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Valley Oak Restoration Site Suitability in the Los Alamos Valley, Santa Barbara County, California

A group project report submitted in partial satisfaction
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by

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Santa Barbara County, California

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ABSTRACT

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In the central coast region, ongoing clearing of valley oak woodland and the lack of natural regeneration, creates a need for effective mitigation of losses. Our goal is to increase the effectiveness of efforts to restore valley oaks, by identifying those sites where restoration will have the best chance of establishing self-sustaining oak communities. We have created a knowledge-based model that examines the suitability of sites for valley oak regeneration. The model employs Ecosystem Management Decision Support software that integrates spatial Geographic Information System (GIS) data and an expert system knowledge base to assess the suitability of individual sites for valley oak restoration in the study area, the Los Alamos valley.

Sites are evaluated, with the unit of analysis being a soil polygon, based on their biophysical characteristics, including soil, water, and atmospheric properties. Polygons are classified according to their degree of suitability for valley oak restoration. The model identifies 286 km^2 of unsuitable area, 5.3 km^2 of extremely suitable area, and approximately 170 km^2 of area somewhat suitable for valley oak restoration. We provide suggestions for smaller scale considerations during valley oak restoration efforts, and we discuss how biological community, social, and economic factors can be added to the model to improve and increase its applications.

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1.0 Introduction

California's oak woodlands are declining in both viability and distribution. This decline continues a pattern that began with the arrival of Europeans in the state, and has proceeded largely unchecked. Anthropogenic activities such as agricultural conversion and ever expanding suburban development have reduced the state's original 10-12 million acres of oak woodland to approximately 7 million acres today (Thomas 1997). In the central coast region, ongoing conversion of oak woodland to commercial vineyards creates additional urgency for quantitative resource inventories and effective mitigation of losses.

In addition to anthropogenic activities that eliminate oak habitat, oak regeneration is further threatened by poor recruitment; natural recruitment in valley oak (*Quercus lobata)* is almost nonexistent (Bolsinger 1988). Influences believed to be contributing to poor recruitment of valley oak include cattle grazing, competition with non-native plants, increased herbivory by deer and small mammals, and altered natural fire regimes.

Since valley oaks have little commercial value, the need for restoration efforts in this habitat may initially appear limited to recreational value or aesthetics. But with recruitment in oak woodlands failing, concern has grown regarding the type of communities that will replace oak-associated assemblages. As the dominant oaks succumb to natural mortality, the influence they exert on the adjacent biotic and abiotic environment disappears, leaving behind an altered resultant state. Plants and animals that were associated with the original oak community are often not well suited to this new state. These may be found in the new ecosystem in reduced numbers or not at all; thus loss of the dominant oaks cascades through the community.

An integrated approach to restoring oak woodlands must preserve or restore sufficient habitat and address the requirements for successful recruitment, most probably through human assistance. (Swiecki and Bernhardt et al, 1991). Early efforts at replanting oaks frequently failed due to the same factors that limit natural regeneration (McCreary, 1996). Oak restoration assistance by humans is sufficiently costly to constrain restoration efforts (Swiecki and Bernhardt, 1991). Therefore it makes sense to focus restoration efforts on areas where oaks are most likely to establish.

Currently, riparian valley oak restoration is underway in California within the Consumnes River Preserve, managed by the Nature Conservancy; and the California Department of Parks and Recreation is focusing on restoration of valley oak savanna habitat in Malibu Creek State Park in the Santa Monica Mountains (Pavlik, et al, 1991). In Santa Barbara County, the effects of herbivory are being investigated by researchers from the Department of Geography at UCSB at study sites located in Sedgwick Reserve.

Our goal is to increase the effectiveness of efforts to restore valley oaks, by identifying those sites where restoration will have the best chance of establishing self-sustaining oak communities. To this end, we have created a prototype knowledge-based model that examines the suitability of sites for valley oak regeneration. The model employs ArcView Geographic Information System and Ecosystem Management Decision Support software to assess the suitability of individual sites for valley oak restoration in the Los Alamos Valley in Santa Barbara County.

2.0 Objectives

To accomplish the goal described in the introduction, our project established the following objectives:

1. **Information inventory**
   - Collection of spatial data.
   - Identification of key ecological parameters in the valley oak ecosystem.
   - Identification of data from which to develop “fuzzy logic” rules.

2. **Model development**
   - Through the use of the Ecosystem Management Decision support (EMDS) and ArcView software packages, create a “fuzzy logic” based model that allows inferences to be made regarding habitat restoration suitability and other ecosystem processes.

3. **Model implementation**
   - Evaluate sites for valley oak habitat restoration potential in the Los Alamos valley.

4. **Restoration recommendations**
   - Based on findings from the model, make recommendations to the Santa Barbara County Planning and Development Department regarding future directions for refining and applying the model to Valley oak restoration and mitigation activities in the County.

Collecting and structuring regional spatial data was a necessary step to support the use of both the model and the associated digital maps. Key ecological interactions were identified from literature and expert sources, and as feasible, validated via consultations with experts and examination of aerial photography. Synthesis of the ecological information resulted in the "fuzzy logic" rules that comprised the EMDS model.

Quantitative methods of site suitability analysis offer scientific defensibility and have been shown to offer improved results over ad hoc analyses. (Pressey and Tully, 1994) The fuzzy knowledge modeling approach of Ecosystem Management Decision Support (EMDS) software provides a formalism for representing quantitative and qualitative understanding while explicitly communicating uncertainty in that understanding.

EMDS was then coupled to the ArcView GIS-based regional maps. The spatial display capabilities of GIS alone often deliver insights previously not apparent. The GIS-EMDS model combination offers iterative and flexible site assessment. It is a powerful analytical tool based on spatially correct information and the diverse parameters noted above.

The results of our analysis, maps, model, and use protocols have been provided to Santa Barbara county for future planning efforts. These tools will provide the County of Santa Barbara an adaptable assessment capability that is responsive to changing socioeconomic conditions.

3.0 Background Information

3.1 Study Area Description

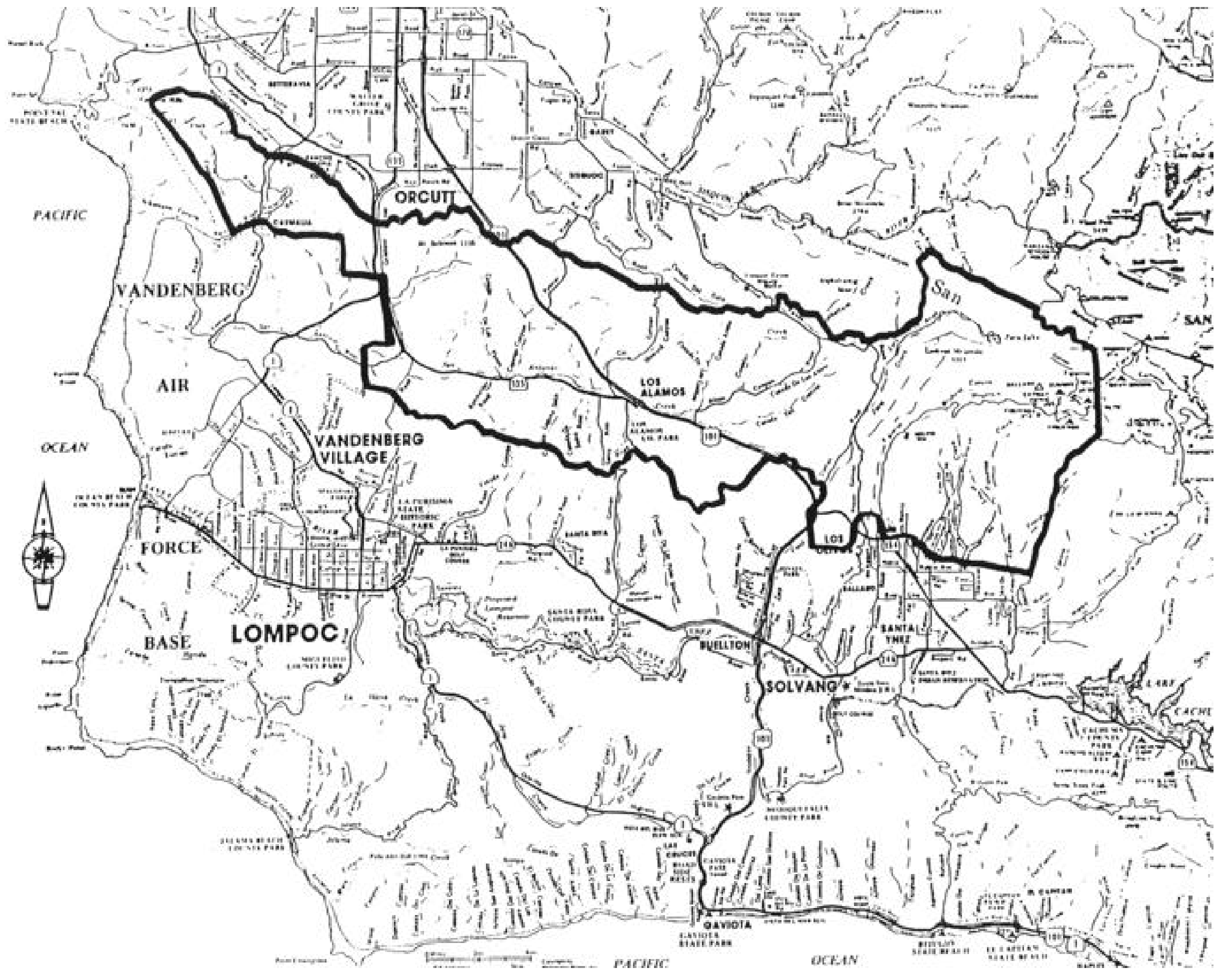
The study area is located in Northern Santa Barbara County in the Los Alamos Valley. The site is bounded to the west by Vandenberg Air Force Base, and otherwise incorporates the San Antonio Creek watershed. The watershed is bounded to the north and south respectively by the Solomon and the Purisima Hills (figure 3-1). The land slopes steeply from an altitude of more than 365 meters along ridges that flank the valley to the north, south, and east, to a narrow, flat floor that slopes gently westward from an altitude of about 240 meters to the Pacific Ocean (Hutchinson, 1980).

The Purisima and Casmalia Hills constitute a barrier to the seaward flow of ground-water. Upwelling of ground-water just east of the barrier has established a 223 hectare marshland in the eastern portion of the study site, known as the Barka Slough (Hutchinson, 1980).

Within the study area, land is devoted to municipal and agricultural uses, including livestock grazing. The town of Los Alamos incorporates 130 hectares in the east-central part of the valley. The rest of the valley is privately owned, with the upland portions primarily used for dry farming or grazing, and the flatlands along the streams used for irrigated farming. Agricultural emphasis has shifted from field and pasture crops to large-scale vineyards and truck crops (Hutchinson, 1980).

The San Antonio Creek valley has a semi-arid climate characterized by mild temperatures and sparse rainfall. Temperatures during the winter generally range from 40^{o} to 60^{o}F and summer temperatures range from 60^{o} to 80^{o}F (Hutchinson, 1980). The long-term average annual rainfall is 38.9 cm (California Department of Water Resources) with approximately 95% of the annual rainfall occurring between November and May.

Figure 3-1


PACIFIC
VANDENBERG
AIR
FORCE
BASE
OCEAN
LOMPOC
ORCUTT
VANDENBERG
VILLAGE
LOS
ALAMOS
BUELLTON
SOLVANG
SANTA
YNEZ
GAVIOTA
San
PACIFIC
OCEAN

3.2 Valley Oak Ecology

Valley oaks have been the subjects of far less scientific research than other California oaks, such as the blue oak. For this reason, the ecology of the species is not well known. Attempts to capture ecological factors influencing the valley oak is further confounded by the species' broad range and the diversity of environments in which it occurs.

The valley oak (*Quercus lobata,* Nee) is a winter deciduous, white oak, endemic to California (Griffin, 1977). Trunk diameters have been reported to be as large as 13 feet, and the trees typically are from 12 to 35 meters tall (Munz, 1974). Valley oak trees can live to be over 300 years old (Elias, 1980). The trees are in leaf from March and November (Swiecki and Bernhardt, 1991) and produce acorns fairly prolifically, albeit sporadically (Jepson, 1910).

Reproduction is almost exclusively by seed, as only young valley oaks are capable of stump spouting (Jepson, 1910). Valley oak acorns do not have dormancy mechanisms, though it has been noted that the valley oak germination process takes longer than for either of the other California white oaks, *Q. douglasii,* and *Q. dumosa* (Matsuda and McBride, 1989).

Q. lobata produces acorns annually, although production varies significantly from year to year, with heavy production years often followed by years of less, or almost no, acorn production (Koenig et al, 1990). Production also varies within years among individual trees. Griffin, (1980) used acorn traps to explore production. He found production rates in high mast years of up to 200 viable acorns per square meter of ground surface, and average rates, calculated from four trees over nine years, of 34 viable acorns per square meter. The production cycle in valley oaks regionally is synchronized and appears to occur at 2 or 3 year intervals (Koenig et al, 1990).

Under natural conditions, acorns on the ground surface lose viability as they lose moisture; (Swiecki and Bernhardt, 1991) germination rate is therefore enhanced by litter and leaf cover over the acorns (Sudworth, 1908).

Valley oak seedlings appear to be relatively shade intolerant, preferring open areas for establishment (Callaway, 1992, Holmes, 1995). Establishing *Q. lobata* seedlings invest more biomass in their roots relative to their shoots than do *Q. douglasii* seedlings (Matsuda and McBride, 1986, Callaway, 1992), and have been observed to have tap roots of 86 cm by the time the first leaves are fully exposed (Matsuda and McBride, 1986). The ability of seedlings to re-sprout after loss of the shoot may be related to the investment in the root system. This re-sprouting capability is important to seedling persistence after fire or herbivory (Swiecki and Bernhardt, 1991).

Valley oaks are tolerant of fire within limits. Young trees that have been top killed by fire may re-sprout from the crown, and older trees are somewhat insulated from fire by thick bark. However the valley oak's bark insulation evolved in response to frequent low-intensity fires typical of California grasslands, and cannot withstand high intensity fires resulting from accumulated fuel material (Mooney, 1977).

Adult valley oak trees root as deeply as 10-20 meters (Lewis and Burgy, 1964). Deep tap root systems reach the water table (Jepson, 1910, Griffin, 1971) and allow valley oaks to be relatively drought resistant (Brown, 1991). There is little seasonal variation reported in the xylem sap tension of valley oaks (Griffin, 1973), attesting to their ability to withstand the summer dry period typical of the Mediterranean climate of California.

Oak Communities

The initial period of European settlement in California rapidly converted prime valley and riparian habitat to agricultural use. Much of the remaining oak habitat existed on rolling terrain economically suited for livestock grazing. As rangeland, large blocks remained intact, and only partially disturbed, until such time as further development occurred. These rangelands thus provided valuable water storage capacity and regions of semi-disturbed habitat for a variety of wildlife.

The structure and composition of valley oak communities vary markedly from site to site. They range from open widely spaced savannas to dense riparian woodland, in response to a complex matrix of climatic, hydrologic, soil and geographic variables. Savannas typically occur on valley floors or hills away from creek channels and support a sparse canopy, generally less than 5% of the ground surface, with an extensive understory dominated by annual grasses (Rawlings, 1996). Riparian woodlands are characterized by a more dense canopy, generally greater than 65% of ground surface, formed by bands of trees that grow in and adjacent to drainages (Rawlings, 1996). However, the divisions between categories are arbitrary; gradations of communities exist between the savanna and riparian types.

The community of oak-associated plants, vertebrates, invertebrates, and soil microflora, likewise varies from site to site, in response to site-specific conditions, and the extent of influence by the dominant oaks. Within these communities, structural complexity is enhanced by the presence of riparian areas, downed woody debris, snags, and diverse ages and conditions in oaks and other plants. As the dominant species, valley oaks provide complex physical structure for sheltering, feeding, and reproductive activities of associated species throughout their life and in for many years after death.

Statewide, oak woodlands are home to a tremendous number of vertebrates and invertebrates (Pavlik et al, 1991). Barrettt (1980) found the valley oak to be utilized by 21% of the California's mammals, more than any other oak species. Acorns appear to be a sufficiently important food source that squirrels and deer populations fluctuate with the annual mast crop (Barrett, 1980). Over 30 species of birds alone consume acorns, and unknown others consume the 5000 species of insects associated with oaks. (Pavlik et al, 1991) Forage from oaks in the form of shoots and leaves is also important (Barrett, 1980).

The California Department of Fish and Game has assembled a database of information, the California Wildlife Habitat Relationships (CWHR) system, on habitat relationships for 650 regularly occurring birds, mammals, reptiles and amphibians. Within the general category of oak savanna, the CWHR finds from 8-19 amphibian species, 30-32 reptile species, 38-72 mammal species, and 99-132 bird species in savanna habitats, depending on the richness of structural complexity associated with individual sites. Similarly, the denser valley oak woodland across a range of canopy covers from 60-100% boasts 8-17 amphibian species, 22-24 reptile species, 27-61 mammal species and 74-96 bird species. However, once again, primary research is scant. Only 3 studies exist in the literature to support the WHR model for Valley oaks (B. Garrison, pers. Comm.)

Distribution

Within California, *Q. lobata* occurs west of the Sierra Nevada peaks, generally restricted to elevations less than 2000 feet, although some valley oaks occur as high as 5000 feet elevation in Southern California (Swiecki and Bernhardt, 1991). The specie's southern-most occurrence is in the Santa Monica Mountains (Swirsky, 1986) and its northern-most occurrence is near Shasta Lake (Griffin and Critchfield, 1976). The widely spaced savanna community type is found on alluvial soils of valley floors and broad ridge tops throughout the Coast Ranges (Griffin and Critchfield, 1972, Griffin, 1977). The denser riparian forests are found along the margins of rivers, especially in the Central Valley (Rossi, 1980). *Q. lobata* is not entirely restricted to alluvial soils, though the species is generally only found as a major community component on loamy soils (Allen, et al, 1989). Valley oaks are not found in valleys directly exposed to the coast; (Griffin, 1976) the species is sensitive to salt aerosols (Ogden, 1980; Jepson, 1910).

The wood of valley oaks is not valuable for lumber, and the primary use during early European settlement in California was for firewood (Swiecki and Bernhardt, 1991). However, because of their occurrence on deep, fertile soils, valley oak habitat was actively cleared for agriculture and urban development for 200 years, dramatically reducing its range (Swiecki and Bernhardt, et al, 1991). In 1980, Rossi cited stock raising, wood cutting, agriculture, flood control, fire suppression, and urbanization as the leading threats to native California oaks, including the valley oak.

The pattern of habitat loss through conversion of oak habitat to alternative uses continues today. Hagen (1996) estimates that more than 1.2 million acres of all types of oak woodland habitat has been lost throughout California since the

1940's, and predictions of future loss run as high as another quarter million acres by the year 2010 (Bolsinger, 1988).

Declines in Regeneration

In addition to mechanical clearing of valley oaks, observers have noted for many years that *Q. lobata* suffers from low rates of seedling and sapling establishment that support regeneration (Griffin, 1971). Regeneration has been defined as "the process by which trees lost through mortality are replaced" (Muick and Bartolome, 1986). Despite ample acorn production (Griffin, 1973) low regeneration threatens to relegate many existing stands to the “living dead" (Bolsinger, 1988, Brown and Davis, 1991). The lack of recruitment in *Q. lobata* may be visually confirmed from the number of individual trees or stands which exist without nearby seedling or saplings (Griffin, 1976, Muick and Bartolome, 1986).

Regionally, Brown and Davis (1990), documented the decline of valley oaks at 12 study sites in the Santa Ynez Valley between 1938 and 1989. Their work revealed the loss of 20.8% of oaks during the study period. Additionally, no new canopy valley oaks were recruited into the sites during the period studied.

Research efforts to determine the cause of regeneration failure have revealed no simple answer. Based on studies of Blue oak (Q. douglasii), a number of determinants appear to be involved, which may interact, as well as vary from site to site and from year to year (IHRMP, 1998). The causes of regeneration failure continue to be an area of active investigation, but competition with introduced annual grasses for scarce moisture, and the cumulative effects of numerous herbivores are thought to be the main factors (Borchert et al. 1988; Sweicki and Bernhardt, 1991). Changes in fire disturbance regime appear to play a somewhat lesser role. Changes in historic water table levels, global climate, and other variables may contribute as well.

Concurrent with the 200 year history of active oak removal, California's native perennial grasses have been replaced by introduced European annual grasses (Griffin, 1973). Whereas native perennial grasses deplete soil moisture gradually over a longer growing season, non-native annual grasses deplete soil moisture more quickly. Equally important, this depletion occurs at the point in the growing season in which annuals compete more directly with oak seedlings (Danielson, 1990). Knudsen (1987) demonstrated how valley oak seedling establishment increased as the density of grasses decreased, especially in the case of non-native annual grasses. Moisture stress related to competition is believed to be an important factor inhibiting the development of a seedling to a sapling, as well as to the initial seedling establishment (Adams, et al, 1997). In addition to their effects on soil moisture, dense annual grasses provide habitat for small mammal herbivores, compounding the impacts on regeneration (Bernhardt and Swiecki, 1997).

A variety of insects, rodents, birds, deer, and domestic or feral livestock preferentially consume acorns, both on the tree and on the ground, due to the high nutritional content (Barrett, 1980, Griffin, 1980, Swiecki and Bernhardt, 1991). Even in years of high acorn production the cumulative consumption by predators leaves few or no acorns on the ground surface by spring. In contrast, animals such as scrub jays, *Aphelocoma coerulescens*, and squirrels, that bury acorns but do not consume their complete cache, have a mixed effect, and may assist reproduction. (Griffin, 1971) Individual mule deer can consume 300 acorns per day; (Pavlik et al, 1991) Scrub jays have been observed harvesting acorns from valley oaks at a rate over 400 per hour (Griffin, 1980).

Following seedling emergence, insects, rodents and other mammals continue to attack the roots and shoots of the seedling. Burrowing pocket gophers, *Thomomys bottae,* and ground squirrels uproot young seedlings, and devour roots, leading to high rates of seedling mortality, in some cases approaching 100% (Griffin, 1980, Swiecki and Bernhardt, 1991). Cattle and deer may severely browse shoots, keeping the seedling in a shrub-like state, and inhibiting development into an adult form (Griffin, 1971, Rossi, 1980). Under repeated heavy browsing, the seedling may exhaust its energy reserves and eventually die (Swiecki and Bernhardt, 1991).

Researchers have reported widely variable herbivory-related mortality by species and area. For example, in one area pocket gophers may destroy large numbers of seedlings, while in another, pocket gophers are absent, and deer and cattle browsing-related mortality is prevalent (Griffin, 1979, Swiecki and Bernhardt, 1991). Compounding the difficulty in assessing the effects of multiple herbivores is the variability between years in the same area (Swiecki and Bernhardt, 1991).

In high mast years, those few acorns that survive predators, or those dispersed by squirrels and scrub jays, may germinate. But the resulting seedlings rarely survive the continuing onslaught of insects, rodents, and mammals to reach a browse-resistant age which may be as old as 20 years of age (Griffin, 1980). Researchers have speculated that current populations of oak herbivores may be considerably higher than in the past (Griffin, 1976, 1980). Reduced populations of predators such as foxes and coyotes promote larger rodent populations, and similarly, loss of larger predators favors the deer population.

Changes in understory vegetation from introduced forage grasses and row crops may have also enhanced rodent numbers.

Two other possible factors in oak recruitment failure deserve mention: changes in ground water levels, and changes in natural fire disturbance regime (Muick and Bartolome, 1986). Brown and Davis, (1990) found that the period of greatest oak mortality in the Santa Ynez Valley was correlated with a period of very low ground water tables.

3.3 The Expert System Approach to Solving Problems

The complexity of the valley oak ecosystem, the number of factors thought to be involved in regeneration, and our incomplete knowledge of this ecosystem, combine to preclude a simplistic response to the challenge of oak restoration.

Two approaches were considered for the analysis of site suitability: statistical based models, and expert system models. Statistical based methods of decision making and problem solving use the data being evaluated to build models describing the relationships between variables (Srinivasan and Richards, 1990). Such approaches include classical statistical methods such as multiple regression, analysis of variance, logistic regression, as well as non-linear and non-additive methods such as tree-based models (Michaelson, et al, 1994).

Expert systems establish the relationships between data and hypotheses a priori, i.e. before applying the system to the external data to be evaluated. The expert system approach allows for the use of empirical knowledge separate from the data used in evaluating the problem, to make decisions (Srinivasan and Richards, 1990). This approach also more easily incorporates multiple and varied types of data into the analysis. (Skidmore, 1989)

Given the data available in this project, statistical models to identify suitable sites for restoration of valley oak woodland habitat are not appropriate. A statistical approach would utilize the characteristics of sites in the current distribution of valley oaks to predict additional potential habitat. However current valley oak sites no longer accurately represent general oak habitat due to the extensive alteration previously noted. Accurate historical records of valley oak distribution, which might be used to construct such a statistical model, do not exist.

In contrast, a fairly complete literature on the qualitative and quantitative aspects of the bio-physical factors that influence the success of valley oak establishment is available. Careful synthesis of this information may be used to predict new sites on which valley oaks can be established with good chance of persistence. Therefore, we opted to use an expert system, with relationships between these factors explicitly described in a knowledge base, to formalize the information synthesis and prediction of suitable sites for restoration of valley oak woodland habitat. The expert system selected was Ecosystem Management Decision Support (EMDS) described further below.

Simply, expert systems have been described as programs that solve complex problems by reasoning like human experts (Skidmore, 1989). More formally, an expert system is an inference engine that interprets external data, relative to hypotheses, using explicit established rules or relationships, to solve the problem at hand (Reynolds, 1998). Combining these descriptions, an expert system solves problems in a mode similar to human reasoning by using 1) data, 2) a description of the relationships among data, and between data and hypotheses, 3) an inference engine to control the order and the method that data and hypotheses are evaluated, and 4) an interface between these three components and the user and the real world (Graham and Jones, 1988; Reynolds, et al, 1998; Skidmore, 1989; Srinivasan and Richards, 1990).

The data, and the description or "rules" established for how data and hypotheses interact, are termed a knowledge base. A knowledge base encapsulates what is known about a particular problem, using an explicit framework (Reynolds, et al, 1998). The inference engine is then the active component, mandating how the knowledge is applied to external data to evaluate the problem (Reynolds, et al 1998; Skidmore, 1989). The interface is what the user interacts with, to supply external data from the real world for evaluation, and to receive the output of the inference engine (Graham and Jones, 1988; Reynolds, et al, 1998).

Knowledge-based approaches to modeling systems are useful when current knowledge of the system is too imprecise to construct a definitive mathematical model. (Reynolds et al, 1998) Ecosystems, with their high degree of complexity, clearly fit this description.

Available quantitative information may be combined with qualitative understanding to create expert systems which may shed new light on relationships, and assist in understanding interactions. The NetWeaver inference engine contained within the EMDS software, utilizes "fuzzy logic" to evaluate and formalize the relationships of both quantitative and qualitative information in the EMDS expert system.

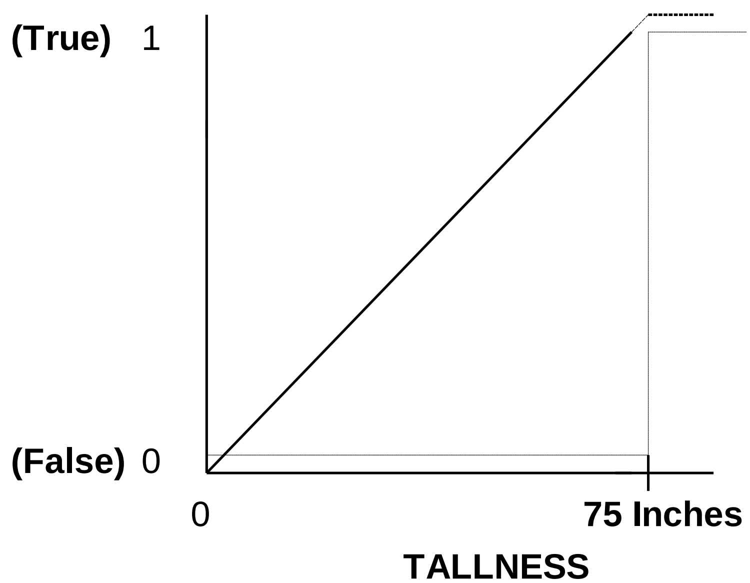
3.4 Fuzzy Logic

Fuzzy set theory was developed by Zadeh (1965) as an alternative to classical set theory (Bezdek, 1987). In classical set theory, an element either belongs, or does not belong, to a particular set (Equihua, 1990). There is no middle ground of partial belonging. This principle of the excluded middle ensures that all statements in conventional logic can only have two values: true or false (Barrow, 1992). In this discrete approach to binary decisions, data classification is limited to those situations in which only a complete match is possible. However, in real life, it is often more useful to evaluate objects or situations based on the degree to which they meet our specifications for membership in a set. (Burrough and McDonell, 1998).

Fuzzy set theory expands upon the classic bivalent system of classification, expressing the degree of membership that an element has in a set (Reynolds, et al, 1998), and dealing with inexact concepts in a definable way (Burrough and McDonnel, 1998). Fuzzy set theory uses concepts of admitted possibility, which are described in terms of the fuzzy membership function. Fuzzy membership functions permit individuals to be partial members of different , overlapping sets (Burrough and McDonnel, 1998). Because of the allowance of 'degrees of membership', the boundaries of sets are no longer discrete, thus they are 'fuzzy' (Equihua, 1990). Fuzziness may be thought of as a type of imprecision characterizing classes that for various reasons cannot have, or do not have, sharply defined boundaries (Burrough and McDonnel, 1998). Fuzziness does not arise from randomness or uncertain membership in a strictly defined classical set, but because the set itself is not precisely bounded (Meesters, et al, 1998).

Fuzziness is not a probabilistic attribute, in which the degree of membership of a set is linked to a given statistically defined function. Rather, it measures the degree to which an individual fits the definition of a set, or that a given statement is true (Burrough and McDonnell, 1998).

Figure 3-2



The classic illustration of fuzzy membership is the example of describing the “tallness” of an individual. Consider the situation in which any person whose height is 75 inches or more is defined as "tall". Figure 3-2 illustrates the differences between the classic set approach and the fuzzy approach.

The dotted line represents the standard bivalent theory viewpoint. As can be seen, a person is not considered to be tall until they reach a height of precisely 75 inches. At a height of 74 inches they are still not considered to be tall.

Conversely, the solid line represents the fuzzy set viewpoint. As a person approaches the height of 75 inches, the proposition that "this person is tall" becomes more true, until at 75 inches it becomes completely true. This illustrates how fuzziness represents the concept that an individual can be "somewhat tall". Fuzzy functions are not limited to the simple linear shape illustrated above, fuzzy membership functions may take the form of sinusoidal or exponential functions, thus capturing a variety of thresholds and relationships. (Burrough and McDonnel, 1998).

For an example more closely related to this project, consider the situation in which sites are to be classified as either "woodland" or "grassland", based on tree cover. Classical set theory would establish discrete boundaries or limits of tree density to assign membership. For this example, suppose that the "woodland" set, will have a tree cover equal to or greater than 50%. All sites with tree cover of 50% or greater would be assigned to the woodland category and all sites with a tree cover of 49% or less would be would be assigned to the grassland category. This simplistic categorization ignores potentially profound differences between sites with a tree cover of 50%, those with a tree cover of 72%, or those with tree cover of 96%. It also fails to recognize that a site with a tree cover of 40% shares some characteristics with a site with tree cover of 50% and some characteristics with sites of 30%. Using fuzzy set theory, and the same tree cover criteria, each site would be assigned a degree of membership in the woodland fuzzy set and a degree of membership in the grassland fuzzy set. Based on the cover of trees, a site could either belong entirely to one set, or be a partial member of both sets, allowing for gradation of "woodlandness" and "grasslandness". A fuzzy curve, such as that in Figure 3-2, concisely describes these relationships, with the result that fuzzy logic often mirrors reality more precisely than the "crisp" logic style found in classical set theory.

Environmental management requires that decisions must be made regarding ecosystems in the face of ecological uncertainty and imprecision. Fuzzy sets provide the flexible framework for the loosely defined relationships and definitions used in describing ecosystems (Equihua, 1990).

Although the term "fuzzy" may imply a lack of clear thinking, this is not the case. Fuzziness does not imply lack of rigor, as boundary conditions for the descriptive fuzzy curve must still be chosen with care, and reflects the synthesis of much information. In appropriate applications, construction of accurate fuzzy curves may require more information than simple binary operations, and provide greater information in analysis output. (Burrough and McDonnel,1998).

Ecosystems are large complex systems with poorly defined boundaries (Bosserman and Ragade, 1982). Modeling of these systems is well suited to the advantages offered by fuzzy logic and expert systems. The variables and relationships in any ecosystem in any given location are complex and unique, such that exhaustive description through sampling is impossible. Classification is subjective and elusive, depending on context and the observer. Our model describes certain biological and physical factors impacting valley oak ecology. Fuzzy logic curves may be used to describe as many of these interacting attributes as the modeler cares to consider.

4.0 Methods

This section describes the methods with which the valley oak restoration suitability of sites within the Los Alamos Valley were evaluated.

4.1 The Ecosystem Management Decision Support Model

Ecosystem Management Decision Support (EMDS) software was used to conduct the geographic analysis that identifies areas in the Los Alamos Valley with high potential for successful valley oak restoration.

EMDS was developed by the USDA Forest Service in cooperation with Pennsylvania State University and Knowledge Garden, Inc. EMDS was developed as a decision support tool for resource managers (Reynolds et al, 1998). The software has several goals. EMDS seeks to:

- increase efficiency and consistency in management decision,
- improve defensibility of decisions on the basis of scientific principles,
- improve information organization, analysis, planning and management within and across spatial scales.

EMDS is an application framework for knowledge-based decision support of ecological assessments. Specifically, EMDS integrates the GIS system, ArcView, and the knowledge-base development environment, NetWeaver. The integration of these two applications creates a framework in which an ecological assessment of any spatial scale can be conducted.

NetWeaver

NetWeaver is a knowledge-base development environment, which provides a user interface, an object-oriented knowledge base development system, and an inference engine that incorporates fuzzy logic and expert system rules designed by the individual user.

A knowledge base constructed in NetWeaver is composed of a hierarchy of dependency networks. Each dependency network corresponds to a topic of interest in the problem domain represented by the knowledge base (Reynolds, 1998). A dependency network organizes relevant knowledge about how to solve a topic of interest in the assessment.

Each dependency network represents a proposition about the condition of an ecosystem process (Reynolds, 1998). For example, a dependency network may be built to evaluate the proposition that "soil conditions are good". Factors that influence the quality of soil, such as the soil type and fertility, will be included in this dependency network. Based on data entered into the dependency network, the truth of the proposition will be evaluated.

Dependency networks terminate in data links. Data links request data from the database, and assess the state (truth value) of the dependency network. For example, a dependency network built to assess the proposition that "soil conditions are good" may terminate in a data link that request data about the fertility of the soil. On receipt of this data, the data link will evaluate the state of the proposition that "soil conditions are good", or pass the data to another data link that performs some transformation on the input data (Reynolds, 1998).

ArcView Extension

The ArcView extension component of the EMDS system allows for the processing of a knowledge-base in a GIS application. The ArcView GIS layers constitute the database that informs each data link in the NetWeaver knowledge base. Based on the relationships described within the knowledge-base, and the data in the database, the "truthfulness" of the proposition being assessed is evaluated.

Based on the interaction between the data and the knowledge-base, a truth value is calculated based on the dependency network representing the proposition. Reynolds (1998) describes the significance of truth values as follows:

- If all evidence antecedent to a proposition supports that proposition, then the truth value is 1 (completely true).
- If all evidence antecedent to a proposition is contrary to that proposition, then the truth value is –1 (completely false).
- If there is no evidence for or against the proposition, then the truth value is 0 (undetermined).

Truth values also may be partially true or partially false. Reynolds (1998) describes three conditions that may give rise to this condition.

- Some of the data needed to fully evaluate the dependency network has not yet been supplied when an evaluation of a network is being performed.
- The data missing cannot be supplied.
- One or more of the data items that influence the truth value of a dependency network or node have been evaluated against a fuzzy

argument and found not to have full membership in the fuzzy set defined by the fuzzy argument.

Using this system to define the truth of a proposition, the ArcView extension creates a new ArcView theme that assigns a color to each spatial unit of a map, corresponding to the "truthfulness" of the evaluated proposition at that particular location.

(For additional information on the possible applications of EMDS, see the EMDS website provided by the USDA Forest Service, Pacific Northwest Research Station at:
http://www.fsl.orst.edu/home/usfs/emds/system/endshome/htm).

Steps of an EMDS analysis:

To clarify how an EMDS evaluation works, a short description of the steps to conducting an EMDS analysis follows:

- First, a proposition is formed that can be evaluated as being "true, "false", or some relative degree of "true" or "false'. For example, the proposition evaluated in this analysis is "site is suitable for valley oak restoration".

- A GIS database is compiled in ArcView that contains data that contributes to evaluating the proposition. For example, the GIS database used in this analysis contains data on selected bio-physical factors that influence whether a site is suitable valley oak habitat.

- A NetWeaver knowledge-base is constructed that embodies knowledge about how to evaluate the previously stated proposition.

- The NetWeaver knowledge-base is coupled to the GIS database, and based on the relationships described in the knowledge-base, and the data in the database, the "truthfulness" of the proposition is evaluated.

Benefits of using EMDS

Selecting EMDS as the tool for conducting this analysis provided the following benefits:

- EMDS enables a computationally efficient analysis of a large area. The study area is approximately 465 square km, and is composed of approximately 1800 individual soil polygons. The ability of EMDS to process a knowledge-base in a GIS application makes a spatial analysis of any scale possible.

- EMDS provides a generalized indication of the restoration suitability of an entire soil polygon based on a combination of relevant biophysical factors within that polygon. The condition of the biophysical factors within each polygon may not all be 'favorable' or 'unfavorable' to valley oaks. EMDS will evaluate the relative influence of these factors while evaluating the restoration suitability of a polygon.

- EMDS allows for the evaluation of knowledge that is qualitative in nature. While a precise mathematical solution may be possible in principle, current knowledge is still too imprecise to formulate such a solution to our research question. However, there is a fairly complete literature on the biophysical factors that influence the success of valley oak seedling and sapling establishment. EMDS analyzes this qualitative knowledge through the use of "fuzzy logic".

- EMDS provides a user-friendly interface. Within the EMDS framework, the model is easily adaptable to incorporate changing decision criteria, and new knowledge as it becomes available.

Drawbacks of EMDS

While EMDS is well suited to the challenges posed by this project, several weaknesses of using this software package became apparent.

Within the EMDS framework it is difficult to assign relative weights to the factors being evaluated within a knowledge-base. For example, a network in the knowledge-base used in this analysis was constructed to evaluate if "water conditions are suitable" for valley oak restoration. This network is evaluated based on the condition of two factors: ground water depth and available soil moisture. Since these biophysical factors occur at the same hierarchical level in the network, they implicitly are given the same relative weight in determining if water conditions are suitable. In actuality, one of these factors may be more influential in determining if a site is suitable for valley oak restoration. Even if the relative "weights" of these factors are known, it is difficult to account for this in EMDS. When constructing a knowledge base in NetWeaver the opportunity is provided to assign a weight to each factor being evaluated. However, it is very difficult to acquire the desired outcome of adjusting the relative weights of factors. This feature does not behave predictably, and adjusting the relative weights of factors is not encouraged by the creators of EMDS (Keith Reynolds, pers comm).

The ability to construct a curve that accurately depicts the shape of a degree of membership function is limited in EMDS. When constructing a degree of membership function in NetWeaver the user is limited to using a linear relationship to represent the shape of the function between any two points. The degree of membership function may more accurately be depicted by other shapes, such as an exponential curve. For example, a segment of the degree of membership function used to evaluate if "distance from the coast" is adequate to avoid the adverse effects of air-born salt aerosols is described by a linear relationship between 28 to 48km, with adverse effects dissipating as distance from coast increases. The adverse effect of salt aerosols may actually decrease exponentially along this gradient. It is not intuitive how this type of exponential relationship could be represented by a degree of membership function within the EMDS framework.

4.2 A Site Model for Valley Oak Restoration

The purpose of this model is to assess the suitability of sites for oak restoration plantings. The model itself is intended to answer, to the extent possible, the question of which sites in the San Antonio Creek watershed study area are suitable for valley oak restoration? The valley oak ecosystem might be modeled very differently, in response to a different research question.

Creation of the knowledge-based NetWeaver model was an iterative process. The initial steps consisted of literature review, interviewing experts and synthesizing existing knowledge. These resulted in several conceptual models of 1) oak-environmental interactions and 2) non-environmental factors relevant to the criteria for prioritizing and selecting sites for planting or protection. In turn this resulted in refined and modified model versions. The final model is the result of lengthy literature and opinion synthesis, mediated by data constraints.

Early in the model development phase, it became clear that many factors important to valley oak restoration would either be dealt with through management efforts after planting, or that data on a suitable scale was unavailable. These factors have thus been left out of the model in whole or in part. For example, a number of rodent species are known to consume the roots of oak seedlings and saplings. County of Santa Barbara mitigation guidelines (County of Santa Barbara, 1995) require that oak plantings include rodent exclosure fencing. Therefore, it was not necessary to model the distribution of rodents across the landscape. Similarly, the effect of slope and aspect on soil water capacity and evapotranspiration is important, but varies at a scale too fine to be incorporated in this model. Additional detail on this topic is included in the discussion of the methods.

In some cases data is not currently available, but networks are included in the model to a) indicate awareness of their significance and communicate this awareness to future users b) facilitate the incorporation of data into the model which is anticipated to be available in the near future.

Figure 4-1 provides a schematic of the network structure. The resulting top-level hierarchy in the model consists of three networks: connectivity factors, socioeconomic factors, and biophysical factors. These three networks represent intuitive conceptual factor groupings. If a site is determined to be suitable for restoration in each of the three categories, it should be a priority site for restoration or preservation.

Each of these three top-level networks is weighted equally. Equal weighting of all networks at any level is implicit in the model structure.

The biophysical network is the only complete network at this time, and includes the autecology aspects of valley oaks for which we have both data and sufficient knowledge to formulate expert opinions. It is composed of three subnetworks:

- Hydrologic conditions are good,
- Soil conditions are good, and
- Aerosol conditions are good.

These subnetworks may be evaluated independently, although that is not the intent of this model.

The hydrologic network is further decomposed into two data links that access and evaluate the data in the attribute table against the relevant fuzzy relationship. These data links are the suitability of depth to ground water, and the available soil water.

The soil network is further decomposed into two data links, consisting of soil fertility and soil type. These data links access and evaluate the data in the attribute table against the relevant fuzzy relationship.

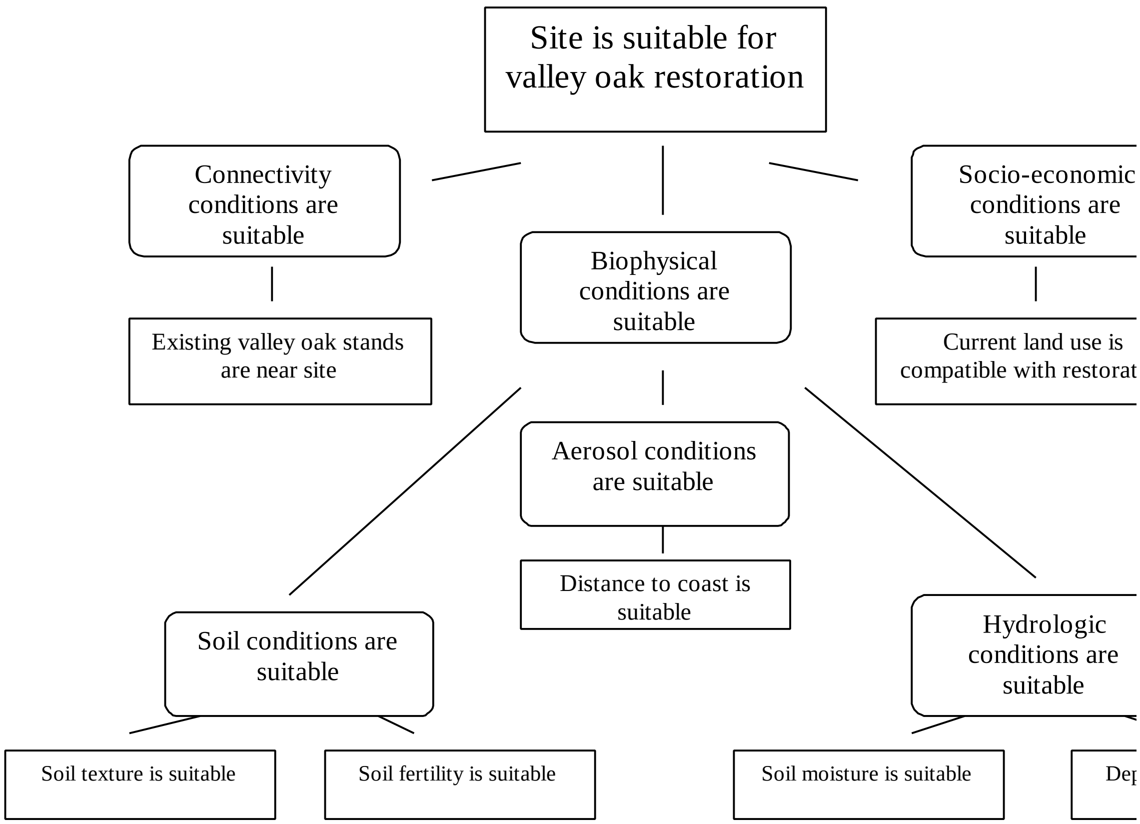
The aerosol network consists of one data link, the distance of the polygon to the coast.

The connectivity network is intended to evaluate, where possible, connectivity level factors or values that may influence site selection decisions. For example, although valley oaks exist in places as isolates, disconnected from stands of oaks, an isolated oak offers less to oak dependent wildlife than a large continuous savanna of many oaks and associated vegetation. The connectivity network includes data links to evaluate connectivity to existing habitat, and to evaluate a buffer distance from identified sources of environmental disruption.

The *socioeconomic network* attempts to capture decision support factors imposed by human influence, such as zoning and land use.

The analysis output described in this report includes only the biophysical network data at this time. Data to inform the connectivity and the socio-economic networks was not available as of the completion of this report.

Figure 4-1


Site is suitable for valley oak restoration
Connectivity conditions are suitable
Biophysical conditions are suitable
Socio-economic conditions are suitable
Existing valley oak stands are near site
Current land use is compatible with restorat
Aerosol conditions are suitable
Distance to coast is suitable
Soil conditions are suitable
Hydrologic conditions are suitable
Soil texture is suitable
Soil fertility is suitable
Soil moisture is suitable

The Spatial Unit of Analysis

The data links within the model are informed by data that exists at inherently different spatial scales. For example, the distance from the coast is available in grid form. However, information such as soil type, soil fertility, and available water capacity is available for the area of a soil polygon. Soil polygons are drawn to consist of a relatively homogeneous soil phase and land use, (see soil type methods section). For each polygon that is delineated in the soil survey, the soil type, fertility, and available water capacity are recorded in the ArcView coverage database. The data used in the model is a mix of grids and polygons.

The soil polygon was used as the unit of analysis. This choice sacrificed the accuracy available for the grid data. However, had the grid cell been used as the unit of analysis, the generalized polygon data would be over-sampled. Assuming that the coarser polygon data is consistent for all grid units included in the polygon would cause a misleading over-estimation of the accuracy of the coarser scale data.

For this reason, the scale of the coarsest data is used. In this analysis, the use of the soil polygon as the spatial unit of analysis requires that the distance to the coast data be generalized across an area the size of a soil polygon. Additionally, the total area of a polygon with ground water estimated to be at a suitable depth must be calculated across a soil polygon.

4.3 Network Data

The following section describes the data links that inform each of the networks. Geospatial data sets were obtained from workers at UCSB's Biogeography Laboratory, including Frank Davis, David Stoms, and Bill Kuhn.

4.3.1 **Soil Conditions**

Soil Type

The model uses soil texture as the characteristic affecting the suitability of a soil polygon for valley oak restoration. The texture of a soil affects the ability of a soil to support different types of vegetation, and the success of tree restoration efforts and seedling survival is dependent on soil texture (Foth, 1984).

The texture of a soil is described in terms of the relative proportions of sand, silt, and clay (Olson, 1981). *Sand* consists of particles 2.0 to 0.05 mm in size. *Silt* is 0.05-0.002 mm in size, and *clay* particles are those particles less than 0.002 mm in size (Foth, 1984). Soils are then defined by the proportion of particles belonging to these three textures.

The model uses a digital version of the 1972 *Soil Survey of the Northern Santa Barbara Area* (Shipman, et al, 1972), as the database that informs the 'soil type' data link in the knowledge base. The digital map was digitized from original soil survey maps by personnel at GRS, Incorporated in Santa Barbara, and subsequently georectified and projected into UTM Zone 1o coordinates by Bill Kuhn of the Department of Geography at UCSB.

It is well documented that valley oaks prefer loamy soils (Jepson, 1910; Griffin, 1973; Matsuda and McBride, 1986; McCreary, 1990; Brown, 1991). Swiecki and Bernhardt (1991) observed that valley oaks occasionally appear on well drained sands and clays, however, the community appears dominant only on soils classified as loams (Allen et al, 1989).

Within the knowledge base, soils classified as loams contributed a truth value of +1 (indicating complete truthfulness) for the proposition "soil type is suitable for valley oak restoration." These soils include the sandy clay loams, the clay loams, the silty clay loams, the sandy loams, the loams, and the silt loams as listed in Appendix A.

The remaining soils classified as sands or clays contribute a truth value of 0, indicating that they neither enhance nor detract from restoration suitability. Soils described as gravelly, cobbly, stony, or eroded, as well as miscellaneous land types such as beaches and landslides, contributed a truth value of -1, indicating that they are completely unsuitable for valley oak restoration. To plot this relationship, the soil types were assigned codes, summarized in Table 4-1.

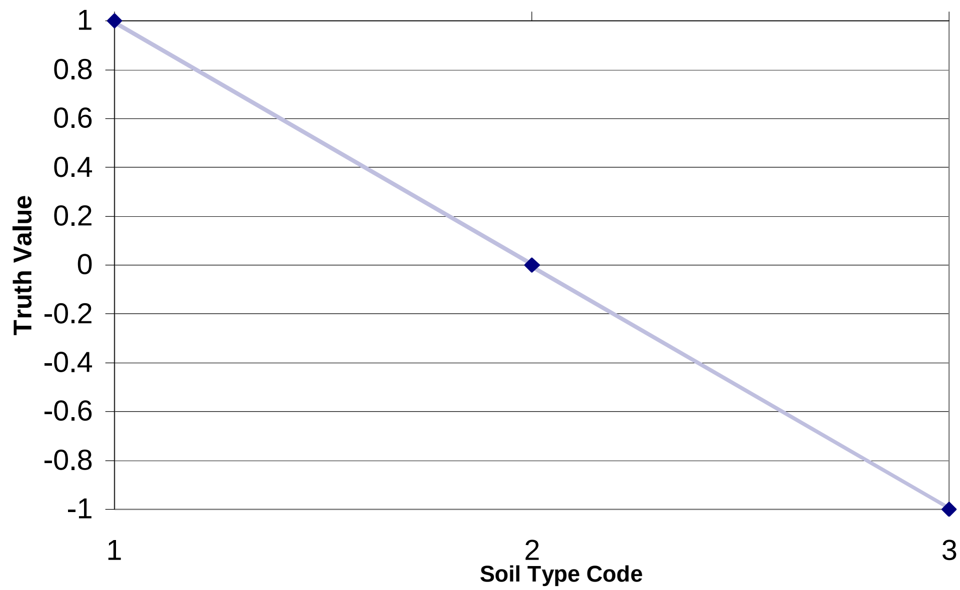
Table 4-1

Soil Type*	Assigned Code
loam	1
sand or clay	2
other	3

*Shipman, et al, 1972

The fuzzy curve describing the truth values assigned to the soil types is shown in Figure 4-2.

Figure 4-2



1= loamy soils
2= sands and clays
3= gravelly, cobbly, eroded, and other unsuitable classes

Fertility

This data link evaluates the effect of soil fertility in a polygon in the context of valley oak growth and suitability for restoration plantings. This fertility of a soil polygon is based on the soil type descriptions in the county soil survey (Shipman et al, 1972)

The data link evaluates the truth value of the proposition: soil fertility is good. This proposition will evaluate to 100% true at values of 4 and greater. Values of 0 evaluate to 100% false, and intermediate values progress linearly between 100% false and 100% true. Hence, a value of 2 would be designated undetermined.

Soil polygons were assigned qualitative categories in the Soil Conservation Service soil survey of northern Santa Barbara area. These categories were coded with unique representative numbers for use in this data link as described in Table 4-2.

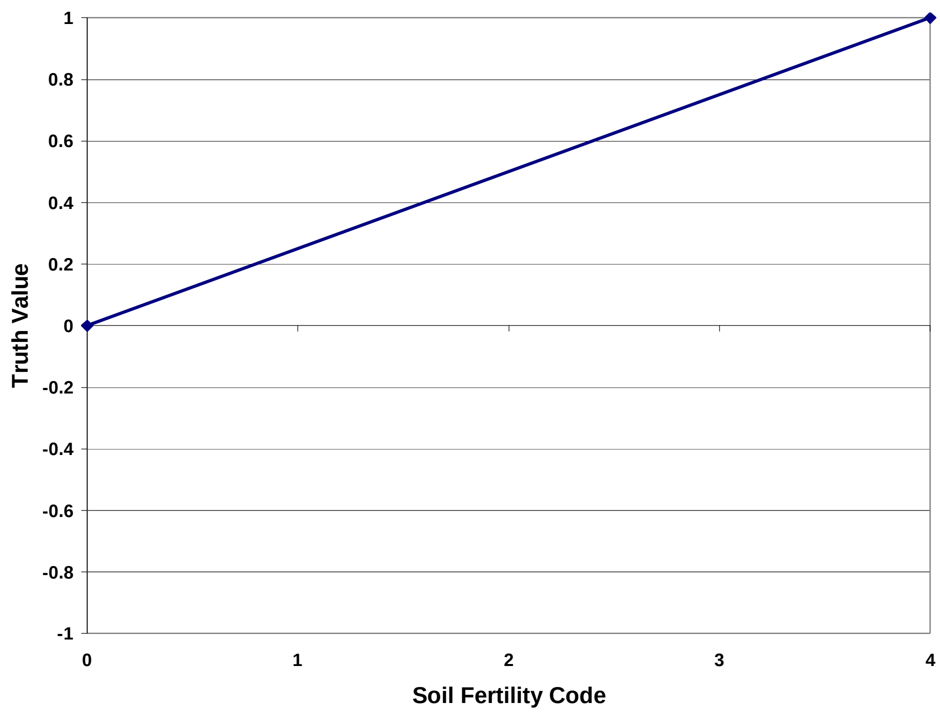
Table 4-2

Fertility Category*	Assigned Code
Very Low	0
Low	1
Low Moderate	2
Moderate	3
High/Very High	4

* Shipman, et al, 1972

Figure 4-3 represents the fuzzy relationship used to evaluate this data link.

Figure 4-3



Based on the qualitative nature of the fertility data, the lack of specific factors and methods employed to determine fertility, and the dearth of specific studies relating valley oak persistence to soil fertility, we opted for a conservative approach to evaluating soil fertility: increased soil fertility is linearly associated with an increased truth value of the data link. This approach is conservative in that it does not allow a soil polygon's suitability for valley oak restoration to decrease due to soil fertility considerations.

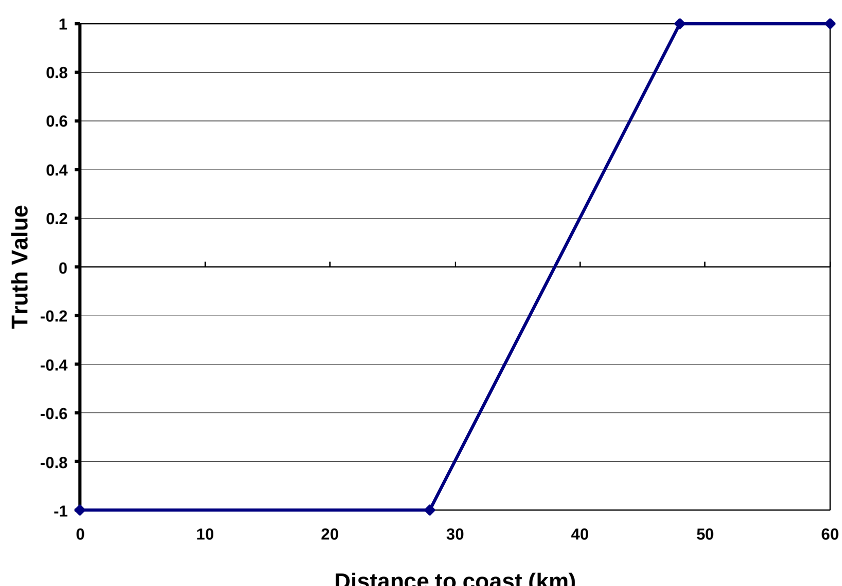
4.3.2 Aerosol Conditions

The distance from the coast of each grid cell was derived using USGS 30m Digital Elevation Model (DEM) data. To use this information in the model, it was necessary to generalize the distance to the coast across the unit of analysis of a soil polygon. The distance to the coast from the center of a polygon was used to represent the distance to coast of the entire polygon.

Chloride ion aerosols from sea spray affect the growth of valley oaks, and the west-east orientation of the valley favors salt spray advection inland (Ogden, 1980). Valley oaks do not occur within 28 km of the coast within the study area, and leaf necrosis, or salt burn, is observed to adversely affect growth up to 48 km inland (Ogden, 1975).

Figure 4-4 provides a representation of the fuzzy curve used as the data link for the aerosol conditions network in the model.

Figure 4-4



At 0 km, the proposition: "aerosol conditions are suitable for valley oak restoration" is evaluated as false. The proposition remains false, corresponding to a truth value of -1, up to 28 km from the coast. The truthfulness of the proposition increases linearly from 28 to 48 km inland until at 48 km the proposition that "aerosol conditions are suitable for valley oak restoration" is evaluated as completely true, with a corresponding truth value of 1. The aerosol suitability was approximated using a linear function consistent with the NetWeaver fuzzy curve capabilities, though the actual effects of salt aerosols are likely to decrease non-linearly with distance from the coast.

4.3.3 Hydrologic Conditions

Depth of the water table

Adult valley oak trees root as deeply as 10-20 meters (Lewis and Burgy, 1964). Deep tap root systems reach the water table (Jepson, 1910; Griffin, 1971) and allow valley oaks to be relatively drought resistant (Brown, 1991). This reasoning is corroborated by the finding that valley oaks have low xylem sap tensions during the entire rainless season, implying that they may be reaching supplementary water (Griffin, 1997).

These findings suggest that favorable sites for valley oak restoration characteristically have a water table at a depth that is accessible by valley oak root systems. In evaluating potential sites in the Los Alamos Valley for their suitability for valley oak restoration efforts, it is important to account for the depth to the water table.

General water table trends where identified using a map of water table contours generated from a 1964 Geologic Survey of the Geology and Ground Water of San Antonio Creek Valley. The elevation above sea level of the water table increases with eastward movement up the valley (Muir, 1964). Based on this trend, a regression analysis was performed. The dependent variable is the elevation of the water table, and the independent variable is the distance from the coast. The following linear relationship was found:

Elevation of the water table (ft) = -46.46 + (0.01874*Distance to Coast)

(R^2 value = 0.9891).

Based on distance from the coast, and using the relationship between the distance to the coast and the water table contours described by the regression equation above, the elevation of the water table was estimated across the entire study area.

Using a USGS 30m Digital Elevation Model (DEM) data to identify topographic elevation, the water table's depth below the surface was estimated for each spatial unit of the study area:

Depth to water table = Surface Elevation – Elevation of Water Table

The spatial unit of analysis used in the EMDS model is a soil polygon. It was therefore necessary to calculate a summary statistic to integrate the various smaller grid values derived from the DEM to a useable value representative of the larger soil polygon. To accomplish this, discrete depth to water table classes were defined at 100 foot intervals. Each grid value derived from the DEM was assigned to a class. The area of each soil polygon within these water table depth classes was calculated.

This process identified general trends in water table depth across the San Antonio Creek Valley (Jon Ahlroth, pers. comm.). It was not possible to calculate the precise water table depth within each polygon, as the topography and underlying geologic formations vary within an area the size of a soil polygon.

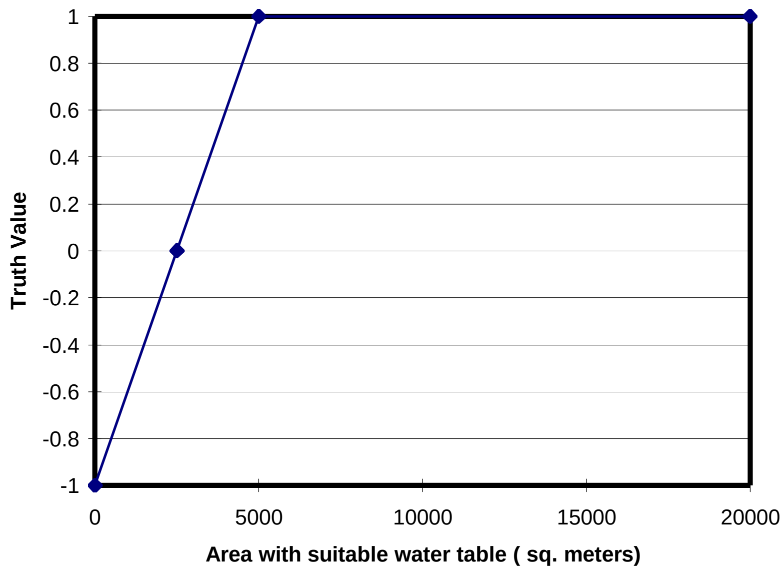
Due to seasonal patterns and changes in ground water pumping intensity, temporal variation occurs in water table depth. For example, between the years 1958 to 1978, an estimated average water-level decline of 3 ft occurred over the ground water basin. In some wells the water levels were higher in 1978 than in 1958, but in many wells the reverse was true (Hutchinson, 1980).

In addition to the dynamic nature of the water table depth, further imprecision is introduced due to the shape of the water table contours. The 1958 water contours used in the analysis are shaped such that the north and south ends of the contour are closer to the coast than the center of the contour. The curved nature of the water contours was not accounted for in the regression analysis, and therefore in certain areas the water table depth was estimated as deeper than it actually occurs (see Appendix B). It would be possible to account for this with a higher order trend surface or by digitizing the contours and reconstructing the surface in the GIS.

To account for these sources of error and uncertainty, margins of error were included in designating suitable ground water depth. "Suitable ground water" conditions were described as the area within a polygon where the calculated depth of the water table was 200 feet or less. To account for size differences between polygons, a polygon must contain a minimum of 5000 square meters in this "suitable ground water" class to contribute to the potential restoration suitability of a soil polygon.

Figure 4-5 provides a representation of the fuzzy curve used as the data link to evaluate ground water conditions in the model. With 0 square meters of suitable ground water conditions within a polygon, the proposition: "ground water conditions are suitable for valley oak restoration" is evaluated as completely false. The truthfulness of the proposition increases linearly from 0 to 5000 square meters, until at 5000 square meters, the proposition that "ground water conditions are suitable for valley oak restoration" is evaluated as completely true, with a corresponding truth value of 1. It is important to note that the threshold of 5000 square meters can be modified to reflect different management goals.

Figure 4-5

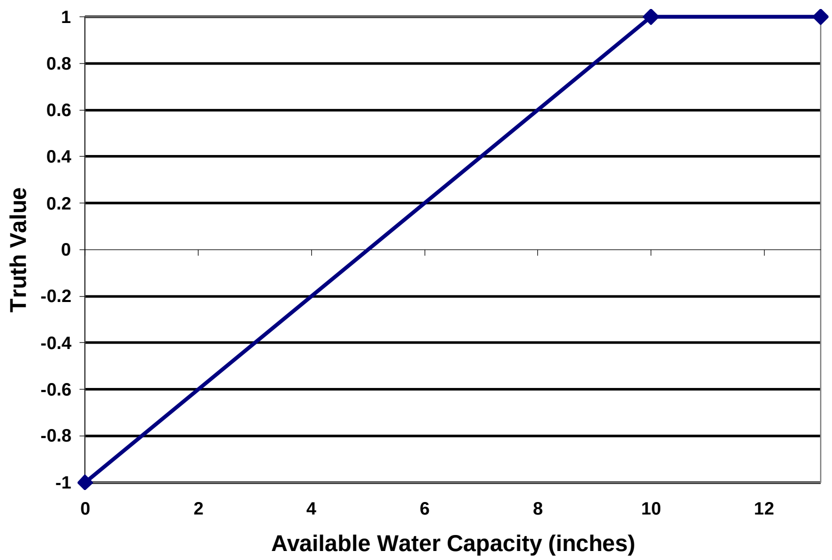


Soil Moisture

This data link, evaluates the available surface soil moisture in a polygon in the context of oak water requirements. Source data for soil moisture availability was based on the county soil survey (Shipman, et al, 1972)

The data link evaluates the truth value of the proposition: available surface soil water is good. This proposition will evaluate to 100% true at values of 10 and greater, as shown in Figure 4-6.

Figure 4-6



This data link is less straightforward and required significantly more data interpretation than the other links in the model. For this reason, additional explanation and background are appropriate. The discussion below describes an expert system approach to the synthesis and use of existing knowledge on oak-water relationships.

The relationships between oak roots and water are not well known. Conventional wisdom on valley oaks states that the trees establish a root connection to the ground water table, and that this connection is essential for valley oaks to survive California's rainless summers, and periodic droughts Other researchers question the necessity of the link to ground water (Swiecki and Bernhardt, pers. comm.) stressing the very large root zone volumes associated with mature valley oaks, as a potential source of adequate water.

Griffin (1973) himself wrote: "Interactions of soil characteristics and tree densities can obscure traditional topographic moisture gradients. For mature trees, ridgetops and upper south slopes were not necessarily 'drier' than north slopes. The widely spaced *Q. lobata* trees on ridges had low tensions. The lack of woody plant competition and moderate soil depth must have allowed these trees to exploit such a large volume of soil that they did not run out of water during the summer."

Empirical observation also provokes questions about the strength of the water table connection hypothesis. Valley oaks occur on terraces (e.g. locally at Sedgwick Reserve) located significantly more than 66 feet above the known water table. A possible explanation would be the presence of perched water tables, but information on perched water tables is not available to evaluate this premise.

In a study of valley oak mortality in the Santa Ynez Valley, Brown and Davis (1991) found that the period of highest oak mortality was correlated with the period of lowest ground water levels. Depth to ground water at this time was estimated at 94 to 111 feet below the surface, significantly lower than the estimated maximum rooting depth 66 feet. If indeed oak survival requires a water table within a root range of 66 feet, *all* of the valley oaks in this area should have perished during this period.

Separate from the question of whether adult oaks may persist for multi-century lifespans without access to ground water, seedlings must survive periods from several months to several years, before a tap root meets ground water, at whatever depth it may be found. A seedling established in a location with ground water at fifty foot depth may be forced to rely on surface soil water through two, three, or more growing seasons.

During this time the seedling or sapling will be competing with surrounding vegetation for available soil water. (Danielson, 1990, Knudsen, 1987, Adams et al, 1997) We suggest that the oak's investment in developing deep roots (Matsuda and McBride, 1986, Callaway, 1992) pays off in this competitive struggle. With an effective rooting depth greater than that of annual grasses, the oak seedling may continue to access water deep in the soil profile, after moisture within reach of grass roots is exhausted. This source of water is available in many soils before oak roots reach ground water depths, or if the water table is not reached at all.

Synthesis of existing knowledge of oak-water relationships resulted in the following conclusions:

1. Given the paucity of information, it is not yet reasonable to conclude that water table access is essential for valley oak persistence. At a minimum, valley oaks will be dependent on surface soil moisture supplies during the seedling to sapling phase.
2. Valley oaks may meet their water requirements by either of two strategies:
   A) Valley oaks meet seasonal water needs over an entire lifespan by establishing a sufficiently large root zone in soils with moderate or greater water holding capacity.
   B) Valley oak seedlings may initially establish in areas with marginal surface soil water capacity during wet years, but must then reach the water table before a dry year occurs to survive to the sapling or adult stage.

We therefore modeled these two strategies as two possible paths to establishment, and sites which met either criterion were evaluated as suitable for oak restoration.

Strategy B is represented by the depth to ground water data link. Supplemental irrigation may provide any additional surface water needed by the sapling during the establishment phase.

Strategy A is represented by the soil moisture data link and required quantifying an estimated minimum amount of soil moisture necessary for an oak seedling, sapling, or adult tree to persist without access to the water table. This establishes a threshold of available soil moisture, below which restoration sites would evaluate as unsuitable for restoration. This may be thought of as a "water budget", with an initial seasonal deposit of meteoric water, and subsequent withdrawals through evaporation and transpiration. If the water budget is positive, or "in the black", at the end of the season, the oak is assumed to persist, and the truth proposition of the data link proposition "Available soil moisture is good" will evaluate to true. A number of generalizations, estimations, and assumptions were required to establish this threshold. It should be viewed as a "rule of thumb".

Calculation of Water Budget

1. Determine the amount of water stored in the surface soil through available water capacity of each soil polygon at a point in time before soil moisture becomes limited.
2. Estimate the seasonal evapotranspiration occurring which is relevant to oak seedlings. This corresponds to the time period

subsequent to the determination of available water capacity but before the resumption of autumn precipitation replenishes soil moisture.

3. Subtract the seasonal evapotranspiration from the initial available water capacity to determine which soils have a positive water balance.

Details of Calculations and Rationale

<u>Step 1.</u>

The characteristic Mediterranean climate of California means that precipitation is consistently absent from late spring through most of the fall (California Department of Water Resources, 1999). Therefore it is not a significant source of water for vegetation during this time, and lacking irrigation, moisture stored in the soil is the only available source.

The Soil Conservation Service soil survey data for the study site includes the category "Available Water Capacity" (AWC). AWC is defined as the amount of water held in the soil between field capacity and permanent wilting point. (Bowers, et al, unknown date) Practically, it is the amount of water available to plants from the soil via root extraction. Other water exists in the soil, but is not extractable by roots (Bowers, et al unknown date). AWC is measured in inches of available water per inch of soil depth; therefore a deeper soil will contain more total available water than a shallower soil of the identical type. For this model, we estimated that soils would reach field capacity throughout the study site at February 28th. This averaged date for field capacity condition was selected as it is preceded by the three months of highest rainfall. It estimates the date that an average soil will have reached saturation, drained to field capacity, yet not have lost additional water to evapotranspiration.

Monthly precipitation averaged since 1908 to the present, from the Los Alamos National Weather Service weather station is detailed in Table 4-3.

Table 4-3

Month	Precipitation -- inches
January	3.05
February	3.16
March	2.6
April	1.34
May	.29
June	.06
July	.03
August	.04
September	.27
October	.47
November	1.44
December	2.55
Total Annual	15.30

Source: California Department of Water Resources http://cdec.water.ca.gov/cgi-progs/stamap?LAL

Annual precipitation reported from Sedgwick Reserve (V. Boucher, pers. comm.) is similar, although rainfall data has been collected at Sedgwick for approximately three years only.

The assumption of field capacity condition on February 28th, while clearly a large generalization, was confirmed as a reasonable representation of field conditions in a year of normal rainfall. (Faber, B. pers. comm.)

Step 2.

This initial supply of soil water, represented by the AWC of each soil polygon, will be modified over time by evapotranspiration.

Monthly Reference Evapotranspiration (ET_0) rates for all regions of California have been determined by the Agricultural Experiment Station University of California, Division of Agriculture and Natural Resources. This information is available in the form of maps contained in Bulletin 1922 *Reference Evapotranspiration for California*. Reference Evapotranspiration (ET_0) is defined as the amount of evapotranspiration that will occur from a pasture of non-waterstressed grass.

For the purpose of this model, oak seedlings may be viewed as isolates embedded in a matrix of vegetation, often dominated by introduced grasses. These grasses will largely determine the evapotranspiration and available soil moisture within their shallow root zone during the spring season. ET_0, as calculated from non-waterstressed grasses, is a reasonable estimate of the actual evapotranspiration which will occur from these grasslands during periods when surface soil moisture is plentiful. As the spring season progresses and surface soil moisture becomes less plentiful, ET_0 becomes a less accurate representation of true evapotranspiration as both evaporation and transpiration will diminish. Evaporation will diminish as a layer of dryer surface soil develops and acts as a barrier to further evaporation. Transpiration will diminish to the extent that individual plant species modify their transpiration rates in response to increasing water stress.

For the months of March and April, when soil moisture is reasonably high, and precipitation inputs may continue, evapotranspiration was modeled across the polygons at the ET_0 rate. Actual evapotranspiration over this two month period may be somewhat less than ET_0, for the reasons noted above. Use of ET_0 over this period therefore allows a margin for error in calculating the water budget. The water budget for March and April, is calculated as shown in Table 4-4:

Table 4-4

Month	Days	ET_0 in mm/day	ET_0 in mm /month	Convert ET_0 to inches	Net ET loss	Net Precipitation Gain	Net Change in water budget
March	31	2.6	80.6	3.17	3.17	2.6	-0.57
April	30	3.5	105	4.13	4.13	1.3	-2.83

At the end of April, soil moisture within the grass root zone may be considered effectively zero. At of this date, grasses are assumed to die, and grass-associated ET ceases. With the assumed death of the annual grasses on April 30^{th}, evapotranspiration is modeled very differently. The presence of a layer of extremely dry soil at the surface now acts as a barrier to moisture transport upward through the soil and consequent evaporation. The layer of dead grasses above the surface serves as an additional barrier to evaporation, comparable to a layer of mulch. The small precipitation inputs during the hot summer months are not added to the water budget. The rationale for this is that these small amounts of water will not penetrate the dead grass layer, but will evaporate into the atmosphere rapidly.

Although grass related evapotranspiration is modeled as zero, evapotranspiration driven by the oak seedling or sapling itself continues. For the period during the months of May 1 through October 31, ET was calculated via the Landscape Coefficient Method (Costello, et al, date unknown). The Landscape Coefficient Method estimates transpiration through comparing subject species density and species-specific water use against known reference values to calculate a coefficient. This coefficient is multiplied by the reference ET for a final weighted measure of evapotranspiration.

A species density coefficient for valley oaks has not been determined. However, agricultural tree crops with high water use have been assigned a species coefficient of 0.9, and this value was selected for valley oaks. Since many agricultural tree species are adapted to irrigation, this coefficient may constitute a conservative value for oaks.

The density coefficient for valley oaks used in this calculation is similarly an estimation. A planting of ornamental landscape trees with a canopy cover of 25% is assigned a density coefficient of 0.5 under the Landscape Coefficient Method. We assumed that any plantings of seedlings will be made at a density less than ornamental trees or will self-thin. Therefore a density coefficient of 0.25 was selected.

Daily transpiration is then calculated as:

Landscape Coefficient = Oak species coefficient * density coefficient

$$= 0.25 * 0.9 = 0.23$$

$$\text{Net Evapotranspiration} = \text{Landscape Coefficient} * ET_0$$
$$= 0.23 * ET_0$$

Monthly values for the period May 1- October 31 are shown in Table 4-5:

Table 4-5

Month	Days	ET_0 in mm/ day	ET_0 in mm/ month	Convert ET_0 to inches	Landscape Coefficient	Net ET loss	Net Precipitation Gain	Net Change in water budget
May	31	4	124	4.88	0.23	1.12	0	-1.12
June	30	4.5	135	5.31	0.23	1.22	0	-1.22
July	31	4.5	139.5	5.49	0.23	1.26	0	-1.26
August	31	4.5	139.5	5.49	0.23	1.26	0	-1.26
Sept	30	3.5	105	4.13	0.23	0.95	0	-0.95
October	31	2.8	86.8	3.42	0.23	0.79	0	-0.79
Total, Mar-Oct								-10.02

Reference ET_0, as determined from the Bulletin 1922 maps, varies slightly in June and July between the western and eastern portions of the study site. The total difference in calculated evapotranspiration amounted to 0.3 inches over the period from May to October. This difference is quite small relative to the estimating procedure, and was ignored. Evapotranspiration was treated as identical over the site.

The seasonal precipitation cycle begins again in November and with it the replenishment of surface soil water (California Department of Water Resources, 1999).

Step 3.

In Table 4-5 the seasonal total of 10 inches of available soil water consumed through evapotranspiration represents the soil water threshold for valley oaks under strategy A. To justify restoration plantings in areas where the water table is moderately deep, soils must contain at least this amount of water through a combination of water holding capacity and depth. This 10 inch AWC threshold value was selected as the minimum value for the data link to evaluate to true.

Key Assumptions and Notes

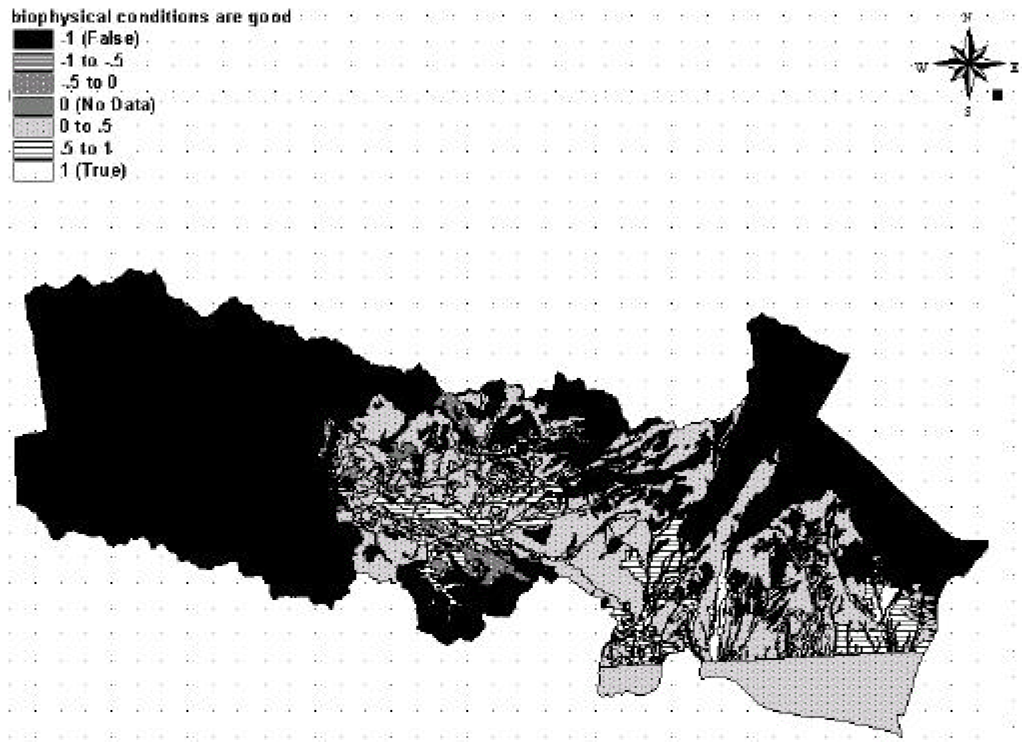
1. 1. All estimations are based on an average rain year. It is not possible to include within season or between season variation. Precipitation is assumed constant over the study site.
2. Un-irrigated soils are assumed to be at field capacity as of February 28 th. This assumption is based on the fact that December, January and February typically have the greatest precipitation.
3. Reference ET_0 represents actual evapotranspiration.
4. Annual grasses are assumed to be dead as of April 30 th. This is an admittedly large generalization. Actual date of death will vary from site to site within the study site in any given year, and from year to year for any given site.
5. Date of death of grasses represents a step-wise change in evapotranspiration.
6. Annual grasses dominate the evapotranspiration regime and can effectively model it. This assumption also does not allow for the possibility that some perennial plants may persist in the vegetation matrix and continue to remove moisture from the soil at depths below the grass root zone.

7. Oak seedling taproot has penetrated below the grass root zone. These roots will have access to remaining available water in the soil profile.
8. During the time period from May 1 through October 31, evapotranspiration for the oak seedling may be estimated by the Landscape Coefficient Method at a reasonable level of accuracy.
9. Oak seedling shoots may appear to die during the spring/summer drought of the Mediterranean climate in the region. If undisturbed however, the roots remain viable and will re-sprout with the arrival of rain in the fall. For this reason, seedlings were assumed to be able to use 100% of the available water remaining in the soil. . This contrasts with the concept of many crops which experience lowered yield when subjected to water stress. Stress may occur when as little as 50% of AWC is consumed. We selected 100% of available water, based on the seedling re-sprouting ability and because the criteria is not maximum crop yield, or an esthetically pleasing product, but seedling survival.
10. Spatial variation in density of grasses, or any other vegetation, and variation in soil characteristics at the sub-polygon level is neglected.
11. The effects of spatial variation due to topography are neglected. This includes such as effects as accumulation of soil water in low lying areas, the increase in evapotranspiration on south facing slopes and the decrease in evapotranspiration on north facing slopes.

5.0 Results

Applying the model to the biophysical data included in the GIS of the study area, the suitability for valley oak restoration of each soil polygon is scored and mapped. The map of suitability values is shown in Figure 5-1.

Figure 5-1



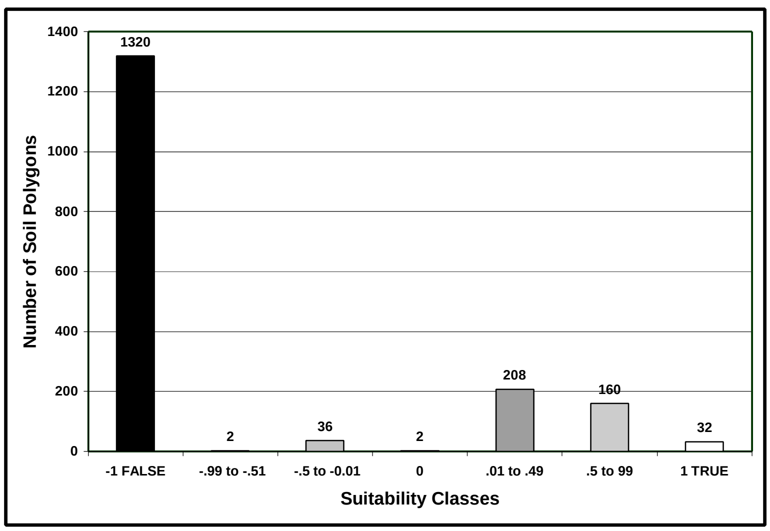
The black polygons indicate areas where the proposition "the site is suitable for valley oak restoration" is evaluated as false. The grey polygons indicate where the proposition is partially false. Falseness of the proposition increases with the darker shading.

The white polygons indicate areas where this proposition is completely true. The light polygons indicate where the proposition is partially true, with truthfulness increasing with lighter shading. The cross-hatched areas identify polygons where the proposition that the site is suitable for valley oak restoration is neither partially true nor partially false.

The model identifies 1320 soil polygons as completely unsuitable for valley oak restoration.

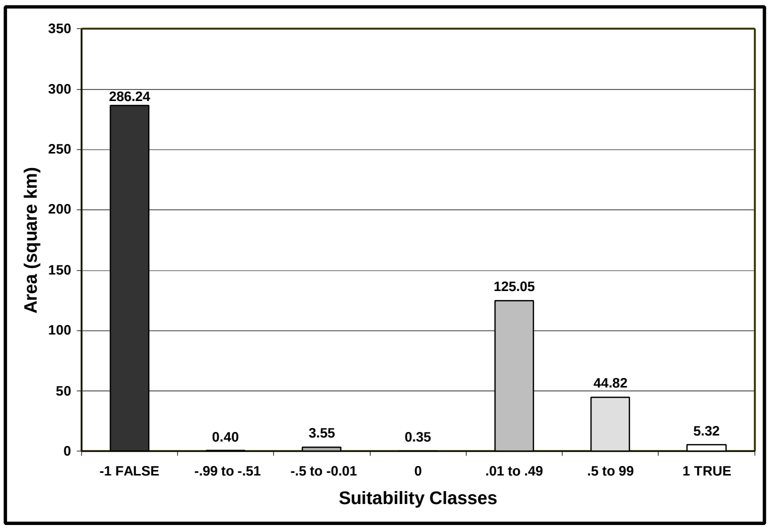
It identifies 32 polygons of highly suitable valley oak habitat, and 368 polygons of intermediate suitability. The classification of soil polygons is summarized in Figure 5-2.

Figure 5-2



Converting the suitability classes to land area, shown in Figure 5-3, the model identifies 286 km^2 of unsuitable area, 5.3 km^2 of extremely suitable area, and approximately 170 km^2 of area somewhat suitable for valley oak restoration.

Figure 5-3



All polygons within 28 km of the coast are completely unsuitable, due to the effect of salt aerosols. Other completely unsuitable areas occur in northeastern polygons of the study area. These polygons have relatively high elevations, resulting in relatively long distances to ground water.

Areas of high suitability consist of soil polygons of fertile alluvial loams, in low lying areas where the water table is relatively shallow, consistent with the Jepson's description (1910) of ideal valley oak habitat.

6.0 Discussion

Output Implications

From the initial model output, it is easily observed that a relatively small amount of land area in the study site is highly suitable for valley oak restoration. These sites would be priority sites and offer the best possible chance for establishing oak communities, unless other factors preclude this.

While these results are important and a significant first step, the influence of the socioeconomic and connectivity networks is conspicuously absent. Polygons of large size may incorporate several owners and a multitude of uses which may dramatically alter the suitability of these sites. Unfortunately, this information is not available at this time.

Rudimentary versions of the connectivity and socioeconomic networks are in place but are not supplied with data. If the biophysical network is evaluated first, followed by the connectivity and socioeconomic networks, as described below, the model structure will intrinsically prevent the designation of new polygons as suitable, and further narrow the number of suitable polygons. This is reasonable: adding more selection criteria should restrict the output.

The pragmatic conclusions for oak conservation are inescapable: little suitable land area is available, choices are limited.

The Model as a Tool for Decision Support

Land use planners today rarely have the luxury of making easy or comfortable decisions. Demand for resources grows more urgent even as threats to habitats multiply and the habitats diminish in quality and quantity. In these difficult circumstances, decision support becomes ever more valuable. The model developed in this project provides a first step in decision support by identifying the best broad scale locations suitable for valley oak restoration efforts.

The results presented in the previous section represent a synthesis of existing knowledge and expert opinion about the factors most critical in successful oak restoration. However, this model output *must* be viewed as only one possible scenario based on one set of expert opinions. Some outputs illustrating alternative data interpretations are explored below.

The model is not static; it may be modified in ways large or small to better represent the users needs. As new information becomes available or decision criteria change, the model can be updated and refined. As a decision support tool, the model output is dynamic, reflecting both the specific input decisions and data interpretation determined by the user. This is perhaps the most significant strength of the EMDS approach.

The EMDS modular network structure fosters exploration of data, and "what if" scenarios useful to decision makers in several ways.

- Individual networks may be "turned on" or "turned off" at any level in the hierarchy, allowing the remaining network to be evaluated without the influence of the disengaged factor(s). For example, when the socioeconomic and connectivity networks are fully operational, turning these networks "off" will result in output identical to that currently generated.

- One network at a time may be evaluated, revealing the influence of this network on the restoration suitability of individual sites, e.g. running the soil conditions are good network.
- Data links containing fuzzy curves or other evaluations may be modified from the original values. The analysis may be re-run and compared to the original, or several other values.
- Data in the attribute tables may be modified to reflect changes over time in factors e.g. depth to ground water may be changed after a new survey is completed.
- New networks may be added at any level in the hierarchy.

Limitations of the Model in its Current Form

The model demarcates large areas, as defined by polygons, with appropriate loamy soils of relatively high fertility and available water capacity, with ground water accessible by valley oak root systems, and with an adequate distance from the coast to avoid the adverse effects of salt aerosols.

As noted earlier, the data describing these factors were generalized across each soil polygon. In effect, the model treats each soil polygon as a homogeneous unit, characterized by a single soil type, soil fertility, soil moisture, distance to ground water, and distance from the coast. This simplification ignores the fine scale variations within a soil polygon which afford both advantages and disadvantages.

On the advantage side, identifying soil polygons most suitable for valley oak restoration is a useful first step. By viewing a map (see Figure 5-1) it is possible to immediately determine that many areas of the Los Alamos Valley would not be likely to support successful valley oak restoration projects. Elimination of these sites from consideration immediately increases the efficacy of the site selection task and the probability of successful results.

Also an advantage is the computational efficiency gained by using the polygon as a unit of analysis. Evaluations of the entire study site, or selected parts of the study site, can be completed in minutes. This facilitates exploring alternative interpretations of data, alternative networks of sites, or hands-on planning sessions. These functions would be less useful if the computing time required was several days.

Loss of microsite level detail is the most significant and obvious disadvantage from generalizing information over the polygon. Many of these microsite considerations are critical to persistence of oaks, and establishment of oak communities. This is an important limitation. Users need to be cognizant of this constraint and take additional steps to avoid unanticipated outcomes.

The biophysical conditions within a large land unit such as a soil polygon are heterogeneous. The soil fertility, soil moisture and even the soil series reported in the 1972 USGS Soil Survey varies in a patchy distribution within a soil polygon (Shipman et al, 1972). Topographical variation and underlying geological structures create diversity in the distance to ground water within a land unit the size of a soil polygon. The distance to the coast is not equal for all points within a soil polygon, but this measurement is perhaps the least sensitive to small-scale variation. However, the sheltering effects due to topography vary, such that beyond the completely unsuitable threshold of 28 km inland, aerosol suitability varies within the marginal sites that experience gradually decreasing salt damage (Ogden, 1980).

Currently, fine scale biophysical data is not available in the Los Alamos Valley, but such data could be acquired through intensive fieldwork. The model output under any user-defined set of decision criteria will prioritize those sites where follow-up ground-based investigation provides the most immediate and significant dividends.

Sub-polygon Scale Considerations for Suitable Polygons

To optimize oak restoration efforts, users will need to continue the site selection process at a finer scale. The following suggestions are offered for selecting planting sites within polygons:

1. Visually inspect areas for evidence of large numbers of gophers, squirrels and other rodents. Although the seedlings may be protected with exclosures, rodents are notoriously persistent, and have penetrated exclosure fencing in numerous plantings. Avoidance is the best tactic (Swiecki and Bernhard, 1991). Where possible, potential planting sites should be inspected for rodent activity and situated away from population concentrations.
2. Since the available surface soil water calculation was performed under the assumption of level ground, the generalized suitability of the polygon will not hold true for sloped areas within the polygon. Areas of significant slope will have different ET, precipitation inflow, and soil accumulations. Natural depressions, flat areas, or sites adjacent to

seasonal creeks may offer enhanced surface soil water availability. These sites are likely to have sustained soil moisture as well as greater ground water recharge capacity. Similarly, flat, gently sloping or concave areas will generally accumulate greater soil depth and fertility, also enhancing their ability to support valley oaks.

3. The depth to water table calculation is most accurate for the generally level areas of the valley floor. Uncertainty of the truth value for any polygon increases as the elevation increases. In general, the best planting sites would be on the lowest elevation and most level areas of the polygon.
4. Planting sites within the western half of the study site have been categorically evaluated as unsuitable due to salt aerosol concentration. It is possible that some sheltered sites may exist within this region of the study site. Sheltered sites would be described as those for which advection of salt aerosols is significantly blocked by a range of hills or other obstructions. Trial plantings are recommended in these areas before attempting larger scale plantings, as deposition of aerosols is difficult to determine. For polygons identified as suitable for restoration efforts that occur within between 28 to 48 km from the coast, salt aerosol effects may also present a challenge to seeding establishment. To maximize the probability of successful restoration, sites that are protected by ridges from the west-east salt advection should be chosen, as trees at these sites would suffer less salt damage (Ogden, 1980).
5. Areas with poorly drained soils, dense competing vegetation or significant shade are not suitable.
6. The model does not identify areas dominated by other shrub or tree species, but the potential distributions of valley oaks and other vegetation do overlap (Pavlik, et al, 1991). It is not useful to replace

other native communities with valley oak stands, or to attempt to establish valley oak seedlings within the understory of a shrub habitat.

7. The historic use of sites should be considered. Public sources of data are not available on the history of sites, but this information may be obtainable from current owners. Sites on which significant soil compaction or degradation has occurred since the soil survey was completed may no longer be suitable, or only suitable with significant management.

Additional networks for the model: Socioeconomic and Connectivity Considerations

Considering only the biophysical characteristics of potential valley oak restoration habitat allows evaluation of sites to occur without economic or political biases. However, such an approach is limited and not practical for implementation. Socioeconomic and oak community-level factors also impact the appropriateness of a site for valley oak restoration.

By ignoring social and economic factors, as the model currently does for lack of data, the implicit objective is to restore valley oaks everywhere they are likely to establish successfully. This is a value statement, and does not acknowledge other competing values in the community's approach to land use. For example, there may be community-established values that agricultural production should be preserved or maximized, or that additional housing is a priority. The community may express an interest in minimizing economic losses while maximizing valley oak habitat restoration.

The balancing of such considerations requires that the community explicitly decide which values their oak habitat restoration policy will represent. Once these values and policies are established, the selection of sites based on biophysical abilities to support valley oaks remains the first step in the process, followed by a further narrowing to reflect socioeconomic values.

To address these issues, knowledge base networks and data layers describing zoning, currently land use, land value and even willingness of a land owner to participate in valley oak restoration could be generated. Intersections of high biophysical suitability and political and economic feasibility could then be identified.

As noted in section 4.2 the three top-level networks are equally weighted. When the connectivity and socioeconomic networks are operational, and an evaluation using all three networks is run, the combined weight of the connectivity and socioeconomic networks could result in sites evaluating as suitable which do not evaluate as suitable based on biophysical factors. This is a serious consideration in the current structure of the model that users should be aware of, as there is no point in initiating restoration efforts on sites which fit these criteria but not the biophysical requirements of the oak. To prevent this situation, two approaches may be taken: 1) the biophysical network may be run first, and the output from this initial evaluation may then be further evaluated by the connectivity and socioeconomic networks, or 2) the weighting of the top-level networks may be altered. (Reynolds et al, 1998)

Oak community considerations are a final concern, if the goal is to establish functioning and viable oak communities, not plantations of trees. On sites identified by the model as potential valley oak habitat, current land uses may restrict where habitat restoration is empirically possible. It may be possible to establish valley oak habitat in areas of intensive agriculture, or where roads, residences, and other urban development occupy suitable areas. However, establishing oaks in these areas would have limited use, as oak associated wildlife is less likely to occupy these areas. Likewise, maintaining desired understory vegetation, or eliminating exotic species may be problematic where nutrient levels, disturbance regimes, or toxicity issues are outside the normal range.

Potential restoration sites located near existing valley oak stands should be given priority, as it is important to establish contiguous habitat. A large body of literature supports the idea that fragmented habitats present a variety of challenges to species dependent on those habitats (Wilcox and Murphy, 1985; Wilcove, et al, 1986; Schumaker, 1996). Habitat connectivity decreases adverse edge effects such as invasibility by weedy species (Alberts, et al, 1993) and damage due to wind and fire (Wilcox and Murphy, 1985; Wilcove, et al, 1986; Hof and Flather, 1995). Additionally, maximizing habitat connectivity increases dispersal capabilities (Fahrig and Merriam, 1985; Schumaker, 1996; Root, 1998;) of species utilizing the habitat, such as the valley oak system.

Ground-truthing the Model

Standard modeling protocol dictate that model predictions be checked against the real world, and evaluated for usefulness and accuracy. Unfortunately, valley oaks have been systematically removed and records of their previous occurrence are incomplete or non-existent. The present distribution of valley oaks cannot be used to ground- truth the model, and an alternative approach to checking the model output is not readily apparent. Field tests involving trial valley oak plantings would confirm or reject the suitability analysis of the model, but are prohibitively expensive and time consuming. Under these circumstances the model remains useful, but management decisions based on analyses should incorporate additional consideration of uncertainty.

As expected, the model identifies tracts of land as potential valley oak habitat on which there are currently no valley oaks.

Additionally, there are locations within the valley currently occupied by valley oaks that are not identified as suitable valley oak habitat by the model. For example, terraces consisting of Pleistocene soils where valley oaks are known to occur are not identified by the model as suitable valley oak habitat. At least two possible explanations are apparent. First, it is possible that these oaks established a century or two ago, when climatic conditions may have presented a favorable wet period that allowed the saplings ample soil moisture. Consecutive wet years may have facilitated sapling survival until root growth allowed deep ground water to be tapped. Alternatively, the existing oaks may benefit from a perched water table existing on these terraces. The map of general ground water trends used in the model is not capable of discerning such occurrences.

Future Areas of Research

Restoration efforts can aid in stemming the decrease in valley oak populations. Choosing the most suitable valley oak habitat available for restoration will increase the chances of successful establishment, and decrease the degree to which intensive management is necessary to achieve this goal. Currently, management of restoration efforts often involves irrigation of seedlings, fencing to protect seedlings and saplings from herbivores, and weed management (Swiecki and Bernhardt, 1991). To better understand valley oak ecology, and to move towards restoration of habitat with minimum anthropogenic input, the factors that influence natural valley oak regeneration must be studied.

Currently, work is being done at Sedgwick Reserve in Santa Barbara County, to understand more about the interspecies interactions in the valley oak community (Davis, pers. comm.). These research efforts focus on the effects of grazers and browsers on valley oak regeneration. Though grazing animals such as cows and deer are known to browse valley oak seedlings and saplings, often preventing their recruitment to an adult form (Griffin, 1973; Griffin, 1976; Pavlik, et al, 1991; Adams et al, 1997), these grazers also reduce the density of annual grasses. As annual grasses compete for soil moisture with oak seedlings (Gordon and Welker, 1989; Danielsen and Halvorson, 1990; Brown, 1991; Adams, et al, 1997), it is not entirely clear what role grazing plays in valley oak systems. Ideally, grass competition and grazing pressure would both be minimal, but in the highly converted oak-grassland landscape, this ideal is not practically attainable. It is important to learn more about the nature of the interspecies interactions occurring, and how valley oak establishment can be enhanced within the confines of the existing land cover and land use.

In addition to the effects of other species, temporal environmental factors may influence the success of valley oak regeneration. Some sites within Santa Barbara County appear to support valley oak establishment events; and the large, old trees in the valley are reminders of a time when valley oak establishment was successful. Age distribution studies to determine the time of recruitment to an adult form could prove to be useful in linking these known recruitment events to temporal factors.

Knowledge regarding the effects of grazing animal species, competing plant species, and temporal events that influence the establishment of valley oaks would aid in recreating the combination of factors that today's remaining valley oaks experienced as saplings. These areas of research will provide a more complete understanding of how valley oak recruitment can be facilitated and how restoration efforts can be improved.

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Appendix A: Soil Series Data

Soil Series	Series Code	Soil Texture	Other Phase Descriptors	Min AWC
Agueda loam	AdA	loam	loamy	6.0
Agueda silty clay loam	AgA	loam	silty clay	11.0
Agueda silty clay loam	AgC	loam	silty clay	11.0
Arnold sand	ArD	sand	sandy	2.0
Arnold sand	ArF	sand	sandy	2.0
Ballard fine sandy loam	ArF3	sand	eroded	1.0
Ballard fine sandy loam	BaA	loam	fine sandy	7.5
Ballard fine sandy loam	BaC	loam	fine sandy	7.5
Ballard gravelly fine sandy loam	BaD	loam	fine sandy	7.5
Ballard gravelly fine sandy loam	BbA	loam	gravelly fine sandy	6.0
Ballard gravelly fine sandy loam	BbC	loam	gravelly fine sandy	6.0
Ballard gravelly fine sandy loam	BbD	loam	gravelly fine sandy	6.0
Ballinger silty clay	BcE	clay	silty	3.0
Ballinger silty clay	BcF	clay	silty	3.0
Ballinger silty clay	BcG	clay	silty	2.5
Bayshore loam, drained	Bd	loam	loamy	8.0
Bayshore loam, drained	Be	loam	sandy	7.0
Bayshore silty clay loam	Bg	loam	silty clay	10.0
Betteravia loamy sand	Bh	loam	silty clay drained	10.0
Betteravia loamy sand	BmA	sand	loamy	3.0
Betteravia loamy sand	BmA3	sand	loamy eroded	0.5
Betteravia loamy sand	BmC	sand	loamy	2.0
Betteravia loamy sand	BnB2	sand	loamy eroded	3.5
Betteravia loamy sand	BnD2	sand	loamy eroded	3.5
Botella loam	BoA	loam	loamy	10.0
Botella loam	BoA2	loam	loamy eroded	10.0
Botella loam	BoC	loam	loamy	10.0
Botella loam	BoD2	loam	loamy eroded	10.0
Botella loam	BsA	loam	slightly wet	10.0
Botella clay loam	BtA	loam	clay	11.0
Botella clay loam	BtA2	loam	clay	11.0
Botella clay loam	BtC	loam	clay	11.0
Botella clay loam	BtD2	loam	clay eroded	11.0
Camarillo sandy loam	Ca	loam	sandy	6.0
Camarillo sandy loam	Cb	loam	sandy drained	6.0
Camarillo very fine sandy loam	Cc	loam	very fine sandy	9.0
Camarillo silty clay loam	Cd	loam	silty clay	11.0

Chamise sandy loam	CeC	loam	sandy	4.0
Chamise sandy loam	CeE2	loam	sandy eroded	3.0
Chamise shaly sandy loam	CfD	loam	shaly sandy	4.0
Chamise shaly loam	CgC	loam	loamy	4.0
Chamise shaly loam	ChD	loam	shaly	4.0
Chamise shaly loam	ChF	loam	shaly	3.5
Chamise shaly loam	ChG	loam	shaly	3.0
Chamise shaly loam	ChG2	loam	shaly eroded	2.0
Chamise clay loam	CkF	loam	clay	5.0
Climara-Toomes complex	CmF	clay	clay	4.0
Coastal beaches	CnB	beach	sandy	0
Cobbly alluvial land	CoB	deposit	material	0
Contra Costa-Lodo loams	CrE	loam	loamy	varies
Contra Costa-Lodo loams	CrF	loam	loamy	varies
Contra Costa-Lodo loams	CrG	loam	loamy	varies
Corralitos sand	CsG	loam	stony	varies
Corralitos sand	CtA	sand	sandy	2.0
Corralitos sand	CtD	sand	sandy	2.0
Corralitos sand	CtD2	sand	sandy eroded	2.0
Corralitos loamy sand	CuA	sand	loamy	4.0
Corralitos loamy sand	CuC	sand	loamy	4.0
Corralitos loamy sand	CuD	sand	loamy	4.0
Cropley silty clay	Cv	clay	silty	8.0
Crow Hill loam	CwE	loam	loamy	4.0
Crow Hill loam	CwF	loam	loamy	4.0
Crow Hill loam	CwG	loam	loamy	4.0
Crow Hill loam	CwG3	loam	loamy eroded	1.0
Diablo silty clay	DaD	clay	silty	4.0
Diablo silty clay	DaE	clay	silty	4.0
Diablo silty clay	DaF	clay	silty	4.0
Diablo silty clay	DaF3	clay	silty eroded	4.0
Diablo silty clay	DaG	clay	silty	4.0
Dune land	DuE	varies	varies	varies
Elder sandy loam	EdA	loam	sandy	7.5
Elder sandy loam	EdA2	loam	sandy eroded	6.0
Elder sandy loam	EdC2	loam	sandy	6.0
Elder sandy loam	EdD2	loam	sandy eroded	6.0
Elder loam	EmA	loam	loamy	9.0
Elder loam	EmC	loam	loamy	9.0
Elder shaly loam	EnA2	loam	shaly eroded	7.0

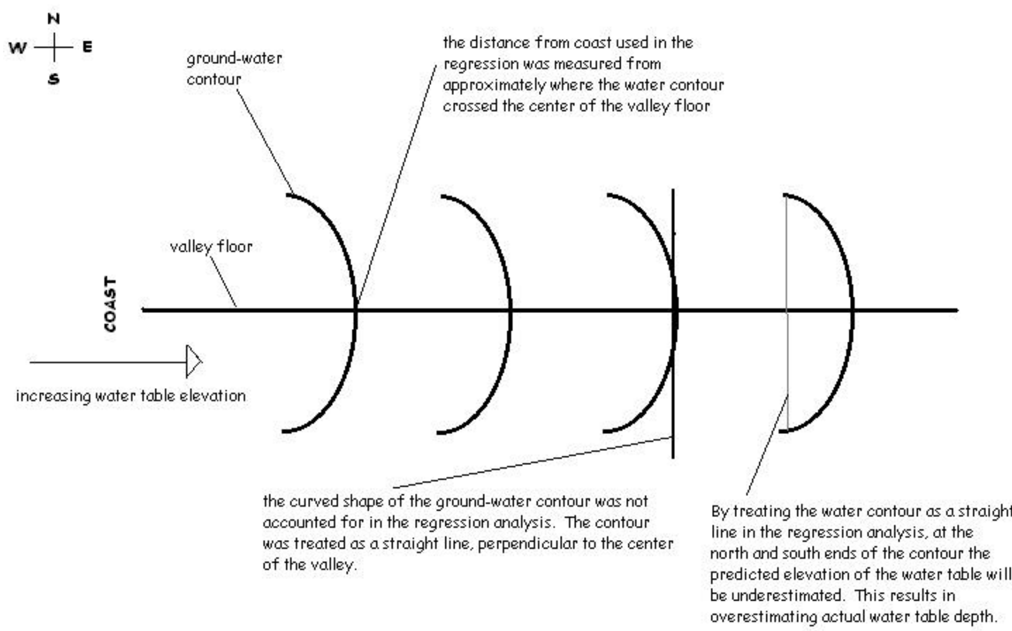
Elder shaly loam	EnC2	loam	shaly eroded	7.0
Elder shaly loam	EnD2	loam	shaly	6.5
Garey sandy loam	GaA2	loam	sandy eroded	6.0
Garey sandy loam	GaC2	loam	sandy eroded	6.0
Garey sandy loam	GaE2	loam	sandy eroded	5.0
Garey sandy loam	GaE3	loam	sandy severely eroded	5.0
Garey loam	GbB	loam	wet	8.0
Gaviota sandy loam	GmD	loam	sandy	2.0
Gaviota sandy loam	GmE	loam	sandy	2.0
Gaviota sandy loam	GmG	loam	sandy	2.0
Gazos clay loam	GsD	loam	clay	4.0
Gazos clay loam	GsE	loam	clay	4.0
Gazos clay loam	GsF	loam	clay	3.0
Gazos clay loam	GsG	loam	clay	3.0
Gullied land	GuE	gullied	varies	varies
Igneous rock land	IrG	igneous	varies	varies
Kettleman fine sandy loam	KtE	loam	fine sandy	3.0
Kettleman fine sandy loam	KtE3	loam	fine sandy severely eroded	1.0
Kettleman fine sandy loam	KtG	loam	fine sandy	2.0
Landslides	LaF	landslides	NA	NA
Linne clay loam	LcE	loam	clay	6.0
Linne clay loam	LcF	loam	clay	3.0
Linne clay loam	LcG	loam	clay	3.0
Lodo loam	LkG	loam	rocky	1.0
Lopez shaly clay loam	LmG	loam	shaly clay	1.0
Los Osos clay loam	LoE	loam	clay	4.0
Los Osos clay loam	LoG	loam	clay	3.0
Los Osos-San Benito clay loam	LsE	loam	clay	3.0
Los Osos-San Benito clay loam	LsF	loam	clay	3.0
Los Osos-San Benito clay loam	LsG3	loam	clay severely eroded	3.0
Marina sand	MaA	sand	sandy	3.0
Marina sand	MaC	sand	sandy	3.0
Marina sand	MaE	sand	sandy	3.0
Marina sand	MaE3	sand	sandy severely eroded	3.0
Marsh	Mh	marsh	NA	NA
Maymen stony loam	MmG	loam	stony	1.0
Metz loamy sand	MnA	sand	loamy	4.0
Metz loamy sand	MnC	sand	loamy	4.0

Metz loamy sand	MnC2	sand	loamy eroded	4.0
Mocho sandy loam	MoA	sand	loamy	4.0
Mine pits	MpG	mine pits and dumps	NA	NA
Mocho sandy loam	Mr	loam	sandy	7.0
Mocho sandy loam, overflow	Ms	loam	sandy	5.0
Mocho fine sandy loam	Mt	loam	sandy	5.0
Mocho loam	Mu	loam	fine sandy	7.5
Mocho loam, overflow	Mv	loam	loamy	9.0
Mocho silty clay loam	Mw	loam	loamy	9.0
Montara rocky clay loam	MyG	loam	rocky clay	2.0
Narlon sand	NrB	sand	sandy	2.0
Narlon loamy sand	NsA	sand	loamy	2.0
Narlon loamy sand	NsC	sand	loamy	2.0
Narlon loamy sand	NsD	sand	loamy	2.0
Narlon sand	NvA	sand	hardpan	2.0
Narlon sand	NvC	sand	hardpan	2.0
Oceano sand	OcA	sand	sandy	2.0
Oceano sand	OcD	sand	sandy	2.0
Oceano sand	OcD3	sand	sandy severely eroded	2.0
Panoche sandy loam	PcA	loam	sandy	7.5
Panoche sandy loam	PcC	loam	sandy	7.5
Panoche sandy loam	PdA	loam	sandy	6.0
Panoche loam	PdB	loam	sandy	6.0
Panoche loam, overflow	PeA	loam	loam	10.0
Panoche loam	PeC	loam	loamy	10.0
Pleasanton sandy loam	PfA	loam	loamy	9.0
Pleasanton sandy loam	PnA	loam	sandy	7.5
Pleasanton sandy loam	PnC	loam	sandy	7.5
Pleasanton cobbly sandy loam	PnD	loam	sandy	7.5
Pleasanton very fine sandy loam	PoE	loam	cobbly sandy	5.0
Pleasanton very fine sandy loam	PrA	loam	very fine sandy	8.0
Pleasanton gravelly very fine sandy loam	PrC	loam	very fine sandy	8.0
Positas fine sandy loam	PsD	loam	gravely very fine sandy	6.0
Positas fine sandy loam	PtC	loam	fine sandy	4.0
Positas fine sandy loam	PtD	loam	fine sandy	2.0
Positas fine sandy loam	PtD3	loam	fine sandy severely eroded	1.0
Positas fine sandy loam	PtE	loam	fine sandy	1.0
Positas cobbly fine sandy loam	PuD	loam	cobbly fine sandy	1.0

Riverwash	Rs	riverwash	NA	NA
Rough broken land	RuG	rough broken land	NA	NA
Salinas loam	SaA	loam	loamy	10.0
Salinas loam, overflow	SaC	loam	loamy	10.0
Salinas loam	SbA	loam	loamy	9.0
Salinas silty clay loam	SdA	loam	silty clay	11.0
Salinas silty clay loam	SdC	loam	silty clay	11.0
Salinas and Sorrento loam	SeD	loam	loamy	10.0
San Andreas-Tierra complex	SfD	loam	fine sandy	4.0
San Andreas-Tierra complex	SfE	loam	fine sandy	1.0
San Andreas-Tierra complex	SfF3	loam	fine sandy severely eroded	3.0
San Andreas-Tierra complex	SfG	loam	fine sandy	3.0
San Benito-Diablo complex	SgF	loam	clay	6.0
San Benito-Diablo complex	SgG	loam	clay	4.0
Sandy alluvial land	Sh	alluvial	sandy	NA
Sandy alluvial land, wet	Sk	alluvial	sandy wet	NA
Santa Lucia shaly clay loam	SmD	loam	shaly clay	4.0
Santa Lucia shaly clay loam	SmE	loam	shaly clay	2.0
Santa Lucia shaly clay loam	SmF	loam	shaly clay	3.0
Santa Lucia shaly clay loam	SmF2	loam	shaly clay eroded	2.0
Santa Lucia shaly clay loam	SmG	loam	shaly clay	2.0
Santa Ynez gravelly fine sandy loam	SnC	loam	gravelly fine sandy	3.5
Santa Ynez gravelly fine sandy loam	SnD	loam	gravelly fine sandy	3.5
Santa Ynez clay loam	SoC	loam	clay	4.0
Santa Ynez clay loam	SoE	loam	clay	2.0
Sedimentary rock land	SpG	sedimentary	rock	NA
Shedd silty clay loam	SrE	loam	silty clay	6.0
Shedd silty clay loam	SrF	loam	silty clay	5.0
Shedd silty clay loam	SrG	loam	silty clay	4.0
Shedd silty clay loam	SrG3	loam	silty clay severely eroded	3.0
Shedd silty clay loam	SsE	loam	silty clay	5.0
Shedd silty clay loam	SsF	loam	silty clay	5.0
Shedd silty clay loam	SsG	loam	silty clay	3.5
Sorrento sandy loam	StA	loam	sandy	7.5
Sorrento sandy loam	StC	loam	sandy	7.5
Sorrento sandy loam, sandy	SuA	loam	sandy	5.0
Sorrento loam	SvA	loam	loamy	10.0
Sorrento loam	SvC	loam	loamy	10.0

Sorrento clay loam	SwB2	loam	clay eroded	11.0
Stutzville loamy sand	Sx	sand	loamy saline	8.0
Stutzville sandy loam	Sy	loam	sandy saline	9.0
Stutzville saline loam	Sz	loam	loamy saline	10.0
Stutzville saline loam	Sza	loam	saline	10.0
Stutzville silty clay saline loam	Szb	loam	silty clay saline	11.0
Stutzville silty clay saline loam	Szc	loam	silty clay saline	11.0
swamp	SzW	swamp	NA	NA
Tangair sand	TaA	sand	sand	3.0
Tangair sand	TaC	sand	sandy	3.0
Terrace escarpments, sandy	TcG	terrace escarpm ents	sandy	NA
Terrace escarpments, loamy	TdF	terrace escarpm ents	loamy	NA
Terrace escarpments, cobbly	TeG	terrace escarpm ents	cobbly	NA
Tierra loamy sand	TmE	sand	loamy	2.0
Tierra loamy sand	TnC	loam	sandy	4.0
Tierra sandy loam	TnD2	loam	sandy eroded	3.5
Tierra sandy loam	TnE2	loam	sandy eroded	2.0
Tierra loam	TrC	loam	loamy	4.0
Tierra loam	TrD	loam	loamy	4.0
Tierra loam	TrE2	loam	loamy eroded	2.0
Tierra loam	TrE3	loam	loamy severely eroded	1.0
Tierra clay loam	TsF	loam	clay	3.0
Toomes-Climara complex	TxG	loam	clay	2.0
Wasioja fine sandy loam	WaB	loam	fine sandy	7.0
Wasioja fine sandy loam	WaC	loam	fine sandy	7.0
Wasioja fine sandy loam	WaD	loam	fine sandy	7.0
Wasioja cobbly fine sandy loam	WcC	loam	cobbly fine sandy	5.0
Wasioja cobbly fine sandy loam	WcF	loam	cobbly fine sandy	5.0

Appendix B: Water Table Depth Calculation



Appendix C: Glossary

clay	a soil textural class; includes particles less than 0.002 millimeters in diameter (Foth, 1984).
coverage	sets of geographic features and their attributes (Environmental Systems Research Institute, 1996).
establishment	an individual tree's achievement of the adult life stage
Geographic Information System (GIS)	an organized collection of computer hardware, software, and geographic data designed for analyzing and displaying geographi cally referenced information Environmental Systems Research Institute, 1996).
field capacity	after heavy precipitation, flooding or irrigation, the pore spaces of a soil will be saturated, or completely filled with water. A proportion of this water quickly drains from the largest pore spaces under the force of gravity. The amount of water remaining in the soil is termed field capacity.
knowledge base	the organization of quantitative and qualitative relationships in a manner that formalizes the decision-making process and aids in drawing conclusions
loam	a soil textural class; includes soils in which sand, clay, and silt are influential on soil properties (Foth, 1984).
permanent wilting point	the point at which plant roots are no longer able to extract water from the soil. At the permanent wilting point, some water remains in the soil, but is bound so tightly to soil particle surfaces, that roots are unable to access it.
polygon	a mapping unit with a consistent spatial characteristic. For example, a soil polygon is a unit of variable size over which the soil type is relatively consistent.
recruitment	survival from the juvenille to the adult life stage

sand a soil textural class; includes particles between 0.05 and 2.0 millimeters in diameter (Foth, 1984).

silt a soil textural class; includes particles between 0.05 and 0.002 millimeters in diameter (Foth, 1984).

truth value the degree to which it is true that a proposition has membership in a set