = the output grid with new data ranges
X = the input grid
oldmin = the minimum value of the input grid
oldmax = the maximum value of the input grid
newmin = the desired minimum value for the output grid
newmax = the desired maximum value for the output grid (ArcInfo Help)

After standardization, grids were combined into a single file (layer stack) for input to an unsupervised classification algorithm.

Correlation Between Data

A correlation matrix between all biophysical variables was generated to understand the relationships between input variables. This matrix identified variables that were highly correlated and therefore provided redundant information. Variable pairs with correlation coefficients above .90 were identified and one variable was eliminated from the analysis. Of all biophysical data layers, only maximum temperature and elevation were correlated above 90% (91%). Therefore maximum temperature was removed from further analysis (See Tables 3 - 5).

Variables

To understand the effects and contribution of various biophysical variables for ecosystem delineation, inputs and clustering methodology were varied in the following ways:

- Convolution filtering of the data
- Vary the number of requested clusters
- Vary the combinations of layers of data

. In addition to the original 1-km data, a convolution filter was used to generalize local variation to try to understand the effect of scale on the analysis. If ecoregions are, in part, a geographical construct based on local environmental variability, the use of focal statistics should help in the automated identification of these areas. To help characterize the spatial variability of the study area, a simple focal mean and focal standard deviation (variance) function was employed to help determine local variability of biophysical data layers. The focal mean function produced an output file whose pixel values were the result of a convolution of all pixels within the defined focal area. Each output pixel was a mean of the surrounding input pixels. The focal standard deviation (STD) function operated in the same manner, but calculated local STD. This generated a new set of output pixels that provided local context. For instance, local variance in elevation allowed the clustering algorithm to consider not only elevation, but also a measure of topographic change.

Two sizes of focal statistical filters were used to evaluate the effect of spatial scale. The first was a 3 X 3 area (9 sq km) and the second a 13 X 13 area (169 sq km). Larger areas were experimented with, but it was determined that spatial integrity was lost.

Another variable considered was the number of output clusters requested from the

Isocluster algorithm. Five, 10, and 15 classes were requested in order to examine the differences in the distribution of output cluster on the output map along with their spatial size and homogeneity. Outputs were compared with the three present ecoregion boundaries in order to determine if there were any relationships between the number of classes requested and the map scale and polygon size of those classifications.

Another variable was the combination of layers used for input in the Isocluster. Multiple combinations were possible from elevation, vegetation, precipitation, and maximum temperature. To meet the objectives of this thesis, various combinations of layer and function substitution were used to evaluate the influence each layer had on the output.

When considering these variables and the three types of data used for input, there were 78 possible different combinations of data that could have been stacked in ArcGrid for preparation as input layers into the Isocluster algorithm (see Input below).

Input for Isocluster algorithm

Four individual layer stacks treated at three spatial scales simulated with convolution filtering were used for input into the Isocluster algorithm and maximum likelihood classification. For each of these combinations, groups of five, 10, and 15 clusters were generated. In total, 78 combinations were compared to determine the best combination of biophysical data at various scales to delineate the Mojave boundary.

1) No smoothing filter (original data)
   - Elevation, NDVI maximum, NDVI minimum, Precipitation
   - Elevation, NDVI maximum, NDVI minimum
   - Elevation, Precipitation

- NDVI maximum, NDVI minimum, Precipitation

2) 3 X 3 and 13X13 Smoothing filter
a)Focal Mean
- Elevation, NDVI maximum, NDVI minimum, Precipitation
- Elevation, NDVI maximum, NDVI minimum
- Elevation, Precipitation
- NDVI maximum, NDVI minimum, Precipitation

b)Focal Mean and Focal Standard Deviation
- Elevation, NDVI maximum, NDVI minimum, Precipitation
- Elevation, NDVI maximum, NDVI minimum
- Elevation, Precipitation
- NDVI maximum, NDVI minimum, Precipitation
* Elevation
* NDVI maximum, NDVI minimum
* Precipitation

* . It was desirable to understand how one biophysical data type alone influenced the cluster output, so a simple layer combination of its focal mean and focal variance was used for input in the Isocluster.

Unsupervised Classification

An unsupervised classification generates statistical clusters of grid cells (pixels) in a multi-stack raster set based on similarities between the stack layers. The algorithm generates class means and covariance matrices based on image statistics. Unsupervised classification is point oriented and has no regard for the spatial contiguity of the pixels that define each cluster. Following cluster generation, clusters are assigned to information classes based on posteriori information (Jensen, 1996).

Arc Grid's command MLCLASSIFY (maximum likelihood) used the signature file generated by ISOCLUSTER to produce an output raster file that represented the spatial distribution of the unsupervised clusters. All *a posteriori* probabilities of cell assignment were evaluated to understand cell assignments and the spatial homogeneity of the clusters. For the various combinations of input variables discussed above, two classification schemes were chosen that met the assumptions and constraints of Mojave ecoregion delineation. All pixels with an *a posteriori* probability higher than .75 or .9 were assigned to a landscape class. Cells with lower confidence were assigned to a "null data" value.

Dendrogram of Similarity

Dendrograms of statistical clusters generated through the ISOCLUSTER algorithm were generated to visually evaluate similarity between spectral classes. All dendograms were produced using the euclidian distance between each pair of classes in the signature file using the following formula:

$$Dmn = \text{sqrt} (\sum (\mu m_i - \mu n_i)^2)$$

where Dmn is the Euclidean distance between the means of classes m and n (Arc/Info Help Manual).

Comparing Classes with Existing Boundaries

The frequency of each cluster was generated for all cells falling inside and outside the established Mojave boundary. This was used to provide a quick estimation of cluster/ecoregion association.

Assumptions and Constraints

As mentioned in the literature review, due to scale differences and variances in interpretation, boundary definitions of any given ecoregion can vary widely, making it difficult to have a purely objective process of classifying ecoregions. However, there tends to be a general agreement on the characteristics that are common to specific ecoregions. As with any scientific process, assumptions and constraints must exist and they must be consistent. The following assumptions are made here in order to evaluate the various outputs of this study:

1) The three boundary delineations from ECOMAP, the EPA, and the MLRA will be used as guidelines to determine the general area that our Mojave Ecoregion will fall in. We expect to find our Mojave cluster at least within the Dry Domain, according to Bailey's classification. Also, any previous geographic knowledge of the regions will be applied. For example, valleys such as the San Joaquin and Death Valley, the Los Angeles Basin, bodies of water such as the Salton Sea and Lake Mead, and high mountains such as the Sierra Nevada, will be used to help identify the characteristics of that particular cluster.
2) Clusters cannot be considered "Mojave Desert" if the same clusters are found in large homogenous areas in both the Dry and Humid Domains.
3) The fewest number of clusters and layers that allow a homogenous Mojave Ecoregion to be uniquely identified according to assumption 1 will take precedence. In other words, the simplest classification scheme will be favored.
4) In an effort to save time, NDVI maximum and minimum layers (correlation of $.80 < r < .90$) will always be considered together in the Isocluster. They will not be treated as separate layers.

RESULTS

Figures 9-13 show Z-normalized input variables of elevation, maximum NDVI, minimum NDVI, precipitation, and average temperature. The Z statistic was used to standardize input values to the same numeric scale.

Tables 3 - 5 show correlation coefficients between the various input layers. Table 3 represents all original data, Table 4 represents mean and variance data across a 3 X 3 smoothing filter, and Table 5 represents mean and variance data across a 13 X 13 smoothing filter. Elevation and maximum temperature were highly correlated ($r > .90$) and NDVI maximum and minimum values are somewhat correlated ($.80 < r > .90$). Maximum temperature was eliminated from further analysis, but elevation used since it represents an input variable to calculate maximum temperature

Figures 14 - 23 and Tables 6 - 14 represent the classification results from the Isocluster and maximum likelihood algorithms. Note that all inputs mentioned in the methods section are not included in these results. These figures and associated tables summarize the results of the process of adding and taking away variables mentioned in the methods section. Some results meet the assumptions/constraints and some do not.

Classification results are displayed by expressing the signature file from the Isocluster in 3 different ways and presented in the figures below : 1) A biophysical signature graph. 2) An image of the maximum likelihood classification. 3) A similarity dendrogram tree of the signature statistics.

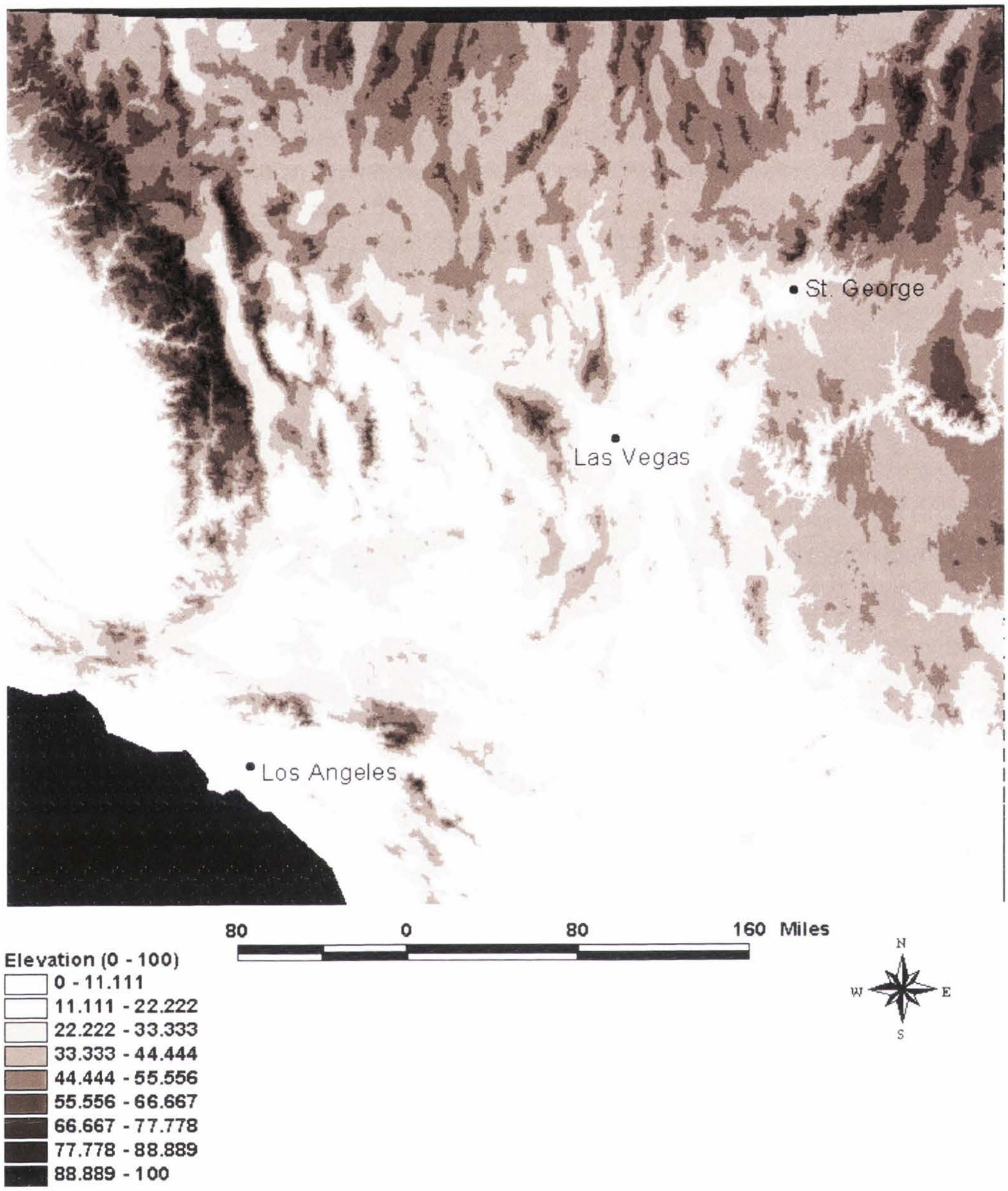


Figure 12. Z-value normalized elevation data.

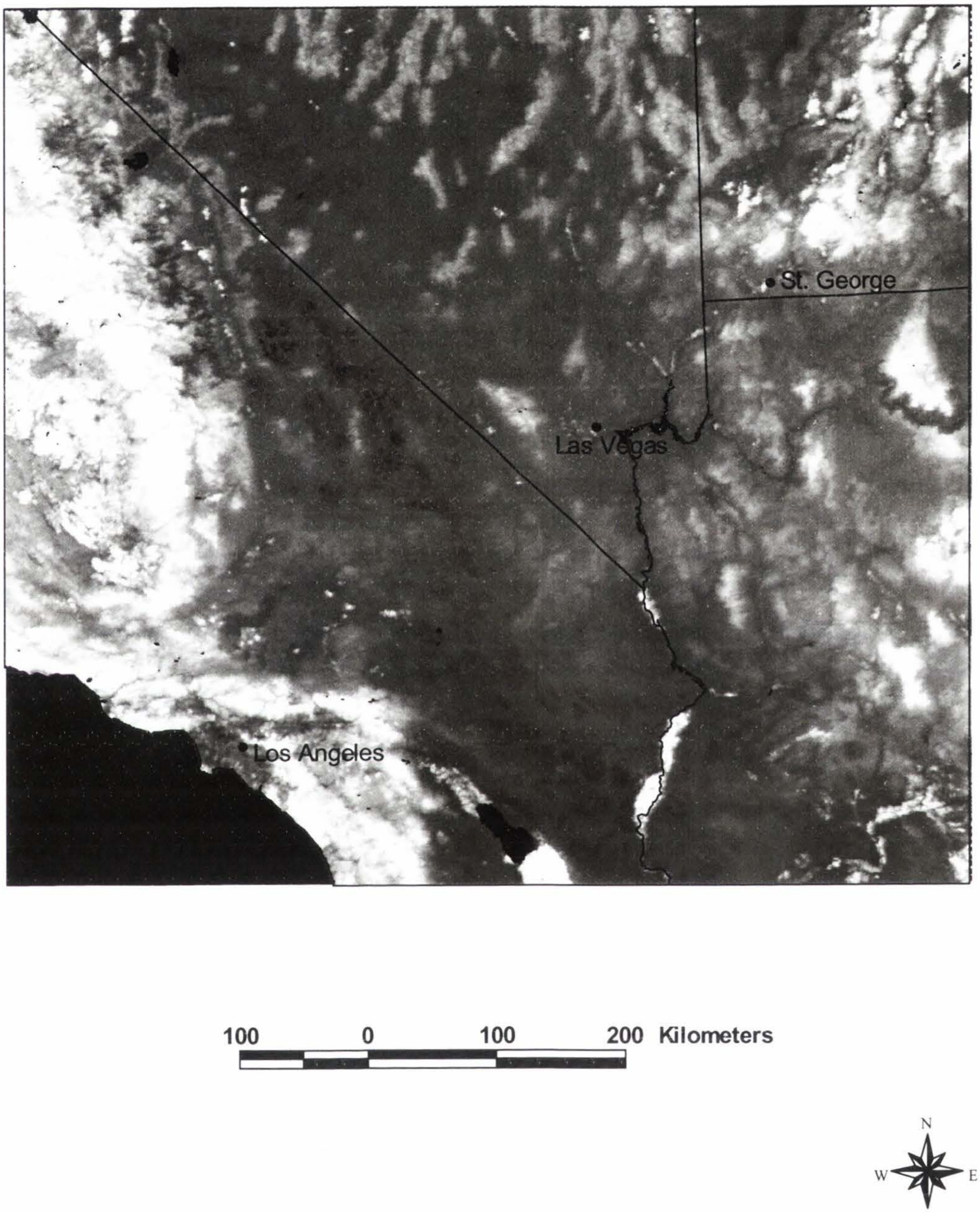


Figure 13. Z-value normalized NDVI maximum. White = Highest percent vegetation greenness

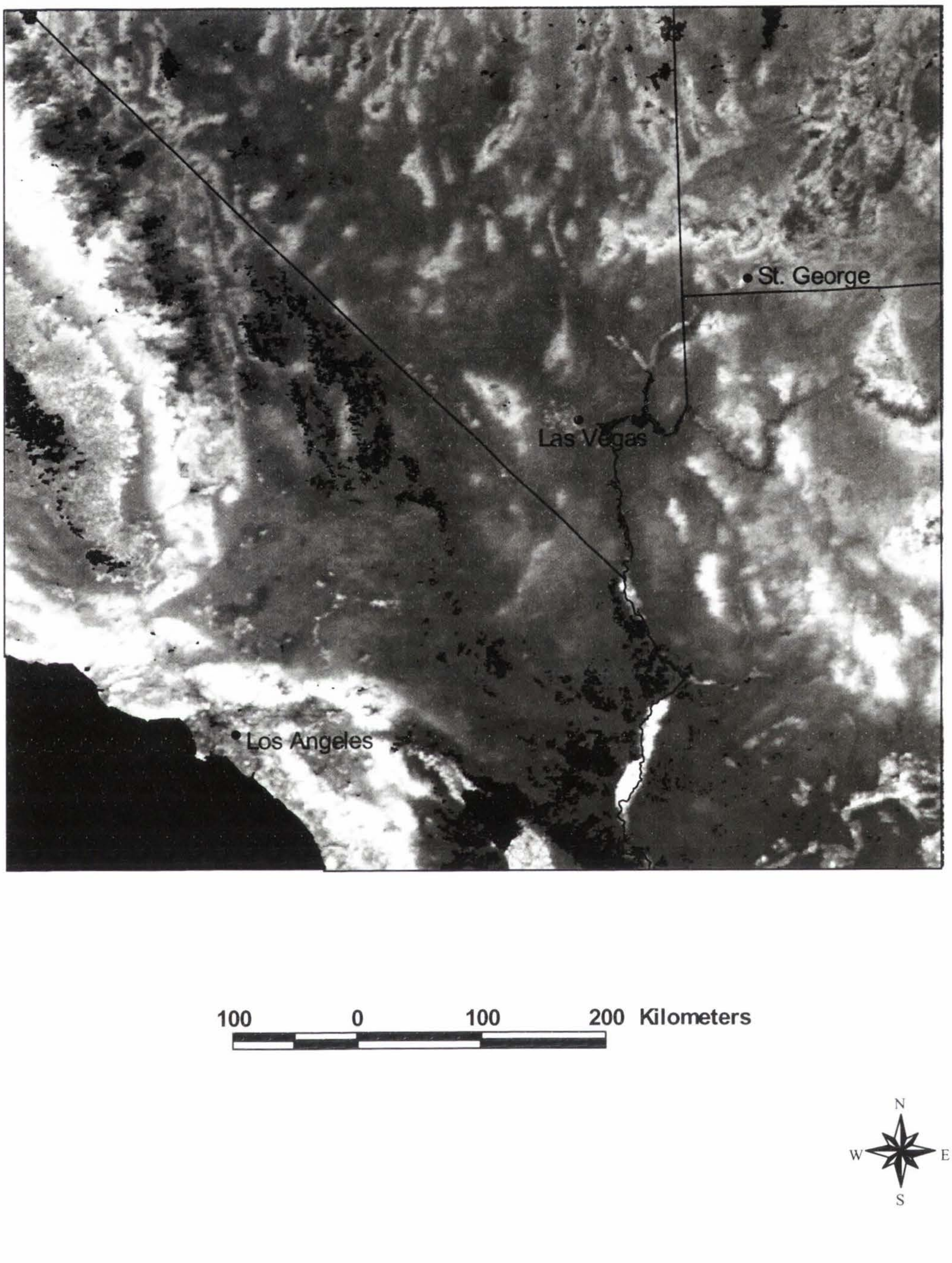


Figure 14. Z-value normalized NDVI minimum. White = Highest percent vegetation greenness.

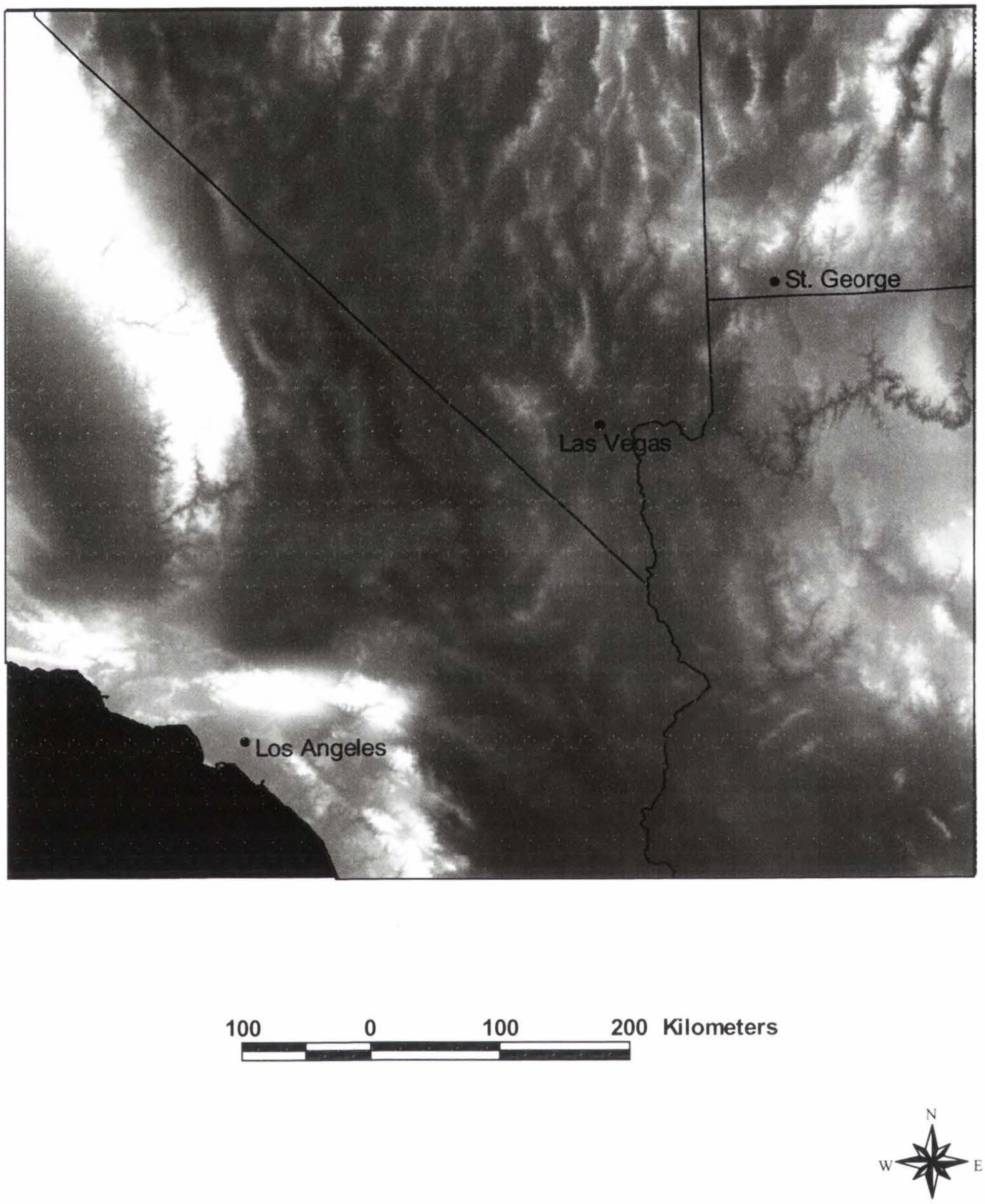


Figure 15. Z-value normalized precipitation data. White = Higher values of annual precipitation.

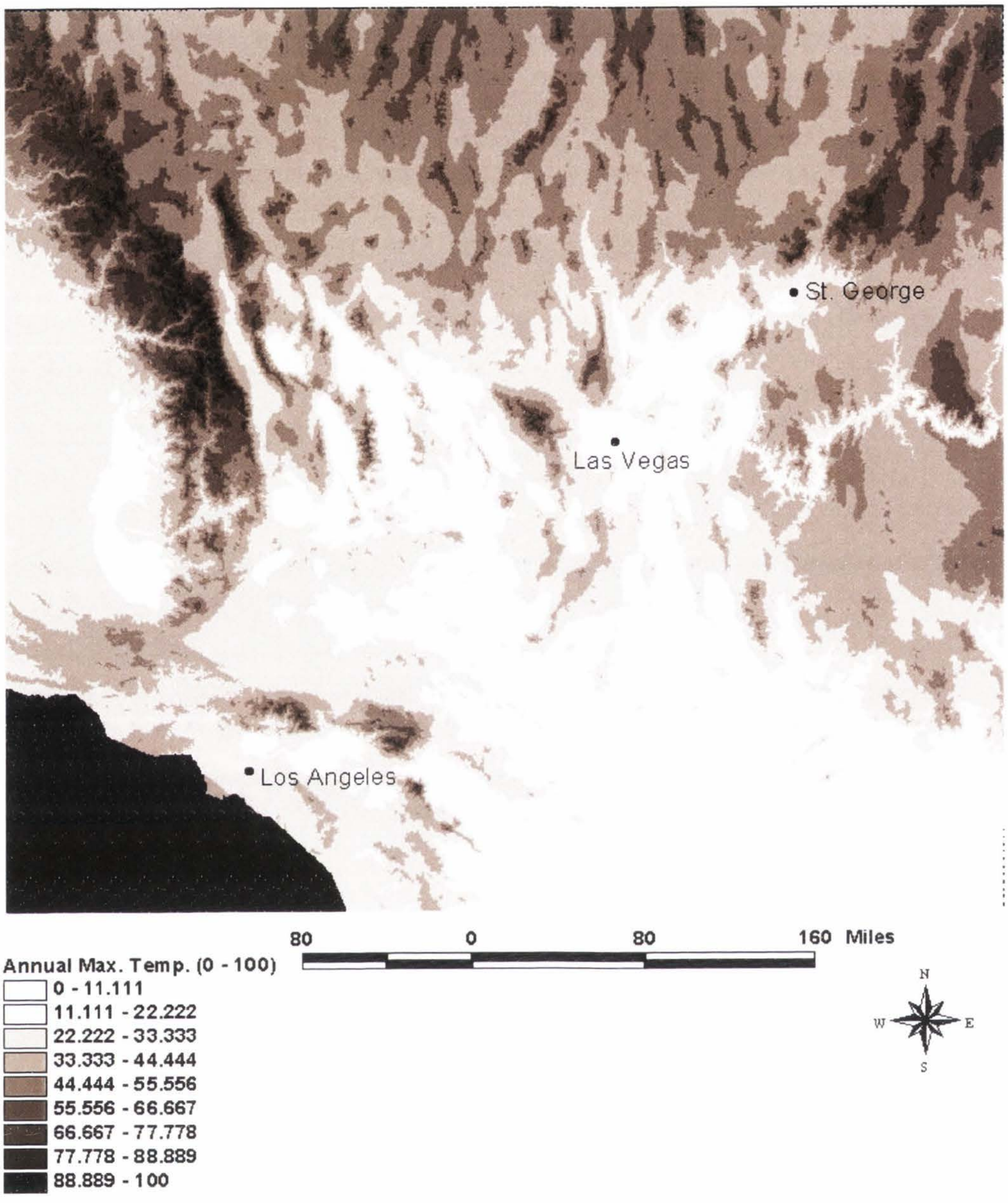


Figure 16. Z-value normalized maximum temperature

Table 3. Correlation of original data (after standardizing): NDVI max and min values, elevation, precipitation, and maximum temperature.

Layers	NDVI Min	Elevation	NDVI Max	Precip.	Max. Temp.
NDVI Min	1.00	0.17	0.80	0.51	-0.27
Elevation	0.17	1.00	0.12	0.47	-0.93
NDVI Max	0.80	0.12	1.00	0.61	-0.28
Precip.	0.51	0.47	0.61	1.00	-0.58
Max. Temp.	-0.27	-0.93	-0.28	-0.58	1.00

The goal of using color image outputs was to use specific colors to identify biophysical clusters that best represent the desert regions discussed, and more specifically the Mojave. In order to be consistent with cluster comparison between classifications, a simple color coding scheme was developed, based on geographic location. Warm colors were chosen to represent clusters found predominantly within the existing desert boundaries (i.e. MLRAs 29 and 30, Divisions 320 and 340, Region 14) and cooler colors were chosen to represent clusters that were more prevalent outside the existing desert boundaries. There were several outputs where small warm colored clusters were found outside the desert boundaries and small cool colored clusters were found within the desert boundaries. An effort was made to assign colors to clusters so that contrast between neighboring clusters was clearly visible. Clusters that were obviously well known bodies of water, such as the Salton Sea and Lake Mead, and any pixels assigned to that cluster were colored a deep blue. Clusters that were obviously high mountain ranges, such as the Sierra Nevada, and any pixels assigned to that same cluster were colored a light purple.

Table 4. Correlation of the means and standard deviations across a 3X3 filter of NDVI max and min, elevation, precipitation, and maximum temperature.

Layers	NDVI Max STD	NDVI Min STD	Elev STD	NDVI Min. Mean	Elev Mean	NDVI Max Mean	Precip STD	Precip Mean	Max Temp Mean	Max Temp STD
NDVI Max STD	1.00	0.76	0.06	0.02	-0.02	0.13	0.20	0.16	-0.07	0.16
NDVI Min STD	0.76	1.00	0.11	-0.08	-0.09	0.04	0.19	0.10	0.02	0.19
Elev STD	0.06	0.11	1.00	0.20	0.40	0.19	0.64	0.37	-0.39	0.74
NDVI Min. Mean	0.02	-0.08	0.19	1.00	0.18	0.81	0.33	0.52	-0.27	0.07
Elev Mean	-0.01	-0.09	0.39	0.17	1.00	0.12	0.32	0.47	-0.92	0.32
NDVI Max Mean	0.14	0.04	0.19	0.81	0.12	1.00	0.38	0.62	-0.28	0.07
Precip STD	0.20	0.19	0.64	0.33	0.32	0.38	1.00	0.63	-0.41	0.76
Precip Mean	0.16	0.10	0.37	0.52	0.47	0.62	0.63	1.00	-0.58	0.28
Max Temp Mean	-0.07	0.02	-0.39	-0.27	-0.92	-0.28	-0.41	-0.58	1.00	-0.35
Max Temp STD	0.16	0.19	0.74	0.07	0.32	0.07	0.76	0.28	-0.35	1.00

Table 5. Correlation of the means and standard deviations across a 13X13 filter of NDVI max and min, elevation, precipitation, and maximum temperature.

Layers	Elev Mean	NDVI Max Mean	NDVI Min. Mean	Precip Mean	Elev STD	NDVI Max STD	NDVI Min STD	Precip STD	Max Temp Mean	Max Temp
Elev Mean	1.00	0.11	0.18	0.45	0.41	-0.02	-0.16	0.35	-0.92	0.32
NDVI Max Mean	0.11	1.00	0.83	0.66	0.13	0.20	0.10	0.43	-0.27	0.00
NDVI Min Mean	0.18	0.83	1.00	0.57	0.15	0.07	-0.03	0.37	-0.28	0.01
Precip Mean	0.45	0.66	0.57	1.00	0.31	0.23	0.17	0.70	-0.57	0.24
Elev STD	0.41	0.13	0.15	0.31	1.00	0.09	0.16	0.61	-0.39	0.82
NDVI Max STD	-0.02	0.20	0.07	0.23	0.09	1.00	0.83	0.35	-0.12	0.27
NDVI Min STD	-0.16	0.10	-0.03	0.17	0.16	0.83	1.00	0.32	0.03	0.33
Precip STD	0.35	0.42	0.37	0.70	0.61	0.35	0.32	1.00	-0.47	0.66
Max Temp Mean	-0.92	-0.27	-0.28	-0.57	-0.39	-0.12	0.03	-0.47	1.00	-0.37
Max Temp	0.32	0.00	0.01	0.23	0.82	0.27	0.33	0.66	-0.37	1.00

These colors that were assigned to consistent geographic shapes and locations were based on assumptions/constraints number 1 from methods.

A summary of figures is listed below. Figures consist of a maximum likelihood classification along with a graph of the biophysical signature, and a similarity dendrogram tree from that particular signature in the previous figure.

Figures	**Explanation**
14 - 19	Original, standardized data. No smoothing filter has been applied.
20 - 25	3 X 3 focal mean filter has been applied.
26 - 31	3 X 3 focal mean and standard deviation filter has been applied.
32 - 33	13 X 13 focal mean and standard deviation filter has been applied.
34 - 37	3 X 3 focal mean and STD filter applied, with *a posteriori* confidence interval
38 - 39	Histograms that compare clusters with boundaries from Omernik, Bailey, and USDA

Figures 14 -19 show various cluster outputs with original, standardized data for input. Figure 14 shows the results of elevation and precipitation at 5 classes. Notice that clusters 1 and 2 (yellow and orange) occur frequently within the existing desert boundaries, and the San Joaquin Valley and Los Angeles Basin (Humid Domain according to Bailey). Comparing Figure 14 with Figure 9 (just elevation), there is a striking resemblance in boundaries , indicating that precipitation may have had no influence in this Isocluster classification. According to the signature graph, cluster 5's precipitation mean is very different from the others', indicating that precipitation only makes a difference within the Sierra Nevada.

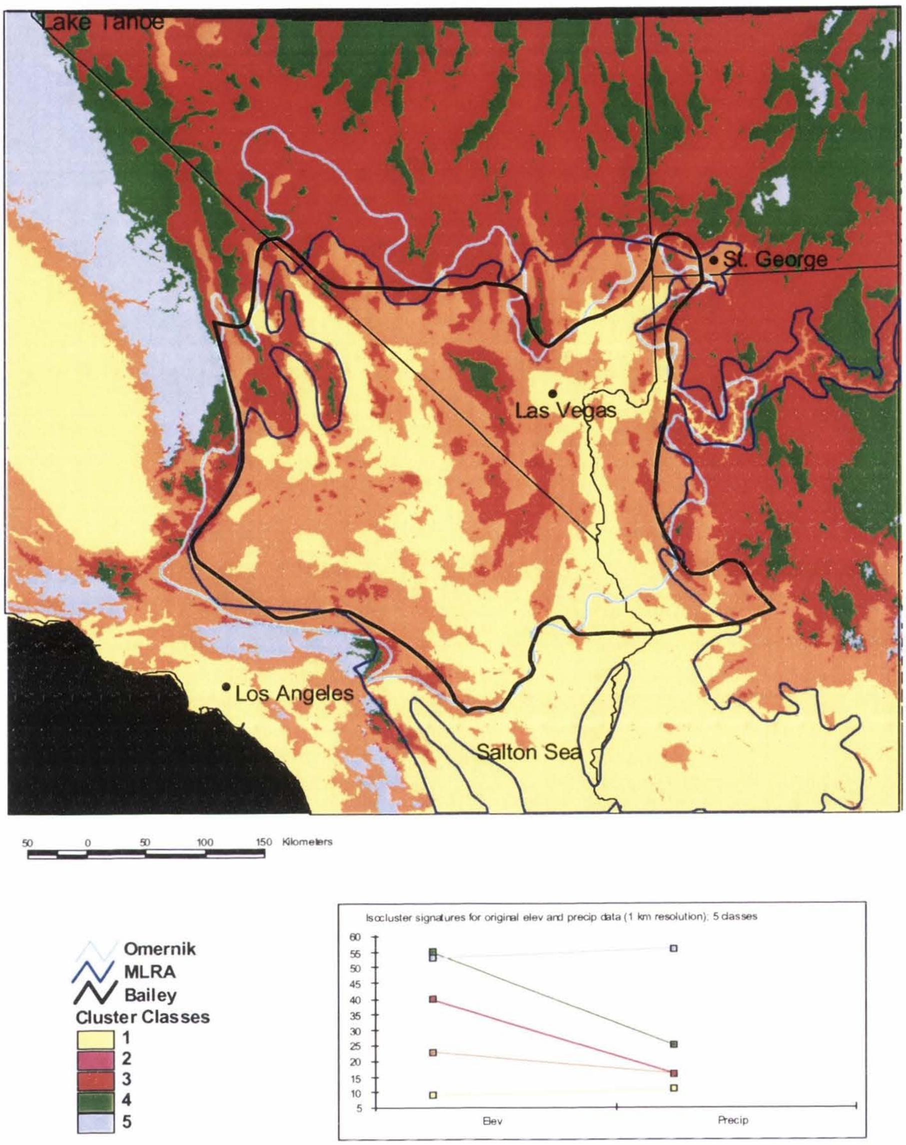


Figure 17. 5 classes; Original data; Elevation, precipitation

Distances between Pairs of Combined Classes
(in the sequence of merging)

Remaining Class	Merged Class	Between-Class Distance
1	2	14.517733
3	4	17.433896
1	3	28.944073
1	5	46.316540

```
        DISTANCE
        0       5.1     10.3    15.4    20.6    25.7    30.9   36   46.3
        |-------|-------|-------|-------|-------|-------|---   ----|---

C       2 ---------------------|
                               |---------------------|
L       1 ---------------------|                     |
                                                     |-----------------|
A       4 --------------------------|                |                 |
                                    |----------------|                 |
S       3 --------------------------|                                  |
                                                                       |
S       5 -------------------------------------------------------------|

        |-------|-------|-------|-------|-------|-------|---   ----|---
        0       5.1     10.3    15.4    20.6    25.7    30.9   36   46.3
```

Figure 15. 5 Classes; Original data; Elevation, Annual Precipitation

Figure 16 shows the results of maximum and minimum greenness and precipitation at 10 classes. While we cannot directly compare cluster outputs with those in Figure 14, do notice that when NDVI is used as input, warm colors can only be found within the Dry Domain and cool colors dominate the Humid Domain. This is due to the major difference in percent vegetation cover between these 2 domains. When comparing Figure 16 with Figures 10 and 11 (NDVI max and NDVI min data), it appears that once again precipitation does not make any difference, except that it reinforces the uniqueness of the Sierra Nevada.

Notice in Figure 16 that a cluster which represents large bodies of water (Lake Mead and Salton Sea) is evident (cluster 1). Other areas that are also classified as cluster

1 are located in large, flat valleys with salty soils and very sparse vegetation. This makes sense considering that NDVI data represents vegetation cover and these areas have no or minimal vegetation. According to the signature graph, this cluster has a very low mean for maximum and minimum greenness.

Finally, notice in Figure 16 the "cool colored islands" that are found within the existing desert ecoregions. One of the clusters is the Spring Mountains, west of Las Vegas. These mountains rise to as high as 11,000 feet and contain a forest zone. Another one is in the Salton Sea area (Imperial Valley) and is due to irrigated agriculture. The other noticeable one is found along the Colorado River on the California/Arizona border and is also due to irrigated agriculture. According to the signature graph, these agricultural clusters have a very high mean NDVI maximum value and very low mean NDVI minimum value, which represents their seasonality. These agricultural areas are classified as Region 31 Imperial Valley by MLRA, which uses land use as biophysical criteria for ecoregion classification.

Figure 18 shows the results of maximum and minimum greenness and elevation at 10 classes. Notice that there is minimal yellow and orange (clusters 2 and 4) found in the Humid Domain and in the Temperate Desert Division (340). For the first time, we can see homogenous clusters that fall within the existing Mojave ecoregion boundaries, but are not found anywhere else in large quantities.

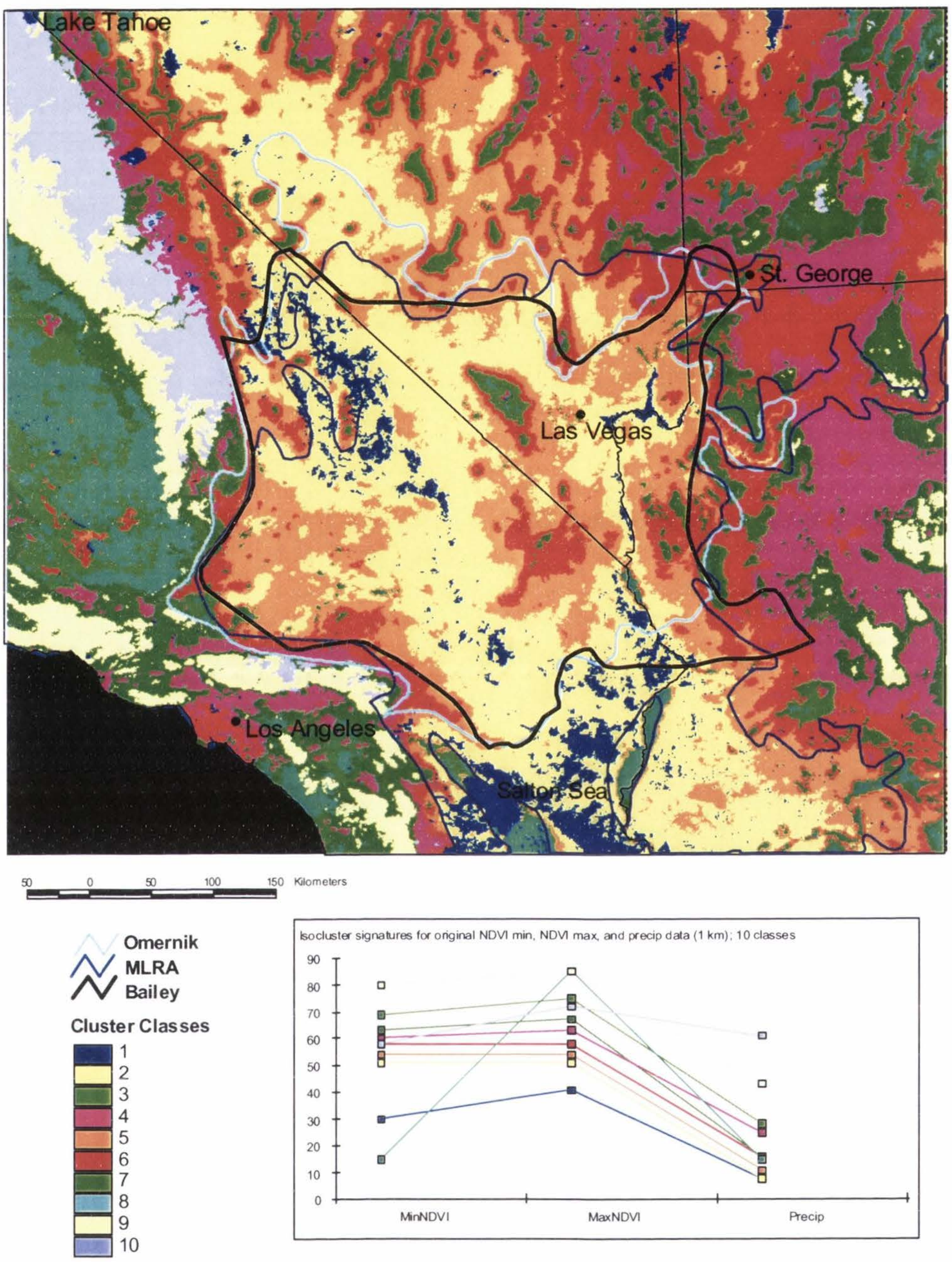


Figure 16. 10 classes; Original data; NDVI min., NDVI max., precipitation

Distances between Pairs of Combined Classes
(in the sequence of merging)

Remaining Class	Merged Class	Between-Class Distance
2	3	5.710004
2	4	9.737386
5	6	10.251266
5	7	14.490613
5	8	18.103658
2	5	22.129355
9	10	31.757681
1	2	34.417327
1	9	42.875825

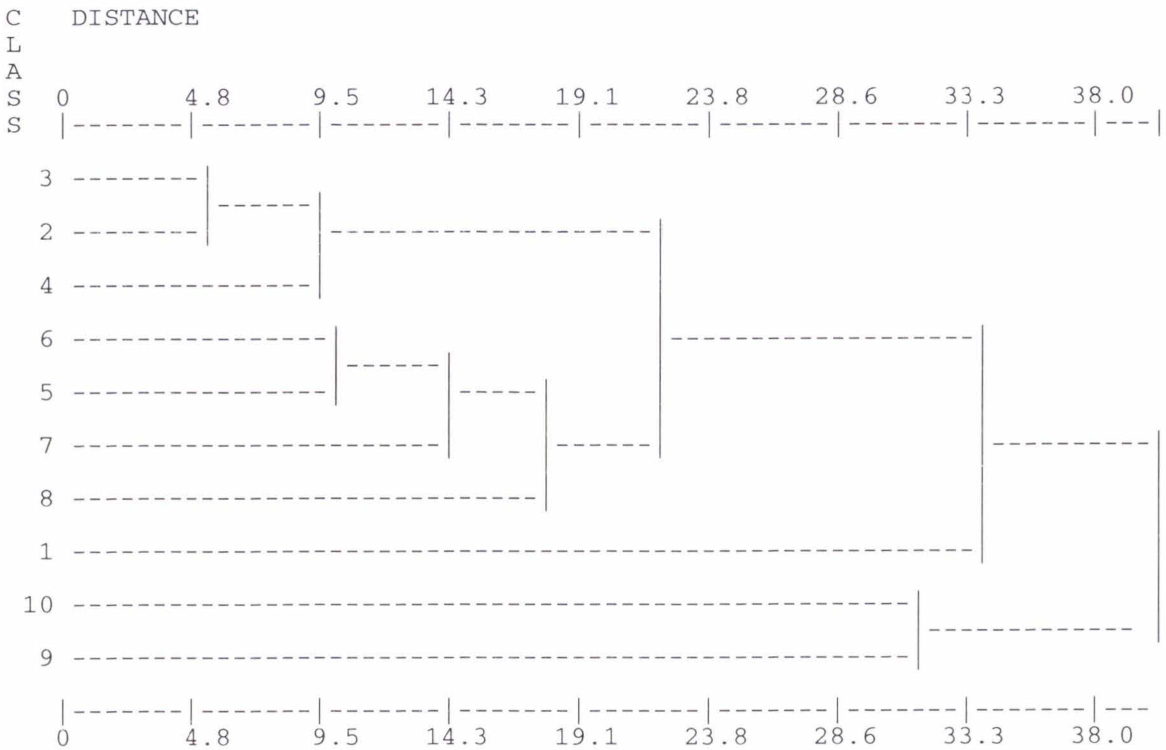


Figure 17. 10 classes; Original data; NDVI max. and min., Annual precipitation.

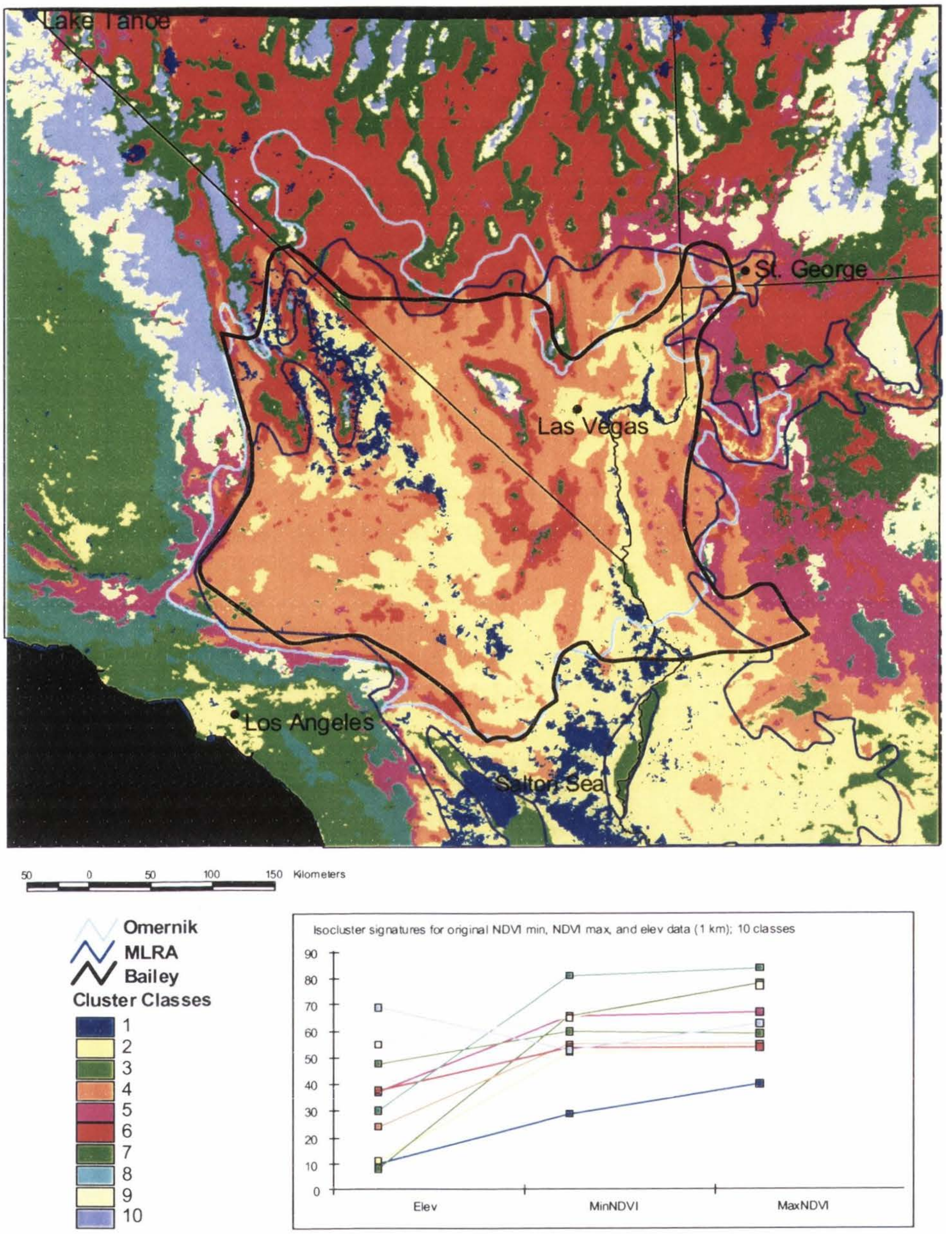


Figure 18. 10 classes; Original data; Elevation, NDVI max., NDVI min.

Distances between Pairs of Combined Classes
(in the sequence of merging)

Remaining Class	Merged Class	Between-Class Distance
6	7	12.479653
2	4	12.888732
5	6	15.942413
9	10	22.724071
5	9	23.317463
3	8	27.472421
2	5	29.032209
2	3	31.818696
1	2	42.704389

```
C   DISTANCE
L
A
S  0      4.7     9.5     14.2    19.0    23.7    28.5    33.2    38.0
S  |-------|-------|-------|-------|-------|-------|-------|-------|-------|--|

  7 --------------------|
                        |----|
  6 --------------------|    |------------|
                             |            |
  5 -------------------------|            |--------|
                                          |        |
 10 -------------------------------------||        |
                                         |-        |----|
  9 -------------------------------------|         |    |
                                                   |    |
  4 --------------------|                          |    |
                        |--------------------------|    |--------------|
  2 --------------------|                               |              |
                                                        |              |
  8 ---------------------------------------------|      |              |
                                                 |------|              |
  3 ---------------------------------------------|                     |
                                                                       |
  1 -------------------------------------------------------------------|

   |-------|-------|-------|-------|-------|-------|-------|-------|-------|--|
   0      4.7     9.5     14.2    19.0    23.7    28.5    33.2    38.0
```

Figure 19. 10 classes; Original data; Elevation, NDVI max. and min.

Figures 20 - 25 show cluster outputs with a 3 X 3 mean filter applied to input data. Figure 20 shows the results of maximum and minimum greenness and elevation at 5 classes. Notice that yellow dominates what we perceive as the Mojave and Sonoran Deserts, or MLRA 30, Division 320, and Province 322. It's evident from the shape of the Salton Sea that large bodies of water were included in this cluster. The dendrogram in Figure 21 shows that all clusters have large distances between their means.

Figure 22 is the same as Figure 20, but with precipitation added as an input variable. Once again, precipitation appears to add no new information to the results, except to the uniqueness of the Sierra Nevada.

Figure 24 shows the results of maximum and minimum greenness and elevation at 10 classes. Notice that when compared to Figure 18 (original data), boundaries are smoother and several small "islands" are gone. Overall, most orange and yellow is found within the Tropical/Subtropical Division (Division 320), as in Figure 18.

Figures 26 - 31 show cluster outputs with a 3 X 3 mean and variance filter applied to the input data. Figure 26 shows the results of maximum and minimum greenness and elevation at 10 classes. Notice the similarities between these results and those in Figure 24. The key difference is that the Grand Canyon has been classified with a unique cluster along with some steep mountain ranges in the northwest portion of Section 322A. In Figure 24, the Grand Canyon was included within the Mojave and some of the steep mountains were classified the same as the Great Basin. The dendrogram in Figure 27 reinforces that cluster 7 is very unique from its neighbors. The signature graph in Figure 26 indicates that cluster 7 has the highest elevation variance among all the clusters.

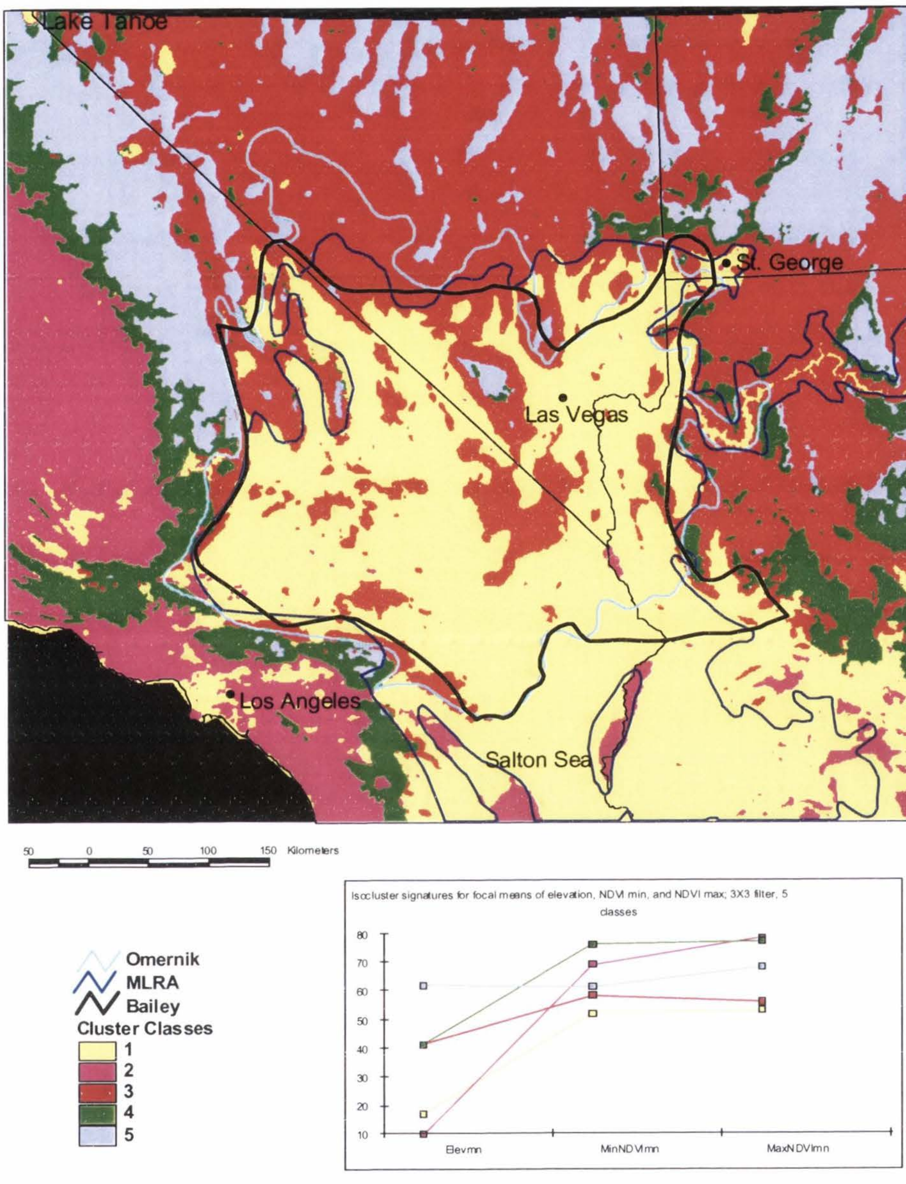


Figure 20. 5 classes; 3 X 3 mean filter; Elevation, NDVI max., NDVI min.

Distances between Pairs of Combined Classes
(in the sequence of merging)

Remaining Class	Merged Class	Between-Class Distance
3	5	24.498142
3	4	24.803848
1	2	30.504596
1	3	31.598643

```
C   DISTANCE
L
A
S  0       3.5     7.0     10.5    14.0    17.6    21.1    24.6    28.0
S  |-------|-------|-------|-------|-------|-------|-------|-------|---|

  5 ---------------------------------------------------------|
                                                              |-
  3 ---------------------------------------------------------| |----------|
                                                                |          |
  4 ----------------------------------------------------------|          |-
                                                                          |
  2 ---------------------------------------------------------------------| |
                                                                          |-|
  1 ---------------------------------------------------------------------|

   |-------|-------|-------|-------|-------|-------|-------|-------|---|
   0       3.5     7.0     10.5    14.0    17.6    21.1    24.6    28.0
```

Figure 21. 5 classes; 3 X 3 mean filter; Elevation, NDVI max. and min.

Figure 28 shows the results of elevation mean and variance. Elevation alone, when local variance is included, does a good job of identifying Mojave and Sonoran Ecoregions (Orange and Yellow) when compared to existing published boundaries. Using local variance along with local mean elevation allows the separation of areas with not only different elevation ranges, but also areas with variable terrain. This cleanly separates areas such as the Grand Canyon, the Panamint Range near Death Valley, and the San Gabriel mountains from the desert landscape.

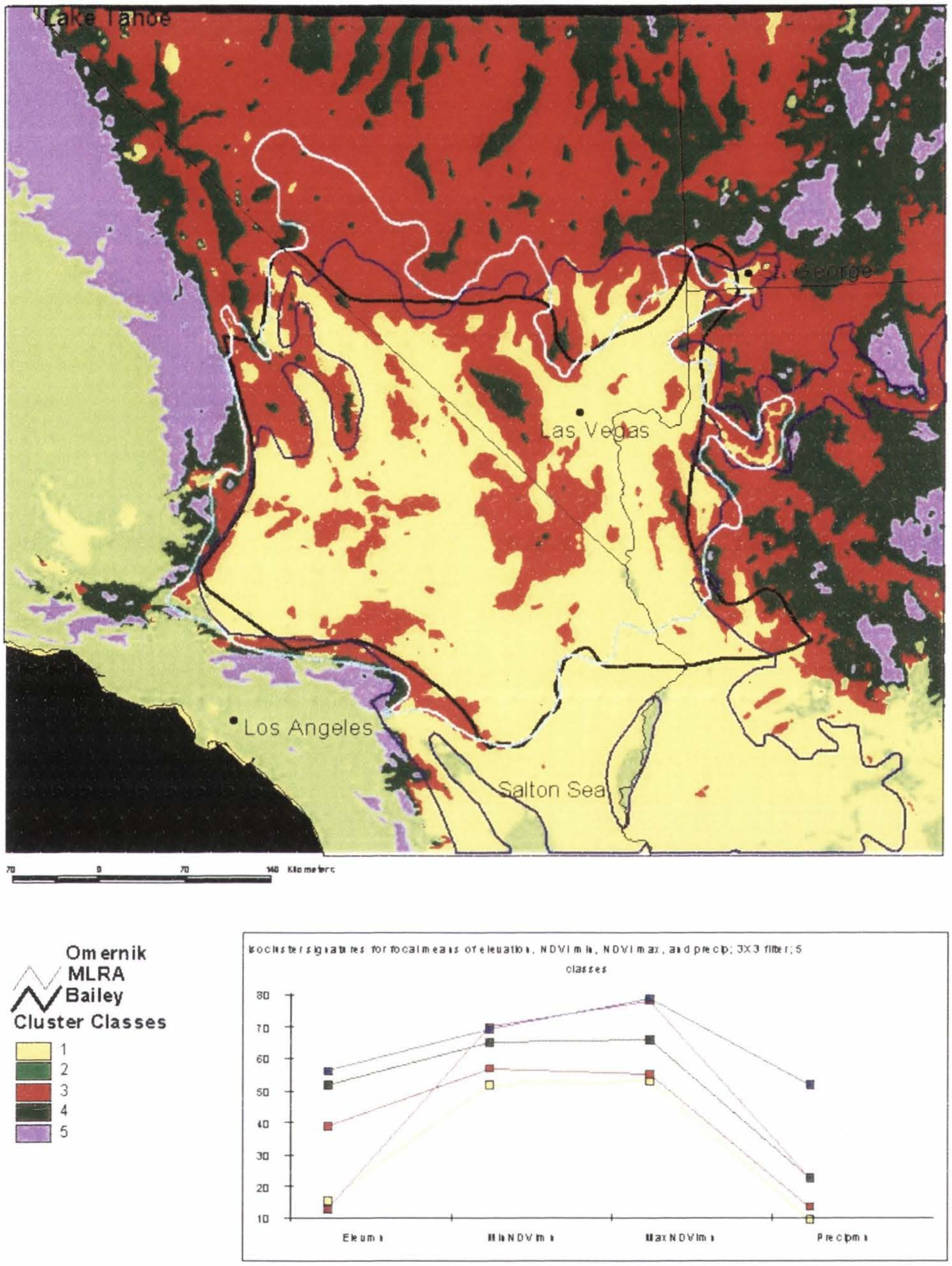


Figure 22. 5 classes; 3 X 3 mean filter; Elevation, NDVI max.and min., annual precipitation

Distances between Pairs of Combined Classes
(in the sequence of merging)

Remaining Class	Merged Class	Between-Class Distance
3	4	20.542669
1	3	31.416416
1	2	33.054882
1	5	48.749898

```
C   DISTANCE
L
A
S  0       5.4     10.8     16.2     21.7     27.1     32.5     37.9     43.0
S  |-------|-------|-------|-------|-------|-------|-------|-------|-------|---|

 4 -----------------------------|
                                |---------------|
 3 -----------------------------|               | -|
                                                |  |
 1 ---------------------------------------------|  |-------------------|
                                                   |                   |
 2 ------------------------------------------------|                   |
                                                                       |
 5 --------------------------------------------------------------------|

   |-------|-------|-------|-------|-------|-------|-------|-------|-------|---|
   0       5.4     10.8     16.2     21.7     27.1     32.5     37.9     43.0
```

Figure 23. 5 classes; 3 X 3 mean filter; Elevation, NDVI max. and min., annual precipitation.

Figure 30 shows the results of maximum and minimum greenness and elevation at 15 classes. Notice that the two clusters that dominated the Mojave and Sonoran (orange and yellow colors) in Figure 26 have been broken into 3 clusters: light blue, orange, and yellow (light blue is a cool color, but is used for better contrast). Yellow seems to occupy the low, flat salty valleys and the interiors of the Salton Sea and Lake Mead, orange seems to occupy the low to medium elevation basins (including in the Sonoran), and light blue seems to occupy the higher elevations and fringes around Province 322 or MLRA 30. The published ecoregion boundaries roughly match this output with particular

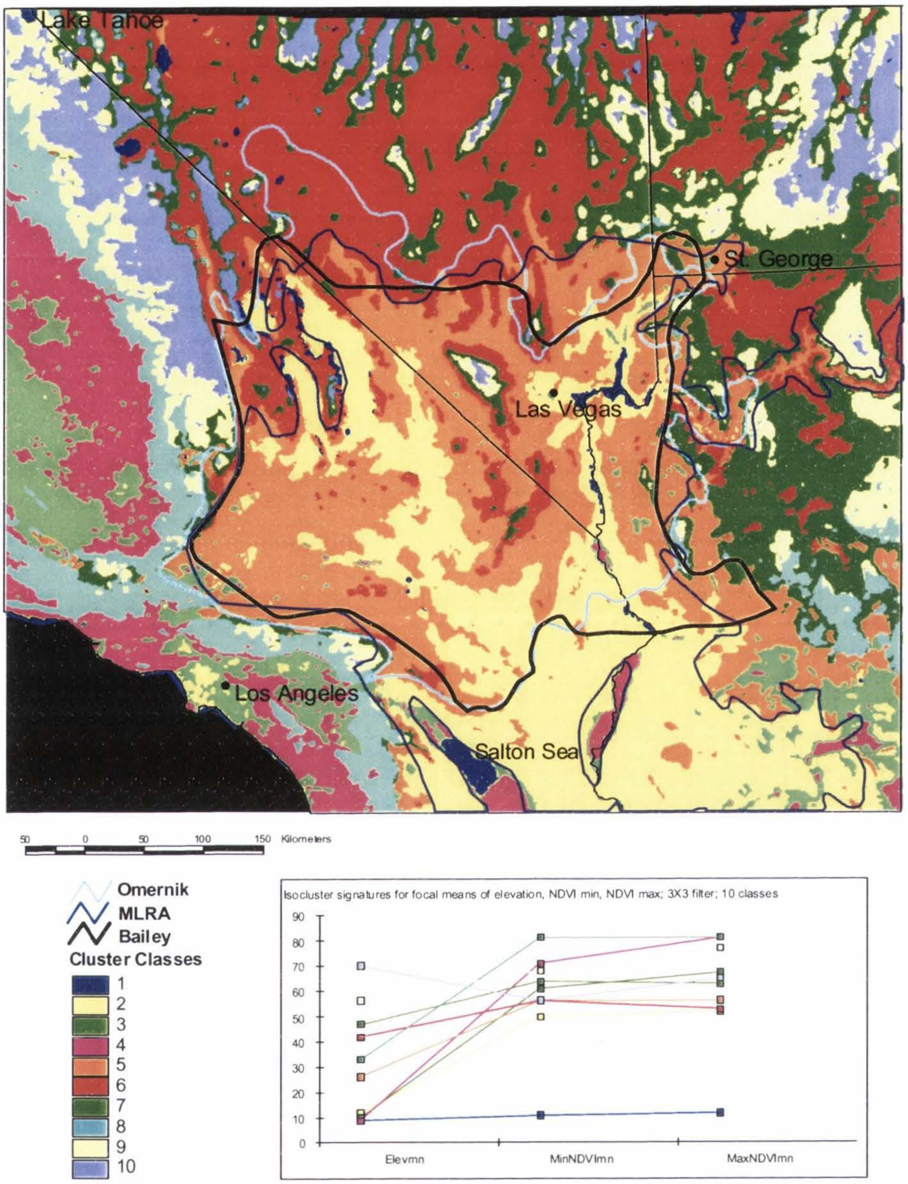


Figure 24. 10 classes; 3 X 3 mean filter; Elevation, NDVI max., NDVI min.

Distances between Pairs of Combined Classes
(in the sequence of merging)

Remaining Class	Merged Class	Between-Class Distance
6	7	13.071608
2	5	15.540868
3	4	17.626170
9	10	21.800702
6	9	23.203045
2	3	26.467776
2	6	32.272215
2	8	30.281131
1	2	73.511075

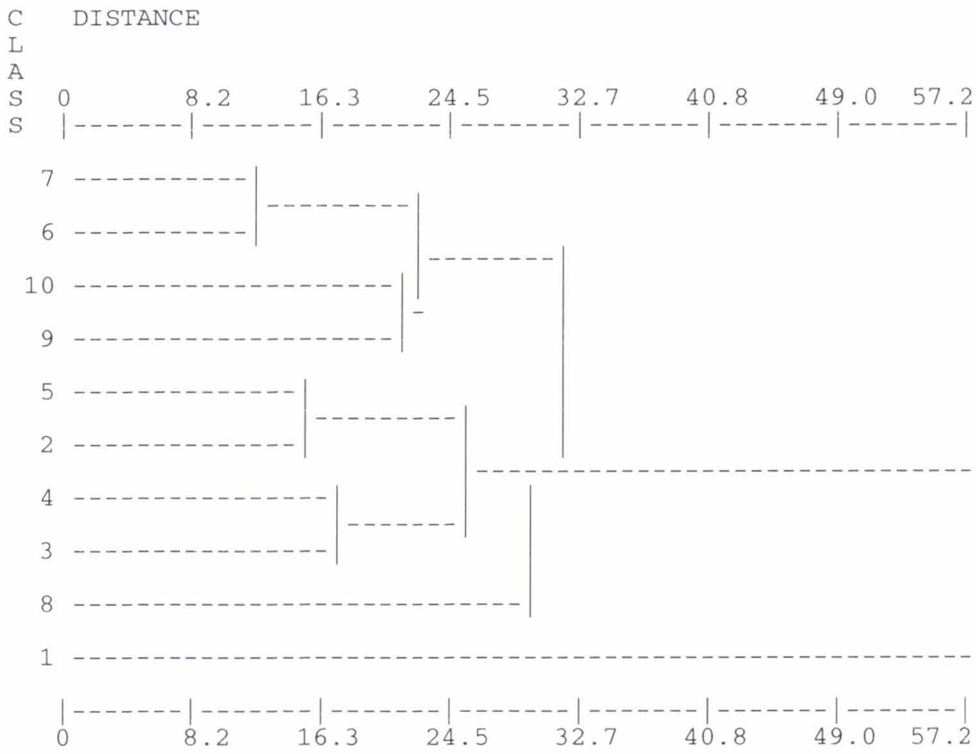


Figure 25. 10 classes; 3 X 3 mean filter; Elevation, NDVI max. , NDVI min.

regard to ECOMAP. The black line is Bailey's Section 322A boundary (1:7.5 million) and the dark blue line is Section 322A subdivided into subsections by the NRCS and U.S.

FS for the state of California (1:1 million). Only 10 of the 15 clusters that are geographically located in the desert regions and their neighboring regions are presented in the signature graph because 15 would have been extremely difficult to create and read in ArcView.

Figures 32 and 33 shows the results of a cluster output with a 13 X 13 mean and variance filter applied to maximum and minimum greenness and elevation at 10 classes. Except for more smoothed lines and more small islands eliminated, these results are basically the same as with a 3 X 3 mean and variance filter. The signature graphs are basically the same too. Notice that the Salton Sea and Lake Mead seem to be expanding beyond their natural boundaries with a 13 X 13 filter. This is an indication that smoothing data over a 169 sq km area begins to break down the spatial integrity of a landscape's boundaries. A general idea of the ecoregion boundaries is there, but all detail is lost.

Figures 34 - 37 show the results of applying an *a posteriori* confidence interval to the maximum likelihood classifications of the Isocluster signature files. Figures 34 and 35 are the same results as from Figure 26 (3X3 mean and variance; elev, ndvimax, ndvimin), but at 75% and 90% confidence intervals. There appears to be a great deal more homogeneity of clusters at 75% than at 90%. Remember that any pixel assignment probabilities of less than .75 or .9 are considered unacceptable and colored black. Notice that all of the Death Valley area is colored black.

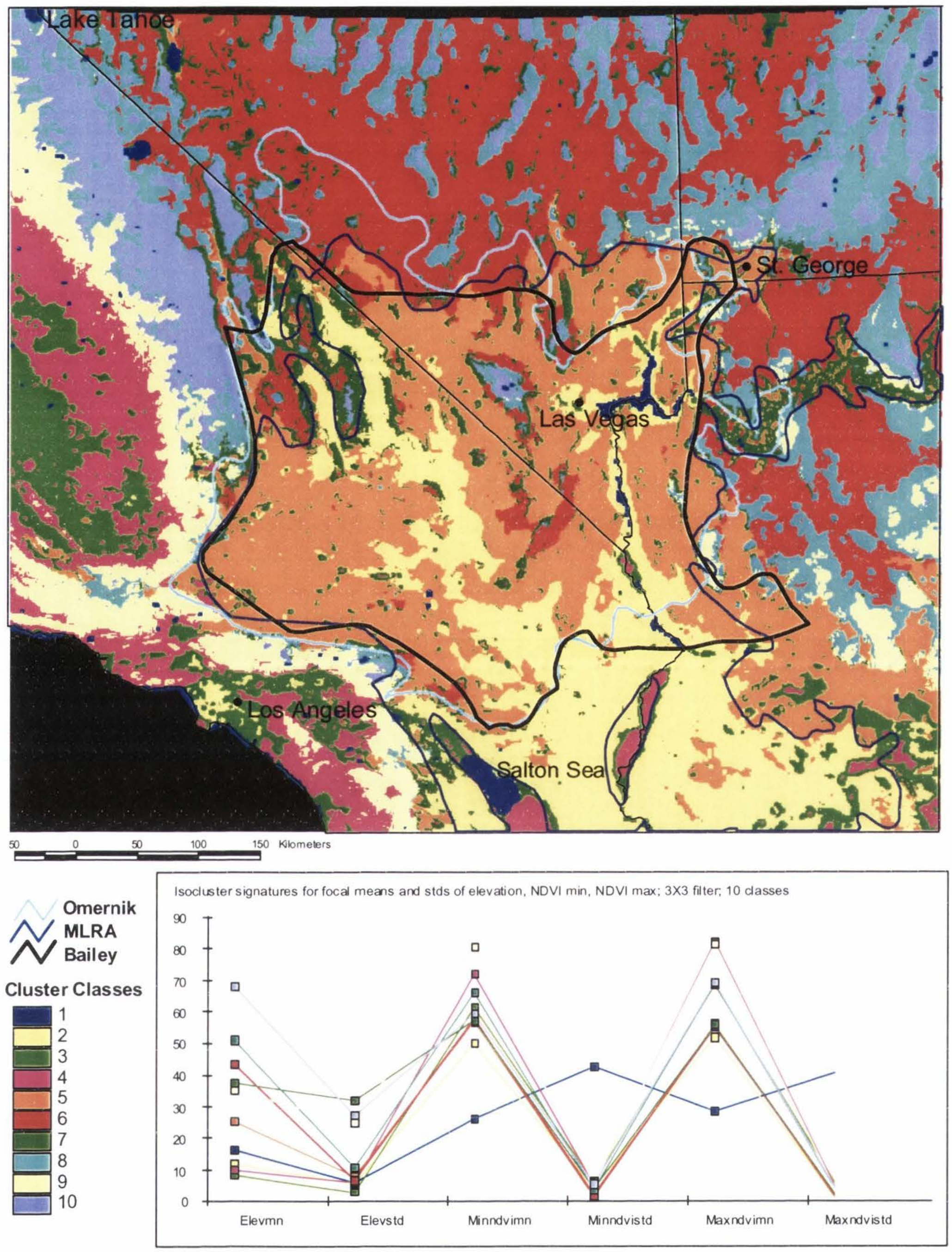


Figure 26. 10 classes; 3 X 3 mean and variance filter; Elevation, NDVI max.and min.

Distances between Pairs of Combined Classes
(in the sequence of merging)

Remaining Class	Merged Class	Between-Class Distance
2	5	15.818327
3	4	17.783783
6	8	18.443534
6	7	25.938591
2	6	27.354496
2	3	32.545682
2	9	35.032975
2	10	42.133025
1	2	74.014025

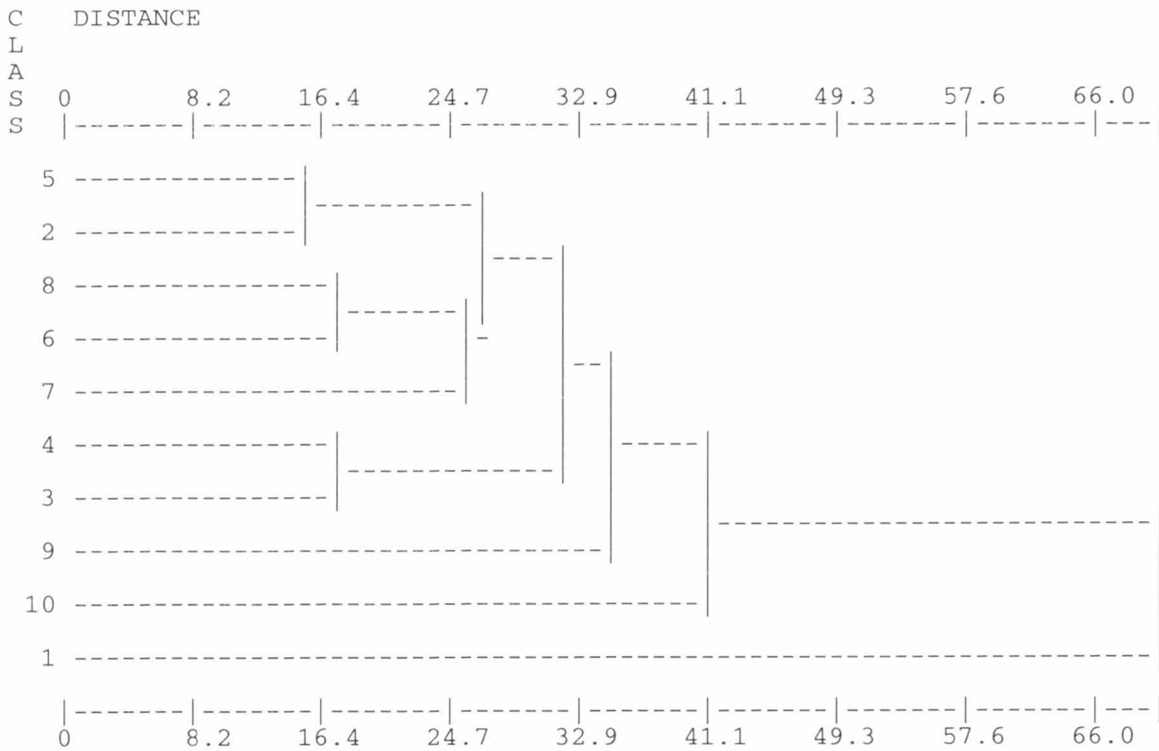


Figure 27. 10 classes; 3 X 3 mean and variance filter; Elevation, NDVI max. and min.

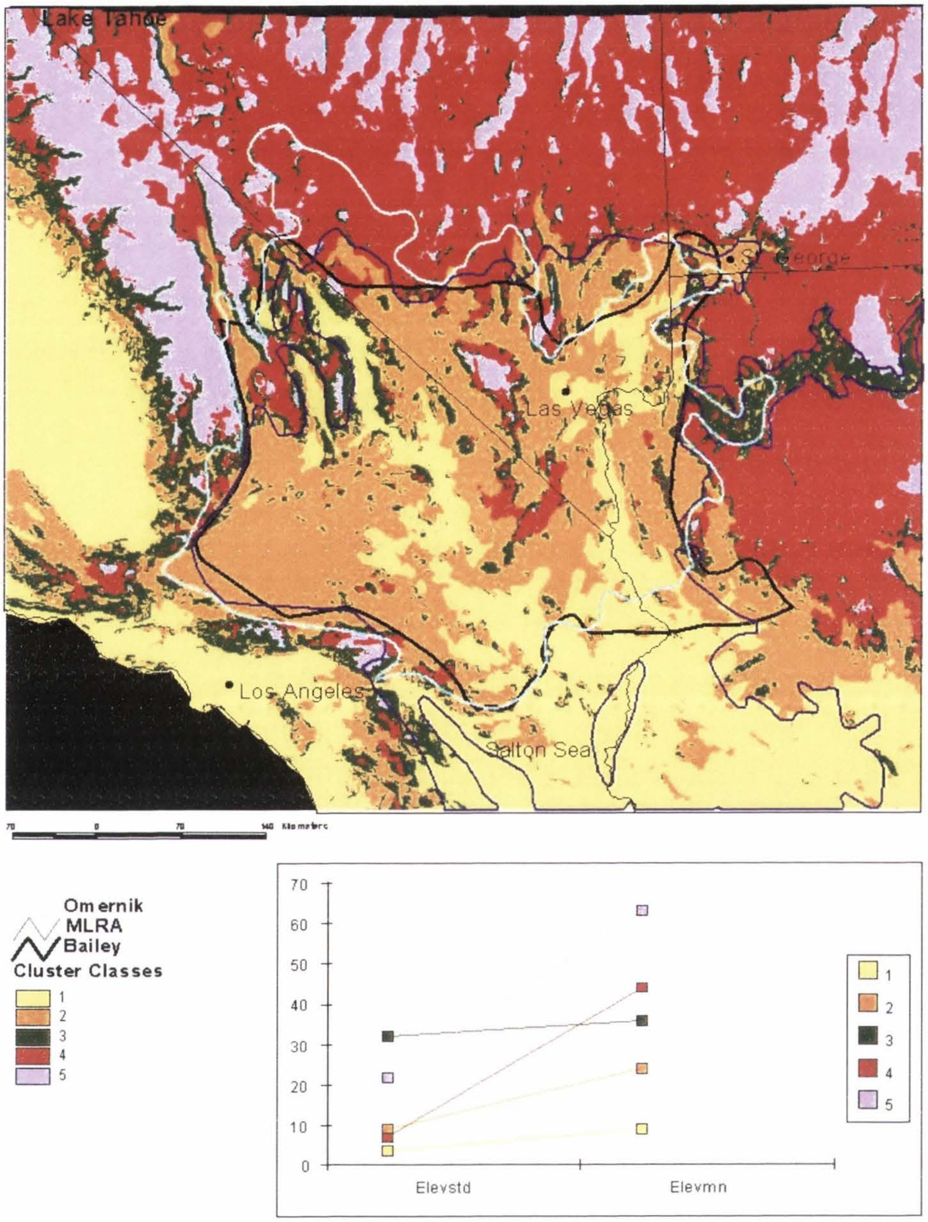


Figure 28. 5 classes; 3 X 3 mean and variance filter; Elevation

Distances between Pairs of Combined Classes
(in the sequence of merging)

Remaining Class	Merged Class	Between-Class Distance
1	2	15.885284
4	5	24.109776
3	4	24.722642
1	3	31.292164

```
C    DISTANCE
L
A
S  0        3.5      7.0      10.4     13.9     17.4     20.9     24.3     28.0
S  |-------|-------|-------|-------|-------|-------|-------|-------|-------|---|

 2 -----------------------------------|
                                      |--------------------------------|
 1 -----------------------------------|                                |
                                                                       |
 5 ---------------------------------------------------------|          |
                                                            |-         |
 4 ---------------------------------------------------------||---------|
                                                             |
 3 ----------------------------------------------------------|

   |-------|-------|-------|-------|-------|-------|-------|-------|-------|---|
   0       3.5     7.0     10.4    13.9    17.4    20.9    24.3    28.0
```

Figure 29. 5 classes; 3 X 3 mean and variance filter; Elevation

Figures 36 and 37 are the results of all possible data input for this thesis at a 3X3 mean and variance filter and at 75% and 90% confidence intervals. Precipitation and maximum temperature have been added, even though it has been shown that max. temp. is very correlated with elevation and that precipitation adds no new information to the classification. The point of adding these variables was to see how proportional cluster homogeneity was with the number of variables. The figures show that there was an increase in homogeneity.

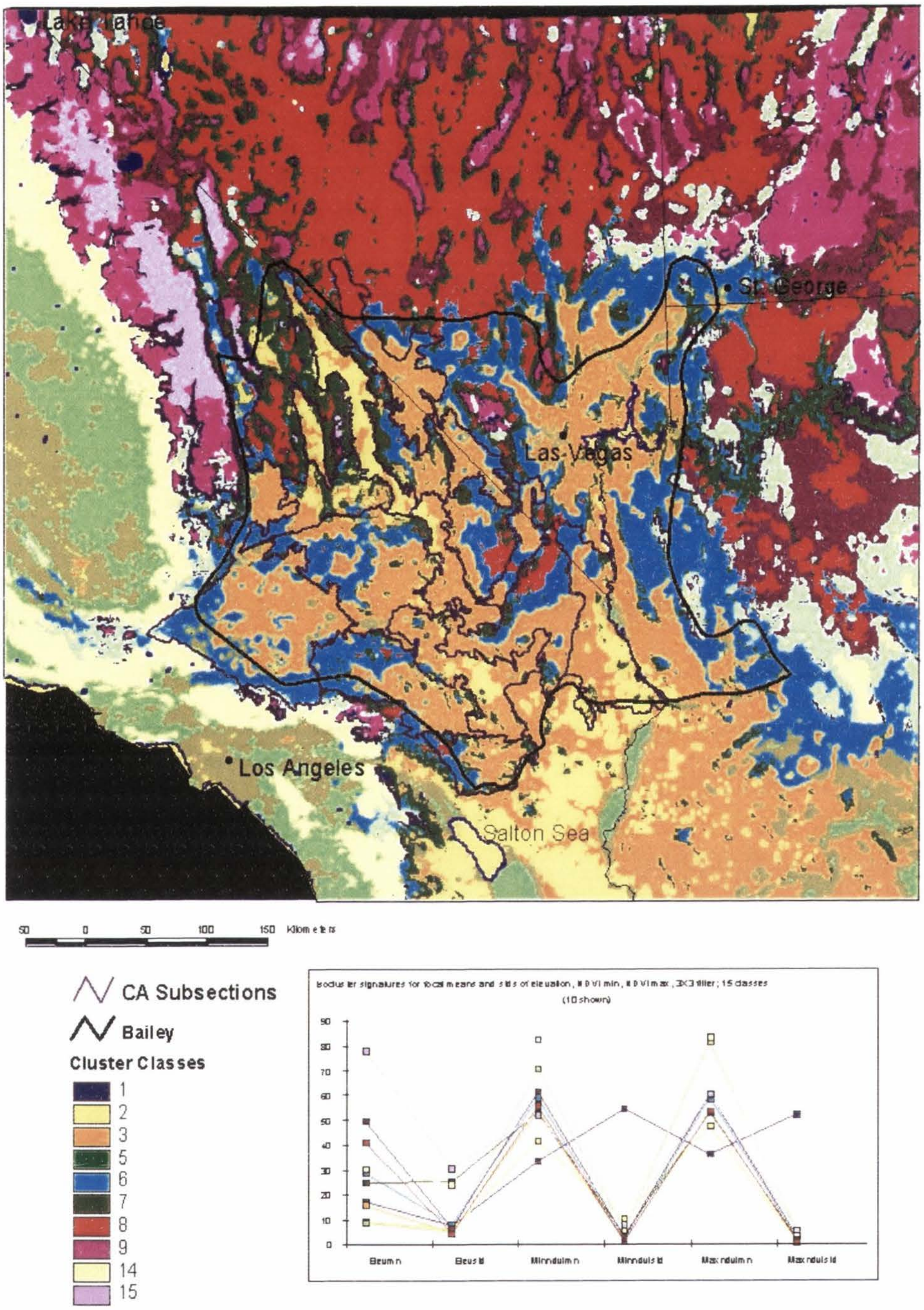


Figure 30. 15 classes; 3 x 3 mean and variance filter, Elevation, NDVI max., NDVI min. NRCS and U.S. FS subsections for California.

Distances between Pairs of Combined Classes (in the sequence of merging)

Remaining Class	Merged Class	Between-Class Distance
8	9	12.819007
3	6	14.919721
8	10	16.103442
4	5	17.613090
3	7	19.973312
8	12	20.977999
2	3	22.058275
8	13	24.479444
2	4	27.760006
2	8	30.541638
11	15	33.335528
2	14	36.226317
2	11	40.844560
1	2	81.188140

```
C   DISTANCE
L
A
S  0       9.0     18.0    27.1    36.1    45.1    54.1    63.1    72.0
S  |-------|-------|-------|-------|-------|-------|-------|-------|-------|---|

  9 ----------|
              |--|
  8 ----------|  |---|
                 |   |
 10 -------------|   |--|
                     |  |
 12 -----------------|  |-----|
                        |     |
 13 --------------------|     |
                              |
  6 ------------|             |
                |---|         |----|
  3 ------------|   |-|       |    |
                    | |       |    |
  7 ----------------| |----|  |    |
                      |    |  |    |
  2 ------------------|    |--|    |---|
                           |       |   |
  5 --------------|        |       |   |
                  |--------|       |   |
  4 --------------|                |   |-------------------------------|
                                   |   |                               |
 14 -------------------------------|   |                               |
                                       |                               |
 15 -----------------------------|     |                               |
                                 |-----|                               |
 11 -----------------------------|                                     |
                                                                       |
  1 -------------------------------------------------------------------|

   |-------|-------|-------|-------|-------|-------|-------|-------|-------|---|
   0       9.0     18.0    27.1    36.1    45.1    54.1    63.1    72.0
```

Figure 31. 15 classes; 3 x 3 mean and variance filter; Elevation, NDVI max., NDVI min.

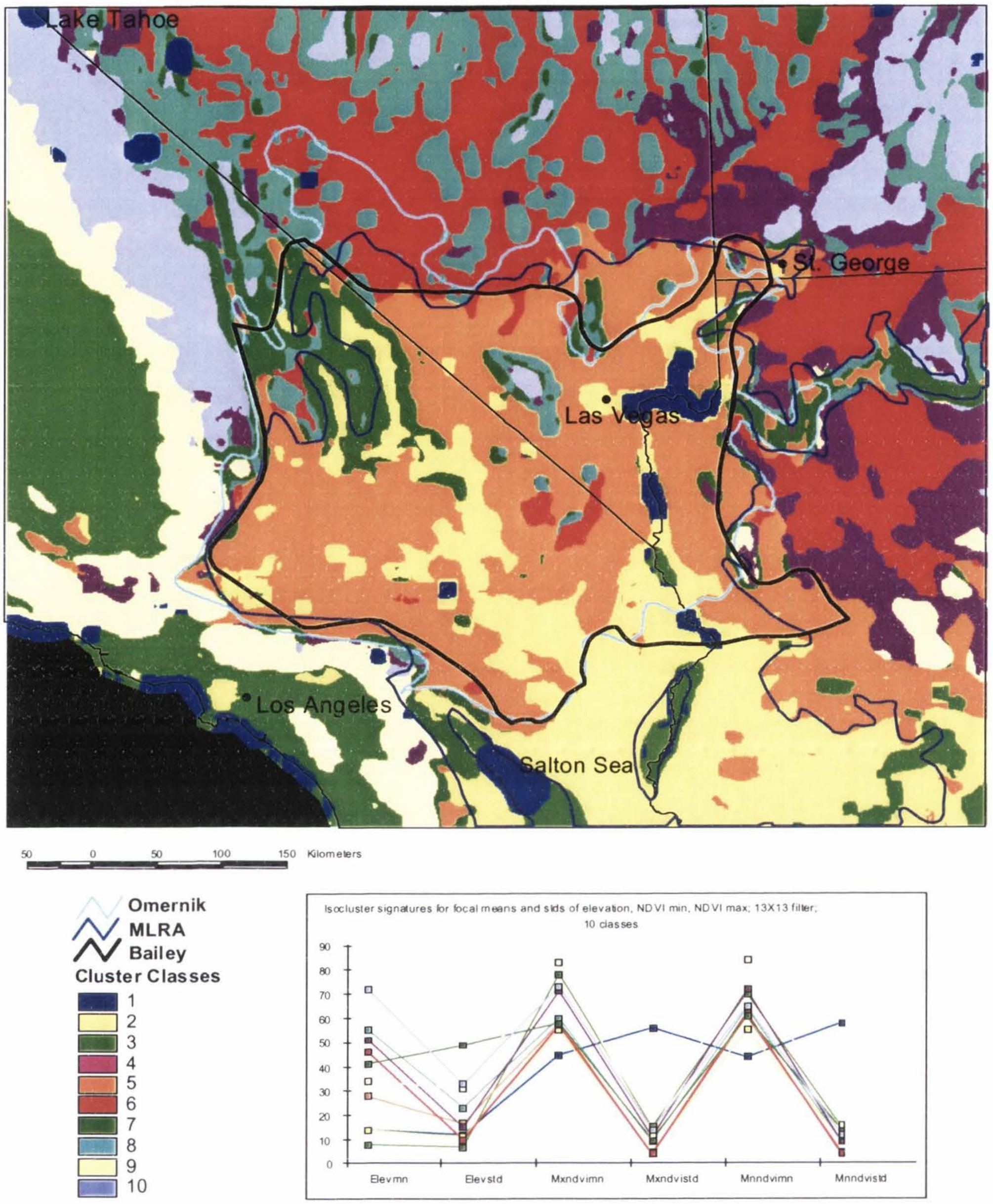


Figure 32. 10 classes; 13 X 13 mean and variance filter; Elevation, NDVI max., NDVI min.

Distances between Pairs of Combined Classes
(in the sequence of merging)

Remaining Class	Merged Class	Between-Class Distance
6	7	16.529332
5	6	16.936582
2	4	17.639746
2	5	30.160794
2	8	35.381376
2	9	36.834515
2	3	37.068158
2	10	43.623888
1	2	76.915334

```
C   DISTANCE
L
A
S  0       8.5     17.1     25.6     34.2     42.7     51.3     59.8     68.4
S  |-------|--------|--------|--------|--------|--------|--------|--------|---|

 7 ---------------|
                  |
 6 ---------------|-------------|
                  |             |
 5 ---------------|             |----|
                                |    |
 4 ----------------|            |    |
                   |------------|    |-
 2 ----------------|                 ||
                                     ||
 8 ----------------------------------||
                                      |-----|
 9 -----------------------------------|     |
                                      |     |----------------------------|
 3 -----------------------------------|     |                            |
                                            |                            |
10 -----------------------------------------|                            |
                                                                         |
 1 ----------------------------------------------------------------------|

   |-------|--------|--------|--------|--------|--------|--------|--------|---|
   0       8.5     17.1     25.6     34.2     42.7     51.3     59.8     68.4
```

Figure 33. 10 classes; 13 X 13 mean and variance filter; Elevation, NDVI max., NDVI min.

Figures 38 and 39 show histograms comparing the classification output with ECOMAP (Bailey), the EPA (Omernik) and the USDA boundaries. Only those outputs that met all assumptions/constraints were analyzed with this comparison. . Comparing the figures shows that eliminating pixels with less than 75% confidence greatly reduced the frequency of orange clusters (perceived to be Mojave) found outside the 3 existing classification boundaries. Keep in mind when comparing the 3 that MLRA Region 30 includes much of the Sonoran Desert (yellow), while Omernik's Region 14 and Bailey's Section 322a do not.

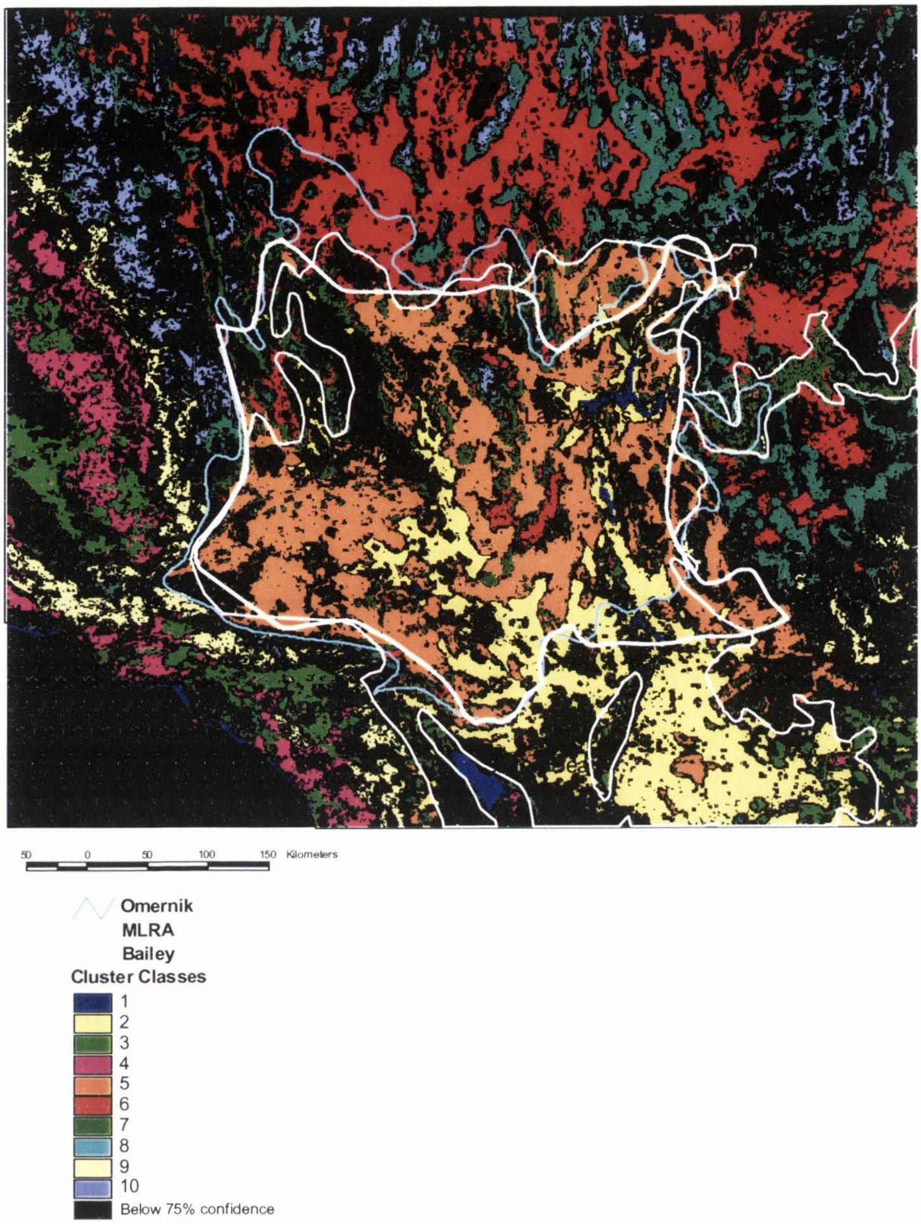


Figure 34. 10 classes at 75% confidence; 3 X 3 mean and variance filter; Elevation, NDVI max., NDVI min.

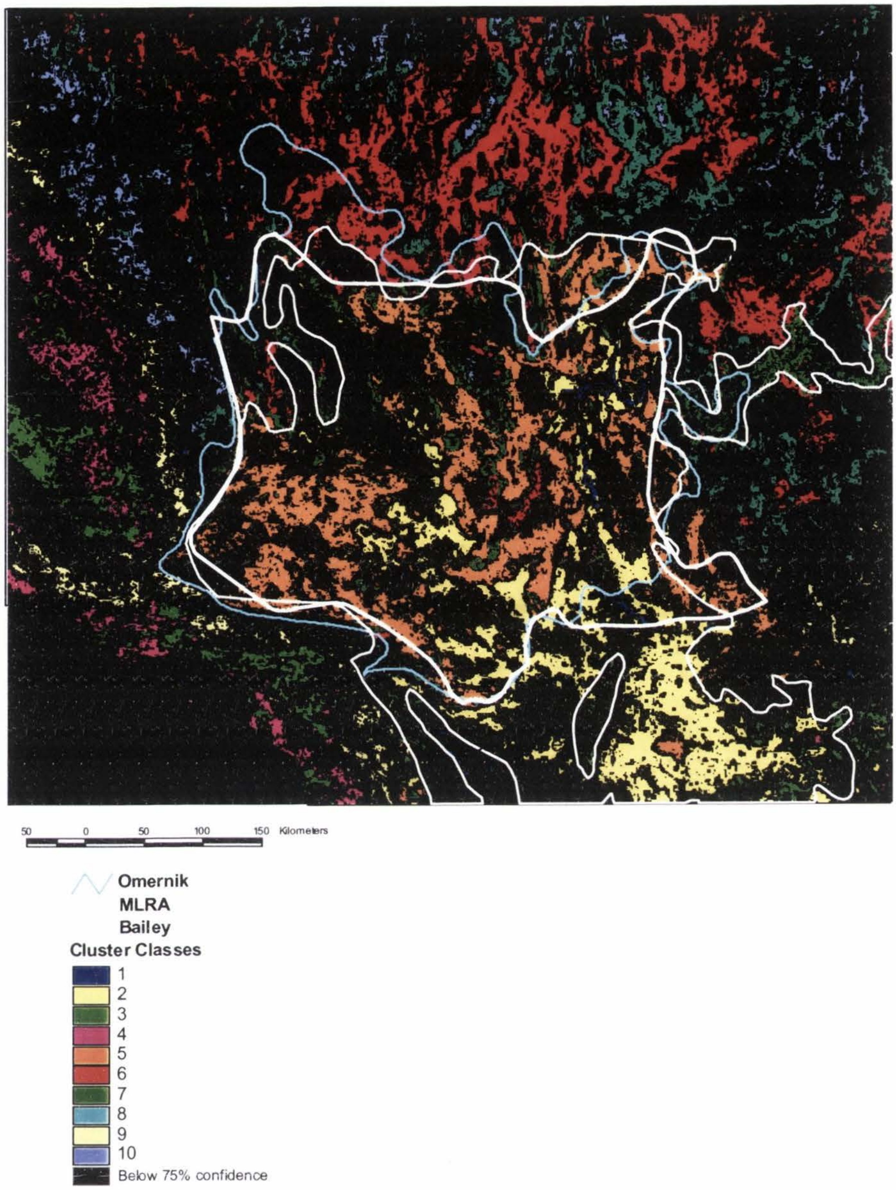


Figure 35. 10 classes at 90% confidence; 3 X 3 mean and variance filter; Elevation, NDVI max., NDVI min

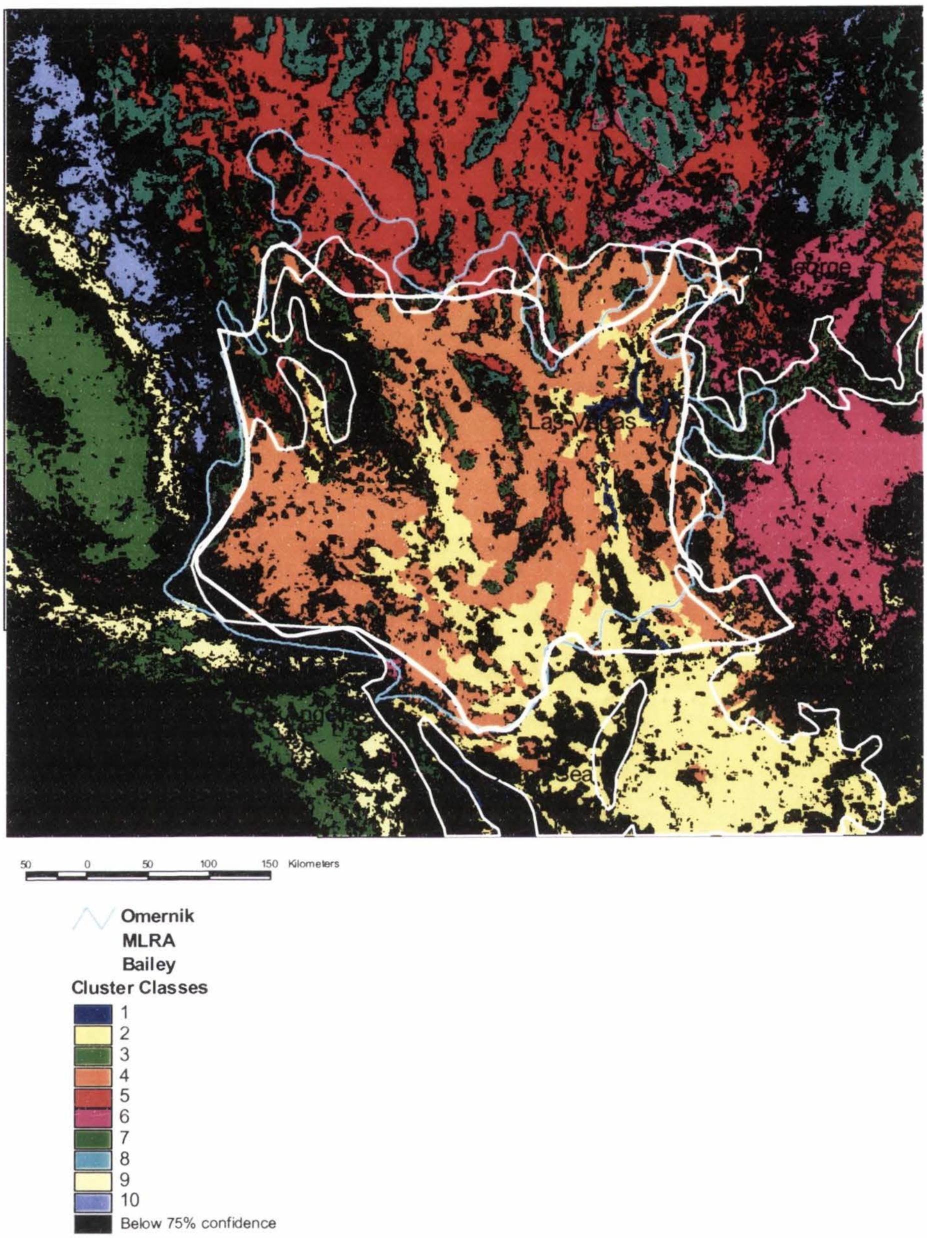


Figure 36. 10 classes at 75% confidence; 3 X 3 mean and variance filter; Elevation, NDVI max., NDVI min., annual precipitation, and annual max. temperature

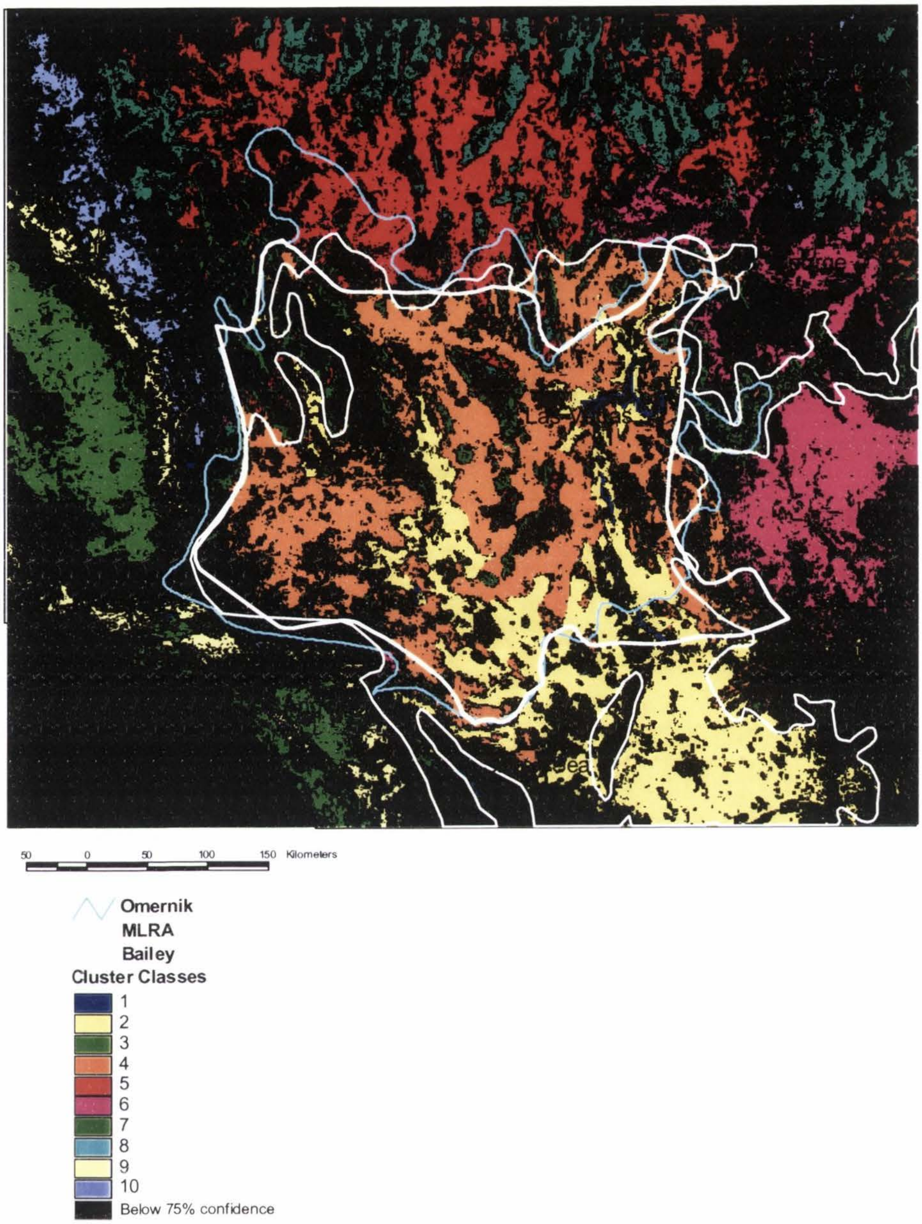
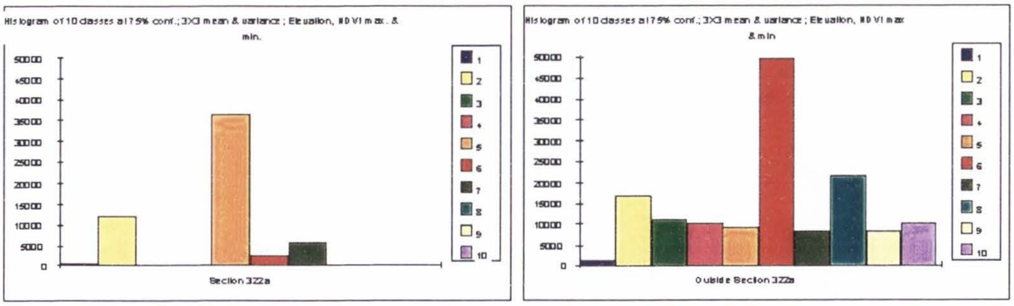
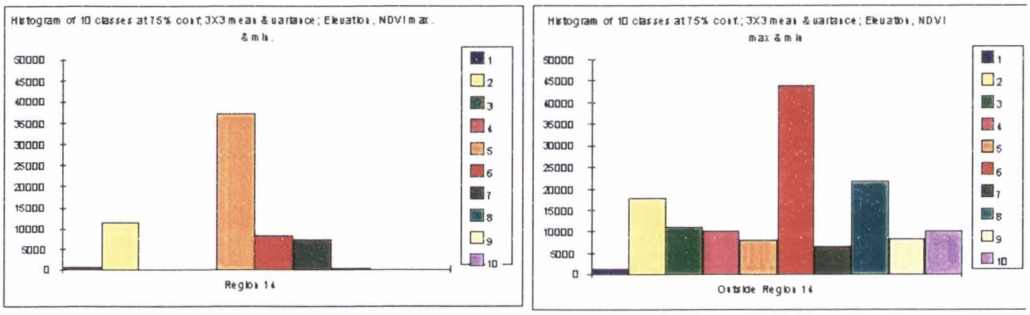


Figure 37. 10 classes at 90% confidence; 3 X 3 mean and variance filter; Elevation, NDVI max., NDVI min., annual precipitation, and annual max. temperature

ECOMAP (Robert Bailey) Section 322a



EPA (Jim Omernik) Region 14



USDA MLRA Region 30

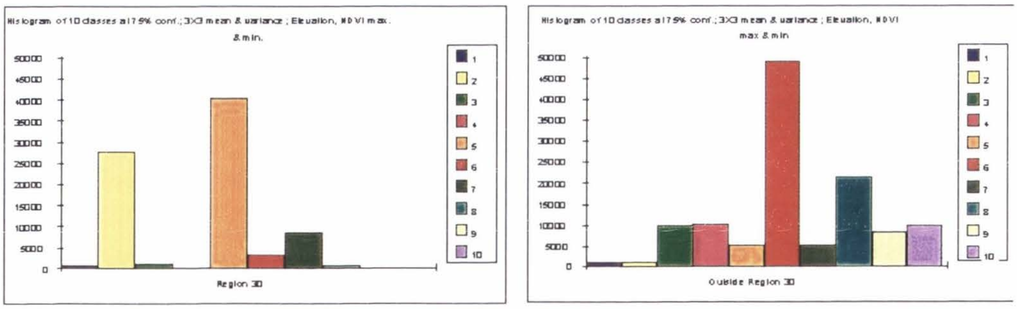
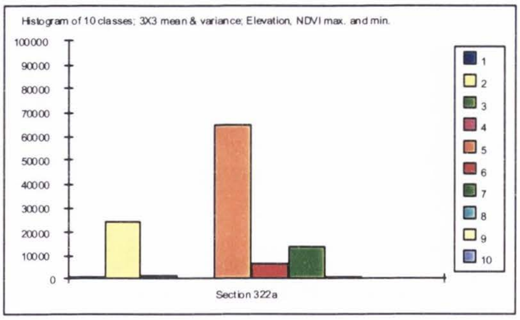
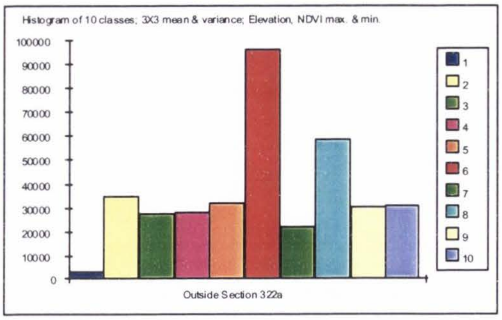


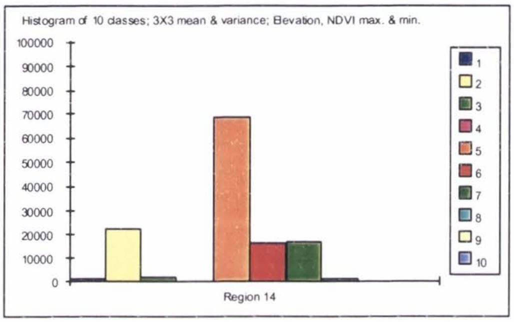
Figure 38. 10 classes at 75% confidence; 3X3 mean & variance; Elevation, NDVI max & min

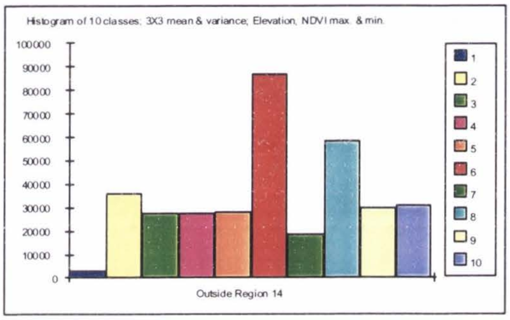
ECOMAP (Robert Bailey) Section 322a



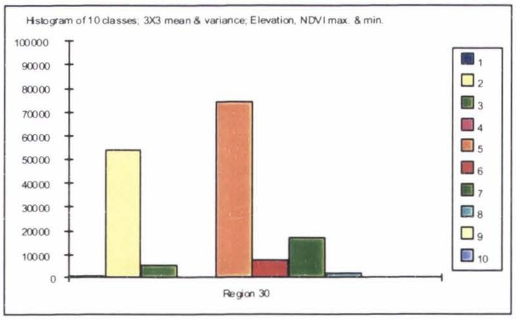


EPA (Jim Omernik) Region 14





USDA MLRA Region 30



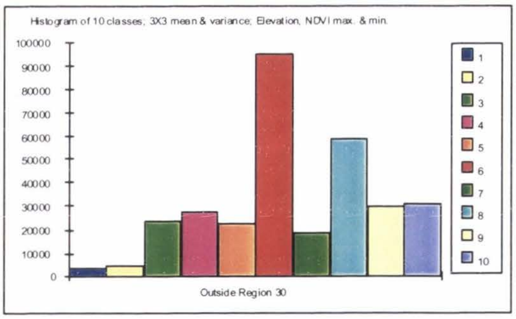


Figure 39. 10 classes; 3X3 mean & variance filter; Elevation, NDVI max., NDVI min.

DISCUSSION

All outputs identify to some degree self similar geographic regions within the desert southwest. However, only a few of the outputs identified cohesive and identifiable boundaries when compared to existing sources. There were some common trends among the various combinations of outputs. In order to simplify this discussion, these trends are summarized based on the following variables.

Layers

NDVI - Whether it was with original data, a 3X3 mean filter, a 3X3 mean and variance filter, a 13X13 mean filter, or a 13X13 mean and variance filter, the absence of maximum and minimum greenness always resulted in large areas of the lower San Juaquin Valley and surrounding foothills receiving the same classification as within existing boundaries. This violates assumption/constraint number 2 since the San Joaquin Valley is located entirely in the Humid Temperate Domain of Bailey's classification. (Figure 14). Notice also that there are no bodies of water (Lake Mead and Salton Sea are absent) or agricultural areas (around Salton Sea). The absence of NDVI data input shows us that elevation and annual precipitation at 1 km resolution alone cannot distinguish between valleys in the desert regions and the San Joaquin Valley.

Elevation - This variable is a powerful surrogate for many ecological factors. Depending on scale, relationships tend to change in complexity from simple (small scale) to complex (large scale). With all class sizes and smoothing filter combinations, the absence of elevation resulted in no discernable desert regions between Divisions 320 and 340 of Bailey's classification (Figure 16). Clusters presumed to be the Great Basin, the Mojave, and the Sonoran deserts are merged into one group. This does not necessarily violate assumption/constraint number 2, since these areas do fall under the same domain. But it does give identical classifications within the temperate desert (Great Basin - Division 320) and tropical/subtropical deserts (Division 340 and MLRA region 30). When comparing Figure 16 with Figure 28, which uses elevation alone as input, it is obvious that elevation is the dominant feature among the three biophysical layers that distinguishes the Great Basin from the Mojave and the Sonoran.

Precipitation - With all class sizes and smoothing filter combinations, precipitation made little difference in the classification results within Divisions 320 and 340, due to its low frequency in these environments. See Figures 20 - 23 for an example. According to the dendrogram similarities, it made the most difference in the Sierra Nevada, which receives the highest annual precipitation in the whole study area.

Number of Classes Requested

5 - Most of the combinations requested at 5 classes resulted in a homogenous classification within the Province 322 or MLRA region 30 (Figure 20 - 23). Notice that there is no unique Mojave region between the yellow and red (Great Basin) clusters. According to the similarity dendrograms, the yellow cluster (1) is very unique from the other classified regions. If we were attempting to classify just Province 322 or MLRA region 30, we could use almost any of the layer combinations at 5 classes. The exception is a combination of only elevation and precipitation, which classifies an orange cluster within the existing boundaries, but also classifies the same cluster to pixels in the foothills surrounding the San Joaquin Valley, as in Figure 14.

10 - Except for the absence of elevation, requesting 10 classes tended to result in a uniquely classified Mojave. With the absence of NDVI as input, the San Joaquin Valley was also classified along with the Mojave, violating assumption/constraint number 1. Adding precipitation made little difference in the spatial distribution or homogeneity of the output. See Figures 16, 17, 18, 19, 24, 25, 26, 27, 32 and 33 for examples of 10 classes. Similarity dendrograms of these iterations show high similarities between what we perceive as the Mojave and Sonoran clusters (often 2 and 4, or 2 and 5).

15 - Requesting 15 clusters often gave similar results as the 10 cluster outputs, with slightly more variability. There was no perceived improvement in the classification when one moved from 10 to 15 clusters.

Assumption/constraint number 3 states that the simplest classification scheme that identifies a unique Mojave will take precedence. 10 classes met this constraint with all combinations. Output with 15 classes could be useful when trying to classify ecoregions at a finer scale (i.e. finer than ECOMAP's sections). For example, the NRCS and U.S. FS delineations of subsections in the California part of the Mojave closely coincide with the regions classified in Figure 30.

Original data vs. Smoothing filters (means and variances)

There were generally few differences between the output classifications of original data and mean values across 3X3 and 13X13 smoothing filters. The biggest difference was that the class boundaries were not as detailed as with the raw data, which was expected. Also, some small areas (islands) within the predicted Mojave that received a different classification with the original data were smoothed away with the filters, making the definition of the Mojave more homogenous.

Adding variance to the mean values across the smoothing filters also made little difference in the output classifications, except in areas with steep slopes and large elevation changes. The two most prominent of these areas are the Grand Canyon and the steep mountain ranges in the northwest part of Section 322a (i.e. Panamint Range). When observing the output from focal mean only (Figure 24), notice that the Grand Canyon is classified the same as the Mojave (orange) and the Panamint Range is classified the same as the Great Basin (red). When observing the output from focalmean and focalstd (Figure 26), notice that the Grand Canyon and the steep mountain ranges are classified together as a unique class that is not similar to any other classes according to the similarity dendrogram.

When comparing these two areas with the 3 classifications from ECOMAP, the EPA, and the USDA, notice that Section 322a includes all the steep mountain ranges in the northwest, but doesn't include the Grand Canyon. Omernik's region 14 includes the steep mountain ranges and a small portion of the Grand Canyon (lower section). MLRA region 30 does not include most of the steep mountain ranges, but does include all of the

Grand Canyon (in the study area). The MLRA boundary lines seem to coincide more closely to the output from original data or focalmean filters at 5 or 10 classes (Figures 18 - 25). It's evident that the advantage of adding variance to the input is to distinguish areas that differ spatially from our definition of the Mojave (see biophysical descriptions in literature review). If we base our assumption/constraints just on ECOMAP's division boundaries, than this is necessary. Otherwise, the simpler classification scheme is to leave out variance and accept the Grand Canyon as part of the Mojave classification, as it appears the USDA has done with MLRA region 30.

Summary of Results (Choosing a Favorite)

If variance is left out, there are a number of outputs from 10 classes that could meet our qualifications for a unique Mojave ecoregion, from original data, a 3X3 filter, or a 13X13 filter. Assumption/constraint number 2 requires that we use NDVI as input and assumption/constraint number 3 requires us to drop precipitation as input, since it adds no more information.

If we choose to use variance, we eliminate the original data as input since the variance is based on a smoothing filter applied to that data. But we do open the opportunity to consider just one data layer by itself, such as elevation. In Figure 28, the mean and variance of elevation across a 3 X 3 filter was used as input and 5 classes were requested. Notice the similarities between this output and the output in Figure 26. The Grand Canyon and the steep ranges in the northwest have a different classification from the Mojave and both figures show a large area of homogeneity. But Figure 28 cannot be considered because, as with other classifications without NDVI as input, clusters defining the Mojave are also found in the Humid Temperate Domain in non-desert California. As with the other classifications, it's evident that if we want to distinguish between the Great Basin, Mojave, and Sonoran at 1 km resolution, elevation is the dominant factor when compared to greenness and climate. And adding the variance of elevation across an area helps us distinguish between the Mojave and the Grand Canyon. This very simple input from 5 classes could meet the main objective of this thesis and may be very satisfactory for a land manager who only wants a general idea of where to draw the boundary lines between the deserts. However, if we want to be consistent with the various nested hierarchies of ecoregion classification (in this example, ECOMAP's), elevation alone cannot discern between the low lying deserts and the San Joaquin Valley and Los Angeles Basin. Greenness from NDVI must be added to the input to separate the two domains.

Figures 26 and 32 show us the results of combining elevation and NDVI greenness and their variances. Notice that except for agricultural areas, there are very few cells in the two different domains that are assigned the same classification. Also notice that the Grand Canyon and steep mountains in the northwestern part of Section 322a have a different classification from the Mojave. These two classification schemes meet all the assumptions and constraints set in this thesis.

When comparing these classifications with the 3 ecoregions boundaries delineated by ECOMAP, the EPA, and the USDA (Figures 38 and 39), most orange classified cells fall within one of the three. Notice in Figures 26 and 32 that a rather large area in the northwest corner of Omernik's (EPA) classification consists of red cells, which we assume contains Great Basin characteristics. This was the case with all the various classifications from Isocluster. Other input data besides topographic, NDVI, or climate must account for this. Also notice that there is an area of orange in the northeast that falls outside the boundaries of Section 322a and Region 14, but falls inside (except for a narrow finger) MLRA region 30. This was consistently the case with all various classifications from Isocluster. Finally, there is a rather large area of orange cells in the southeast corner that consistently fell outside all existing ecoregion boundaries. This is the only appreciable area in question when addressing the main objective of this thesis.

Maximum Likelihood Confidence

We must keep in mind that all images in the figures so far assume that grid cells are assigned to the correct and best class from the signature file. Figures 34 and 35 represent the same output as from Figure 26, but at 75% and 90% confidence intervals. When comparing the output from 75% with the output from 90%, notice that there is more homogeneity among the orange cells and most cells in general. Notice that most of the area outside the southeast corner of the existing ecoregion boundaries is no longer classified as orange. It is classified as null data because the *a posteriori* probability assignment of these cells to any class is below 75%. Notice that the area outside the north and east boundaries of Region 14 and Section 322a is assigned orange at 75% and 90% confidence. MLRA region 30 came the closest to matching this area. We must keep in mind that the 3 Mojave ecoregion classifications presented in this thesis were compiled at different scales and used some different criteria for input.

Finally, notice that there is a rather large dark area that would normally encompass Death Valley in all the figures. One might assume that any of the biophysical data representing Death Valley would be easily associated with Mojave Desert characteristics. But Death Valley is much lower, much drier, and much less vegetated than average Mojave biophysical data. Death Valley is an anomaly (or an island) in the Mojave, no different than the Spring Mountains.

Figures 36 and 37 represent all possible data input for this thesis at 75% and 90% confidence. While it has been shown that maximum temperature is so highly correlated with elevation that it should not be used and that precipitation makes no difference in the output, Figures 36 and 37 show us that more layers reinforce the cell assignment confidence calculated by maximum likelihood. Notice in Table 38 that a larger number of orange cells occur within at least one of the Mojave Ecoregion boundaries, while there are very few orange cells outside. Figures 36 and 37 give us also more visual confidence that there is a large homogenous region of orange between regions of red and yellow, meeting the main objective of this thesis.

CONCLUSIONS

While the number of variables and number of outputs for this thesis could be overwhelming, the overall objective remained simple: to quantitatively identify a Mojave ecoregion unique in biophysical characteristics from its neighboring regions. Quantitatively does not necessarily imply objectively. While this method may have been more objective than those used by Robert Bailey, Jim Omernik, and the USDA, subjectivity, bias, and assumptions were still necessary. Any ecoregion definition depends on the users' objectives and the scale they are working with.

One of the key factors that makes the methods used in this thesis more objective than those used by Bailey, Omernik, or the USDA is that the similarities in the clustered regions can be quantitatively measured. Also, these methods can be repeated and quickly modified, as demonstrated with the large number of variables.

The methods used in this thesis were a means of providing quick answers to "what if" questions. Adding and taking away variables such as number of classes, focal mean, focal standard deviation, and the input data itself was a process to help understand associations between these variables and the classifications of known landscapes and features. It was obvious from this thesis that elevation and its variance is a dominant factor in identifying known landscapes and features across the Basin and Range, the Southwest, and possibly the whole West. But this probably would not be the case east of the Rockies (except the Appalachians). There is probably some other stable biophysical variable that dominates there, such as climate or a derivative of NDVI.

Contrary to assumption/constraint numbers 1 and 2, a classification is not necessarily a "throw-away" just because it falls in two very different ecoregions, such as Bailey's domains. The areas may be unique, but not according to 1 km elevation and NDVI data that has been smoothed with a 3X3 filter. And even if they are identical in several biophysical characteristics, if the majority of their neighbors are different from them but similar to each other, then they will be classified along with their neighbors. This was the case with many "islands" in this thesis at levels lower within the hierarchy. Also, maybe the user could care less that a cluster falls in two different domains. Maybe for his or her objectives, a simple classification scheme, such as elevation mean and variance, is satisfactory. And maybe they will work at a scale where it doesn't matter if 2 neighboring clusters are combined together as one.

Future research regarding the methods of this thesis could consist of experimenting with derivatives from NDVI and climatic data, particularly regarding time. For example, the maximum and minimum greenness values from 21 different NDVI periods were used as input in this thesis. What about the time period itself? Instead of asking what was the maximum value, we could ask *when* was the maximum value (i.e.- spring bloom)? One could logically guess that maximum greenness would occur in the Mojave Desert earlier than in the Great Basin. The same goes with precipitation. Instead of using one value for precipitation that represents a whole year, one could extract which month (or time period) does maximum and minimum precipitation occur. This would help distinguish between eastern parts of the Sonoran Desert, which receives monsoonal rains in August, and the Mojave Desert which receives most of its precipitation in the winter. Temporal data such as these must be treated differently from interval-ratio data, which was the type of data used in this thesis. Other data that needs to be treated differently, but could be very useful, is soils, geology, and landform. These data were not included in this thesis because they aren't interval/ratio data.

Other further research regarding the methods of this thesis could consist of quantifying the relationship between the scale of the study area, the scale and size of the sought after ecoregion (i.e. Section) , the resolution of the data, the number of classes requested in the unsupervised classification, and the number of layers of input data.

BIBLIOGRAPHY

Bailey, R.G., 1996. Ecosystem Geography. Springer, New York.

Bailey, R.G., 1994. Ecoregions of the United States (map). Rev. ed. Washington, DC, Forest Service, U.S. Department of Agriculture. Scale 1:750,000; colored.

Benson, L. and R.A. Darrow. 1944. A Manual of Southwestern Desert Trees Shrubs. Univ. of Arizona Bull. XV, No. 2 Biol. Sci. Bull. No. 6, Univ. of Arizona.

Burrough, P.A., 1986. Principles of Geographical Information Systems for Land Resources Assessment. Clarendon Press, Oxford.

ECOMAP. 1993 (Revised 1996). National Hierarchical Framework of Ecological Units. Unpublished administrative paper. Washington, DC. U.S. Department of Agriculture, Forest Service. 13 p.

Environmental Protection Agency, Office of Information Resource Management. 1996. Level III Ecoregions of the Conterminous United States. http://nsdi.epa.gov/nsdi/projects/useco.htm

ESRI Arc/Info 7.1 Online Help Manual.

Goudey, C.B. and D.W. Smith, eds. 1994. Ecological Units of California: Subsections. (map) San Francisco, CA. U.S. Department of Agriculture, Forest Service. Scale 1:100,000; colored.

Goudey, C.B., 1997. Personal Communication.

Hammond, E. H. 1970. Classes of land-surface form. Map (scale 1:7,500,000). The National Atlas of the United States of America, pp. 62-63. Washington, D.C.: U.S. Geological Survey.

Hargrove, W.W. and R.J. Luxmoore, 1997. A Spatial Clustering Technique for the Identification of Customizable Ecoregions. 8 p. http://www.esri.com/library/userconf/ proc97/proc97/to250/pap226/p226.html

Host, G.E. and P.L. Polzer, 1996. A Quantitative Approach to Developing Regional Ecosystem Classifications. Ecological Applications, 6(2), pp 608-618.

Hunt, C.B. 1967. Physiography of the United States. Freeman, San Francisco.

Jaeger, Edmund. The North American Deserts. Stanford, California: Stanford University Press, 1957.

Jensen, J.R., 1996. Introductory Digital Image Processing. Prentice Hall, New Jersey.

Kaufman, D., 1997. Geomorphology Class Project. Geology Dept. Utah State University.

Kaufman, K., and P.J. Rousseeuw, 1990. Finding Groups in Data, An Introduction Cluster Analysis. John Wiley and Sons, Inc., New York.

Keys, J., 1997, Interagency Meeting, Casper, WY. Personal communication.

Knight, D.H., 1994. Mountains and Plains, The Ecology of Wyoming Landscapes. Yale University.

Koppen, W., 1931. Grundriss der Klimakunde. Berlin: Walter de Gruyter Co. 388 p.

Kuchler, A.W., 1964. Potential Natural Vegetation of the Conterminous United States, American Geographical Society, Special Publication No. 36.

Kuchler, A. W., 1970. Potential Natural Vegetation. Map (scale 1:7,500,000). The National Atlas of the United States of America, pp. 89 - 91. Washington, D.C.: U. S. Geological Survey.

MacMahon, J.A., 1979. North American deserts: their floral and faunal components. In Goodall, D. and Perry, R.A. (eds), Arid-land ecosystems: structure, functioning and management. Vol. 1. Cambridge University Press, Cambridge. Pp. 21-82.

MacMahon, J.A., 1992. Deserts. The Audobon Society Nature Guides. Alfred A. Knopf, Inc. New York.

McMahon, G., S.M. Gregonis, S.W. Waltman, J.M. Omernik, T.D. Thorson, J.A. Freeouf, A.H. Rorick, and J.E. Keys. 2001. Developing a Spatial Framework of Common Ecological Regions for the Conterminous United States.

McNabb, W.H. and P.E. Avers, eds. 1994. Ecological Subregions of the United States: Section Descriptions. Washington, DC. U.S. Department of Agriculture, Forest Service. Publication WO-WSA-5.

Miles, S.R. and C.B. Goudey, eds. 1997. Ecological Subregions of California, Section and Subsection Descriptions. San Francisco, CA. U.S. Department of Agriculture, Forest Service.

Mojave Desert Ecosystem Program. RS/GIS Laboratory, Utah State University. 1998. Produced Under the U.S. Dept. of Defense Legacy Program and in Cooperation with the Dept. of the Interior.

Morgan, S., 1995. Ecology and Environment. Oxford University Press, New York.

Omernik, J.M., 1987. Ecoregions of the Conterminous United States. Annals of the Association of American Geographers. Vol. 77(1), pp. 118-125.

Omernik, J.M., 1995. Ecoregions: A Framework for Managing Ecosystems. The George Wright Forum. Vol. 12, pp. 35-50.

Omi, P.N., L.C. Wensel, and J.L. Murphy. 1979. An Application of Multivariate Statisitics to Land-Use Planning: Classifying Land Units into Homogenous Zones. Forest Sci. 25 (3): 399-414.

Paris, K., 1997. NRCS, Davis, CA. Personal Communication.

Peterson, F.F., 1981. Landforms of the Basin and Range Province, Defined for Soil Survey. Technical Bulletin 28. Nevada Agricultural Experiment Station. University of Nevada at Reno.

Ramsey, R.D., 1997. Personal Communication.

Rowe, J.S., 1992. The Ecosystem Approach to Forest Management. Forest Chronicle 68: 222-224.

Rowe, J. S. 1980. The Common Denominator of Land Classification in Canada: An Ecological Approach to Mapping. Forest. Chron. 56: 19-20.

Shreve, Forrest. 1942. The desert vegetation of North America. Botanical Review. 8(4): 195-246.

Smith, S., Brook, R., and Tisdale, M., (1994). Understanding ecosystem management (article and foldout). Science and Children, 32(3), 33-40.

Thornton, P.E., S.W. Running, M.A. White. 1997. Generating Surfaces of Daily Meteorological Variables Over Large Regions of Complex Terrain. Journal of Hydrology, 190: 214-251.

Trewartha, G. T. 1968. An introduction to weather and climate. 4th ed. New York: McGraw-Hill. 408 p.

Trimble, S., 1989. The Sagebrush Ocean. A Natural History of the Great Basin. University of Nevada Press, Reno/Las Vegas.

U.S. Department of Agriculture. Natural Resources Conservation Service. 1998. Northern Basin and Range Region MLRA Office # 3. http://www.nv.nrcs.usda.gov/mlra/p1/mlrapg1.htm

West, N.E., 1998. Personal Communication.

West, N.E., R.D. Ramsey, and T. Tilton, 1998. Modifying the National Hierarchical Framework of Ecological Units for Utah's West Desert. Unpublished manuscript. Utah State University.

West, N.E., 1995. Deserts. Encyclopedia of Environmental Biology. Vol. 1, pp. 475-495