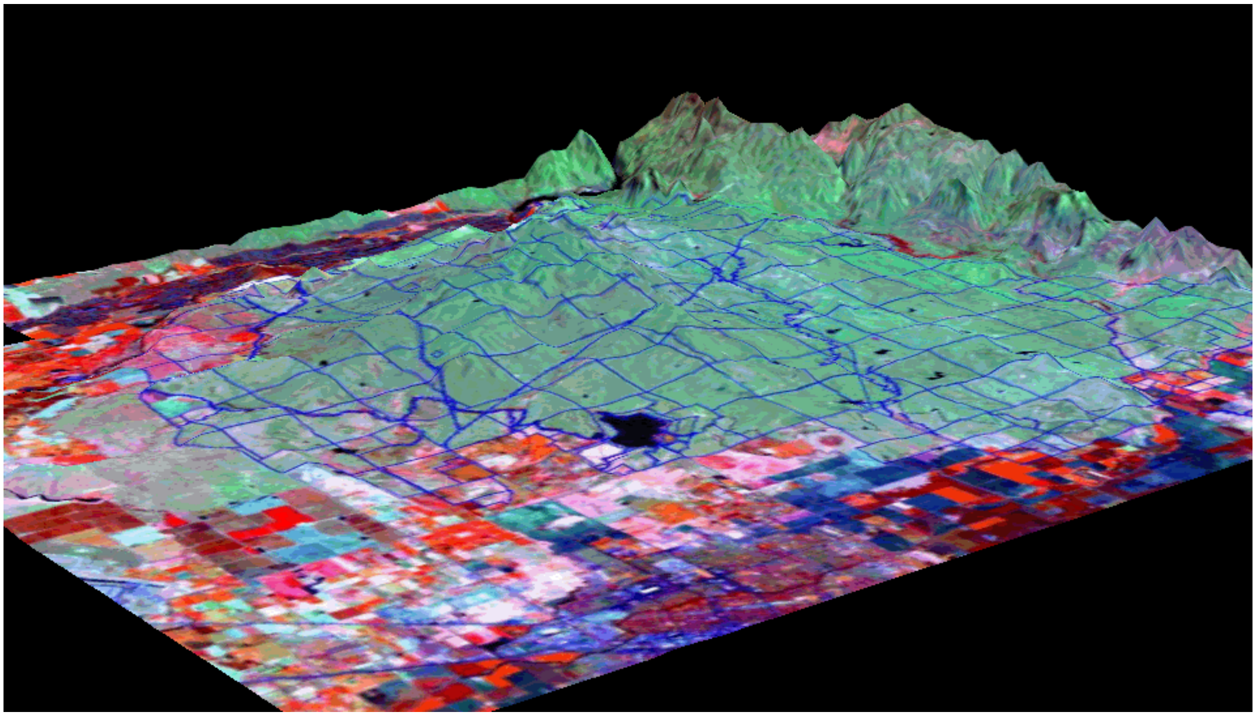

A knowledge base to assess site suitability for ecological field stations

A case study for the UC Natural Reserve System at UC Merced

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Project Summary

Many programs designate networks of sites for nature reserves, some of which are designated for scientific research, education, and environmental monitoring (e.g., Long-Term Ecological Research, Man and the Biosphere, Research Natural Areas, National Estuarine Research Reserves, and universities). The University of California Natural Reserve System (UC-NRS) is the world's most extensive example of the latter, with 33 natural reserves (encompassing nearly 50,000 ha) affiliated with its eight of its nine campuses. While these programs describe the qualities of suitable research reserves, they seldom prescribe a formal procedure for assessing a large region to identify the most suitable candidate sites, particularly when the rating criteria may conflict.

In planning for a new University of California (UC) campus near Merced, the UC Office of the President is considering establishing one or more additional NRS research and teaching reserves in the neighboring Sierra Nevada or the San Joaquin Valley. To support this planning process, we developed a generic top-down decision support tool for selecting new sites to expand the NRS based on University guidelines (University of California 1984). The tool was then applied specifically to assess site suitability for establishing an NRS reserve in vernal pool/grassland habitat. The NRS guidelines include a combination of scientific, academic, and administrative criteria that are not always compatible. Our approach explicitly deals with these potentially conflicting objectives and with the issue of the availability and resolution of data. Existing decision support software was adapted to formulate and solve the former problem by exploiting a fuzzy logic network model for combining evidence of suitability. To address the lack of detailed site-level information across the entire planning region, we developed a three-staged assessment process involving the use of relatively coarse data to successively screen the set of candidate sites in the first two stages before preparing a more detailed assessment of finalist sites in Stage 3.

The project had several objectives:

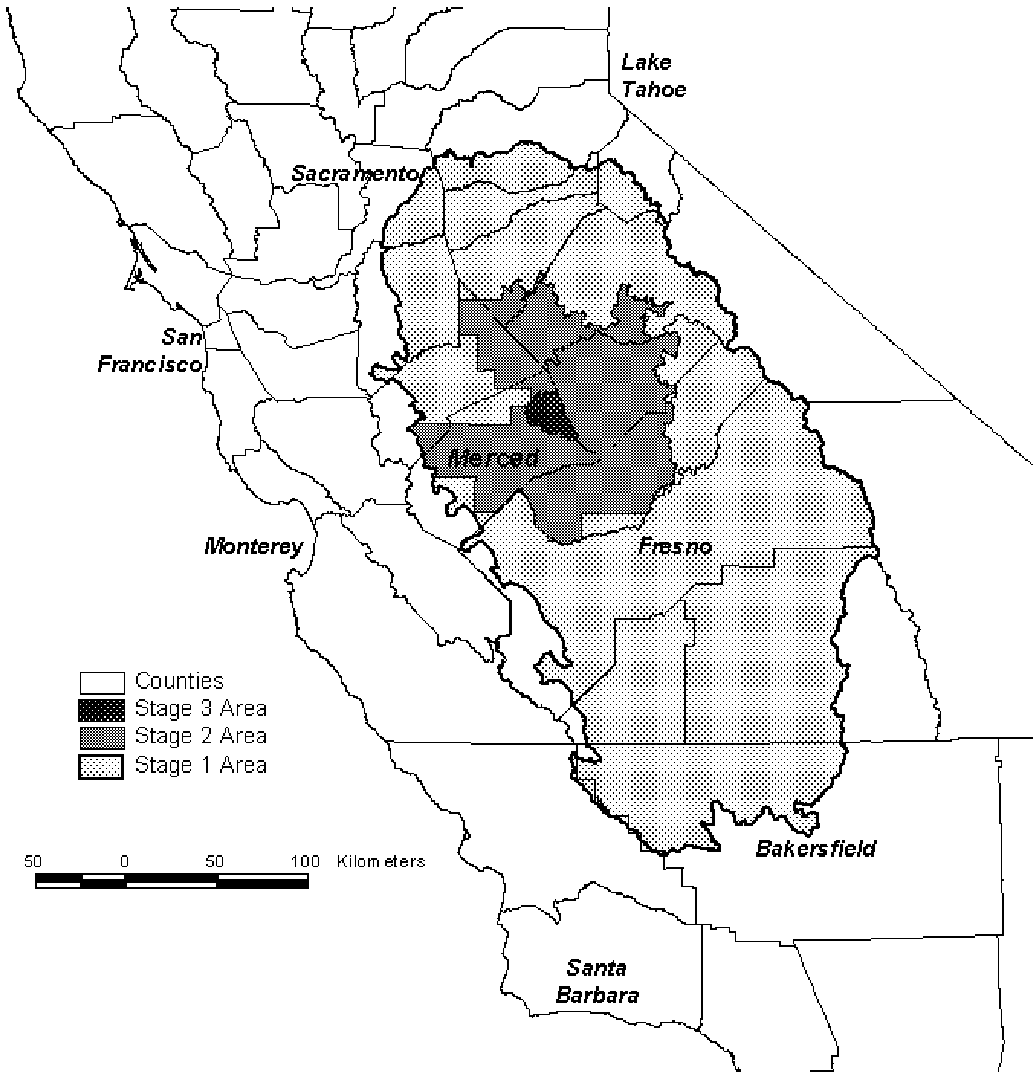
1. To develop a generic top-down decision-support modeling tool, based on the established guidelines, that could be used to rate the suitability of sites in future UC-NRS assessments.

2. To apply the knowledge base to assess the suitability of existing NRS reserves and their contribution to representativeness of California's environmental diversity.

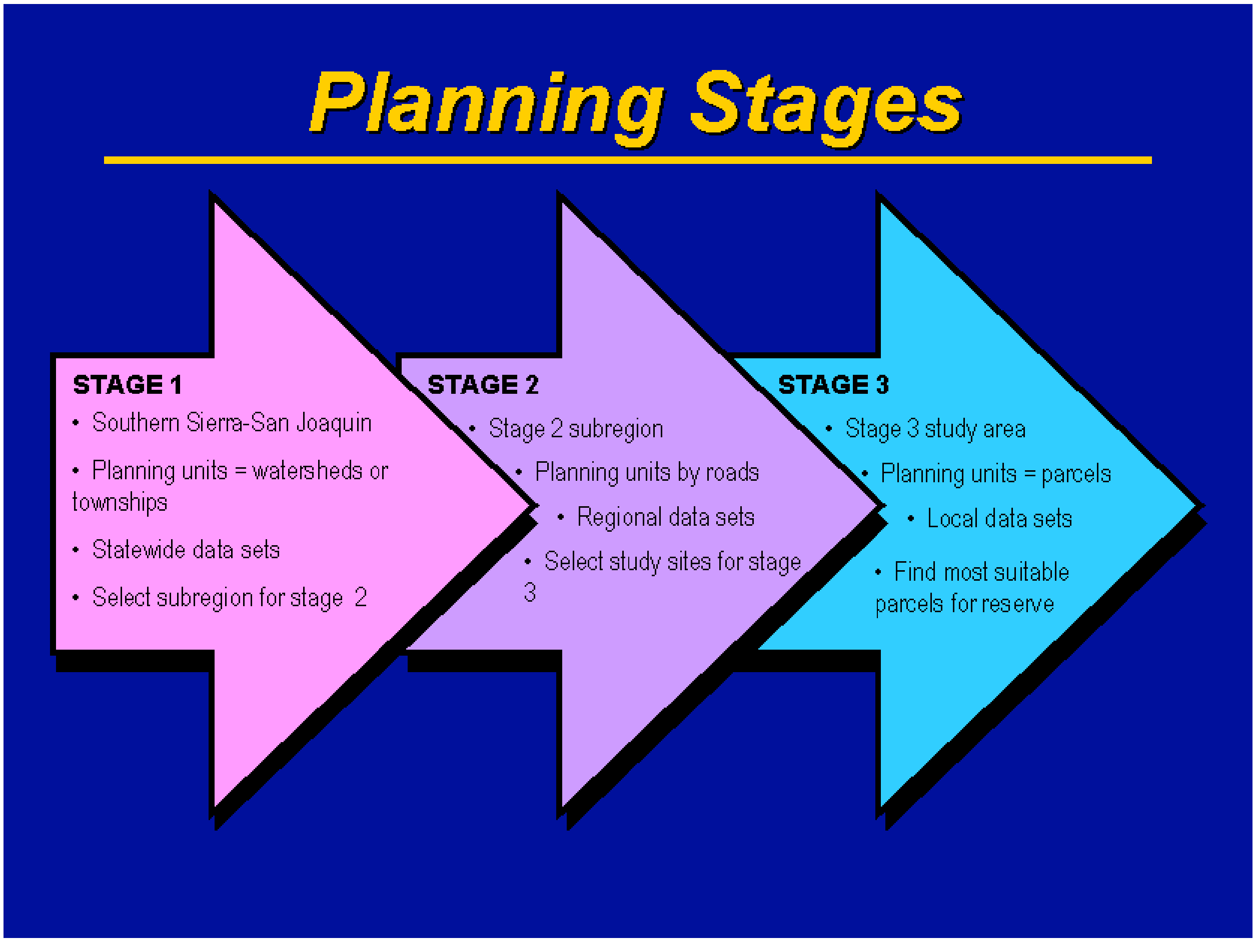
3. To apply the knowledge base to assess the suitability of lands within the San Joaquin Valley and southern Sierra Nevada as potential NRS reserves.

4. To adapt the generic knowledge-base network to assess the suitability for the vernal pool/grassland habitat type that might be represented in the NRS at the Merced campus, using a multistage approach of successively smaller assessment regions with increasing spatial resolution.

5. Apply the model to an assessment region around the proposed Merced campus to identify the most suitable parcels for a vernal pool reserve according to our interpretation of the UC guidelines.



Study area of the three stages surrounding the proposed UC Merced campus site.



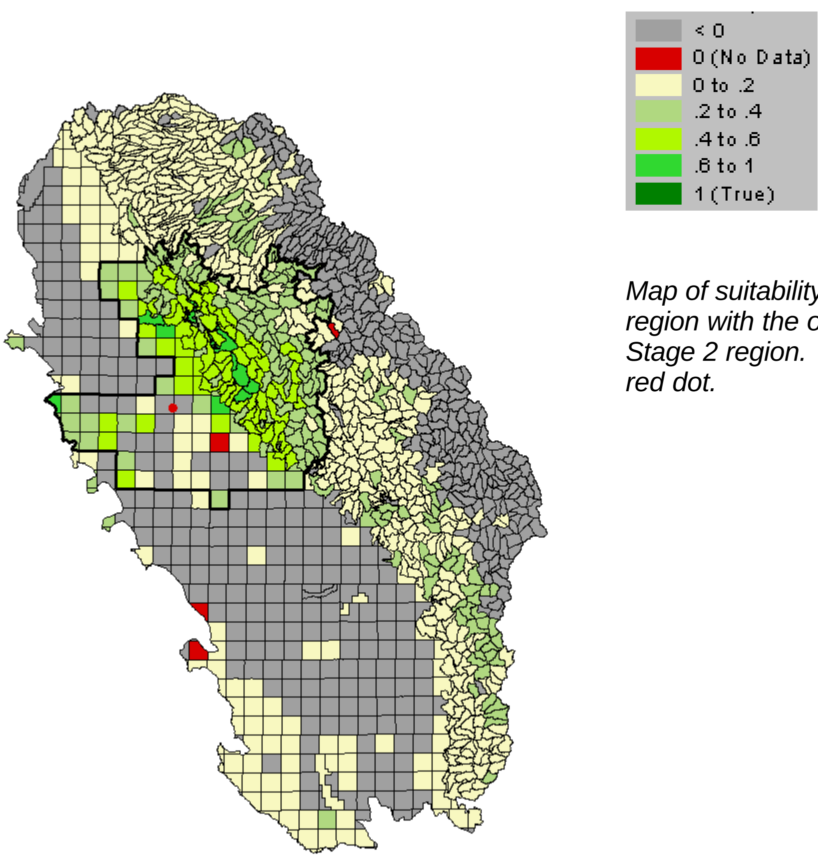
Three stages of the suitability assessment.

The University of California's Natural Reserve System (NRS) employs a set of guidelines for evaluating and selecting new reserves. These guidelines are organized hierarchically. The topmost level is organized in three categories of criteria—scientific, academic, and administrative suitability. More specific antecedents similarly define each of these criteria. All these criteria are only general guidelines, however, and do not specify variables with threshold values as minimum (or maximum) acceptable levels. It is left to each assessment committee to determine how the guidelines will be interpreted, whether with precisely measured variables or with a qualitative estimate of condition. Many of the criteria are semantically imprecise, such as "*close* to a campus" and "include *typical* samples of *widely distributed* habitat types" [italics added]. These characteristics suggested the use of a fuzzy, knowledge-based approach in which the decision rules are formulated as a series of propositions. The propositions are evaluated not as "true" or "false" in a Boolean fashion (e.g., distance from campus = 25 km from campus) but as continuous truth values in which distance from campus is mapped into membership values in the set "close to campus." The result is a map of truth-values for every proposition in the network, including the overall proposition that "the site has high suitability for an NRS reserve." Formulating the problem in a knowledge base both formalizes the set of criteria and the linkages to actual data, as well as providing insights about what factors are critical in determining the suitability of a site. The task of assessing the suitability of sites as potential new UC reserves was undertaken using the Ecosystem Management Decision Support (EMDS) system from the U. S. Forest Service. The NRS guidelines were interpreted into a logic network, starting with the three primary criteria of scientific, academic, and administrative suitability. Because the guidelines do not identify quantitative variables to use for evaluation (data links in EMDS terminology), this general logic network was adapted for each of the three stages used in the UC-Merced case study. We believe this study is the first to apply fuzzy logic to assessing land suitability for scientific research reserves.

One of the overarching aims of the NRS program is to provide representation of California's environmental diversity. Representativeness is important for providing comprehensive opportunities for teaching and research. Measuring representativeness of a set of sites is not a trivial problem, however. We developed an alternative method of assessing representativeness of the NRS, in which the environmental variability of California was characterized by a principal components analysis of biophysical data sets, covering climate, topographic, and soil productivity factors. We generated a measure of representativeness contributed by each existing reserve, by assessing its environmental distance from all other reserves and for every location in California from the reserve with the most similar biophysical environment. From this assessment of representativeness, we conclude that some regions are less well-represented by the NRS, including subalpine environments, some desert environments, the mid-elevation conifer zone in the Sierra and northern ranges, the Central Valley, and the Modoc Plateau. In general, the region centered around the proposed UC-Merced campus, including most of the San Joaquin Valley and the westside of the central and southern Sierra Nevada, are not well-represented by the existing NRS reserves. We therefore applied the suitability assessment methods in a case study for this area.

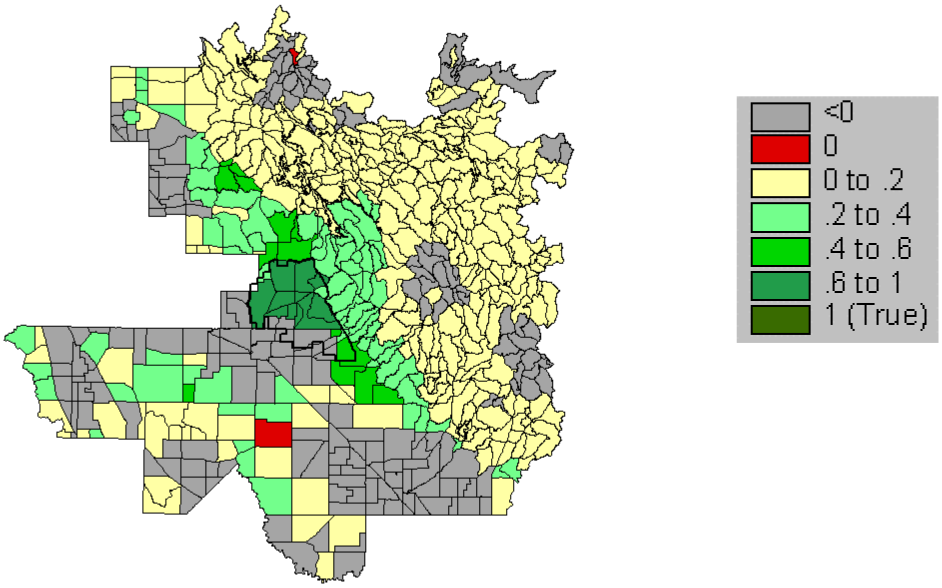
Before assessing suitability of sites for potential NRS reserves at the UC-Merced campus, we tested the knowledge base on the network of existing NRS reserves. This allowed us to do two things. First, it gave an indication of how well existing reserves meet the selection criteria (as interpreted and assessed in our model) and second, how the values for potential sites in the UC-Merced Stage 1 area compare to sites previously identified as highly suitable by less formal means. In other words, it provides a calibration of truth-values that are not in any verifiable units. To be consistent with the assessment in Stage 1, however, the assessment was conducted for small catchments that contain the reserves and not for the actual reserve footprint. The overall suitability values for NRS reserves ranged from moderately high to very low. The highest-ranking reserves (such as the Jepson Prairie Preserve) tend to satisfy all three primary criteria. The lower scoring reserves (such as the Kendall-Frost Marsh Reserve) tend to be excellent in some criteria, but score poorly in at least one. The most common criteria that caused the low scores was the fact that reserves were close to one another and therefore did not contribute highly to representation of the ecological and geographic diversity of the state. They also tended to be located in urban areas (with low ecological integrity as measured by roadedness and native habitat area) and as a result had average to poor scientific suitability values. Most assessment units scored moderately high for the academic suitability criterion, which was based solely on travel time from the sponsoring campus. The key point is that the lowest scoring reserves were not poor in all aspects, but instead were excellent in some aspects and poor in others.

Applying the knowledge-base logic network to the data links from the moderate-resolution GIS database of the Stage 1 assessment region generated truth-values for every assessment unit. The range of suitability truth-values for the Stage 1 assessment region is very similar compared to the range for the existing reserves, and the highest values in the assessment region are comparable to the best NRS reserves. No assessment unit was totally suitable according to our logic. The mean suitability score for the existing reserves is slightly higher than the mean suitability of all assessment units in the assessment region. Existing reserves do slightly better on scientific criteria, on average, than the assessment region, but relatively worse for administrative criteria. The scientific results can be explained by the large number of assessment units that are highly impacted by urban and agricultural land uses in the Stage 1 assessment region. The administrative result appears to be related to the distinctiveness of the study area, in both ecological and geographical distance, from existing reserves. By the academic suitability criterion, the existing reserves score much higher on average than the assessment region, because existing reserves are generally closer to their sponsoring campus than assessment units are to the proposed Merced campus site. Our results indicate that there are some assessment units in the Stage 1 assessment region that are comparably suitable to existing NRS reserves as defined by the logic network based on the NRS guidelines. This only represented an initial screening of sites to focus a more-detailed (Stage 2) assessment. The Stage 2 assessment region was delineated as a contiguous region in the Sierra Nevada with a roughly circular outline where ratings of assessment units were consistently high, and a small cluster of assessment units with similar scores west of Merced near the wetland areas of the San Joaquin Valley.



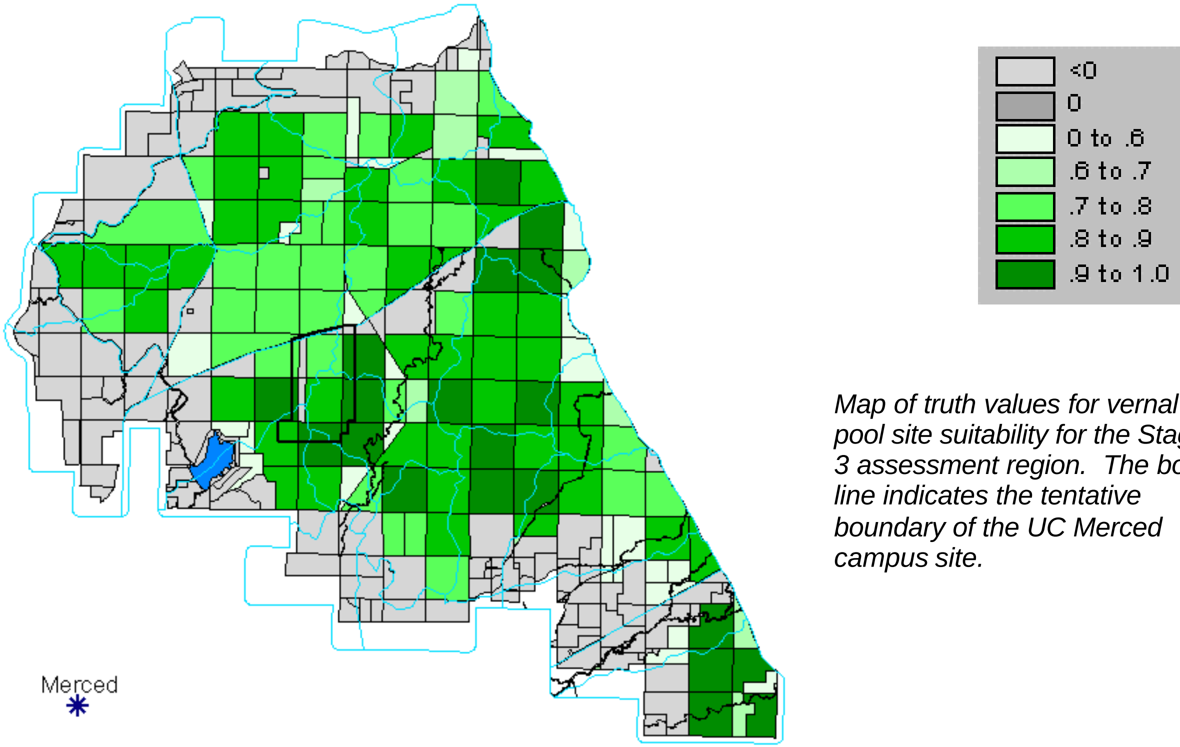
Map of suitability in the Stage 1 assessment region with the outline (bold) of the proposed Stage 2 region. The city of Merced is shown as a red dot.

For the Stage 2 assessment, we utilized a more detailed set of criteria within the same logical framework. That is, the higher levels of the logic network were the same, but the data for characterizing ecosystem integrity and so on were more specific. In addition, the suitability of assessment units was assessed separately for the vernal pool/grassland habitat type, whereas in Stage 1, only a generic suitability was considered. The Stage 2 assessment region encompassed over 12,628 km^2, or 20% of the Stage 1 assessment region. Most assessment units were delineated as blocks of unroaded area bounded by roads. The information to calculate data links for the knowledge-based network came from photo-interpreted maps of farmland use and vernal pool quality and density, the 1995 TIGER road files, the San Joaquin Endangered Species Recovery Plan, and maps of private land ownership. As is well-known, the area containing and surrounding the proposed UC Merced campus contains a very dense complex of vernal pools, among the best examples remaining in the Central Valley. From the map of vernal pool density (Holland 1998), the best areas for Northern Hardpan vernal pools occur along the grassy base of the Sierra Nevada in hummocky, old alluvial terraces. A secondary zone of smaller and less dense Northern Claypan vernal pool complexes occurs on lower alluvial terraces along Sandy Mush Road across the Central Valley and in the wetlands near the various wildlife refuges west of Merced. The large extent of dense vernal pool complexes in these assessment units are more likely to contain a diversity in pool size, depth, duration of inundation, and therefore the number of species than sites with small or less dense complexes. These same locations also tend to be of importance for the San Joaquin Endangered Species Recovery Plan. The travel time from campus criterion favored assessment units closer to the proposed campus site, which also contain some of the highest suitability vernal pool sites. The criteria relating to ease of acquisition and management, where such information was available, likewise rated the ranchlands in the vernal pool zone among the highest suitability sites. The overall suitability, therefore, gave the highest truth values to a small set of contiguous assessment units surrounding, and including, the proposed campus site. A few additional assessment units had moderately high scores just north or south of the most highly-rated units. There may be individual parcels within these assessment units that could still offer suitable sites for vernal pool reserves. By following the guidelines for evaluating potential UC NRS reserves, we found that the lands in these assessment units also achieve a high level of concurrence with these guidelines for their scientific, academic, and administrative suitability as well. These sites tend to be relatively intact ecologically, with few roads or converted lands, are the larger ranches rather than small farms or rural residential lots, and are within easy commute for class field trips. There are other vernal pool complexes in the assessment region that perhaps rival those near the campus in size and density. These sites do not meet the other University guidelines as well as those closer to the campus site, however. Thus we recommend only the assessment units in the vicinity of the campus for further consideration in Stage 3.



Map of truth values for vernal pool site suitability for the Stage 2 assessment region. Bold line indicates Stage 3 assessment region boundary.

In Stage 3 the NRS guidelines were interpreted into a logic network that was similar to Stages 1 and 2, starting with the three primary criteria of scientific and administrative suitability. Academic suitability, based on travel time from campus, was considered uniform across all parcels, and therefore was deleted in Stage 3. There were two primary differences in Stage 3. First, the basic logic network was modified to assess the suitability of assessment units as representative of vernal pool/grasslands. In particular, we attempted to address the importance of representing the diversity of pool communities, which differ significantly among landforms and parent soil materials. In the absence of biological inventory data, we relied instead on soil mapping to infer biological diversity. Second, the smaller size of the assessment region permitted more detailed, parcel-level information to be included in the logic networks. A GIS database was compiled for the data links needed by the knowledge-base for each of the 298 parcels. The information to calculate data links for the knowledge-based network came from the GIS parcel coverage and database from the Merced County Association of Governments, photo-interpreted maps of vernal pool quality and density, soil type maps, and the 1:24,000 scale USGS topographic quadrangle maps in digital raster graphic format. Three clusters of parcels had the highest overall suitability (greater than 0.9): the lands south of Highway 140 between Owens and Miles Creeks, the east end of La Paloma Road near the county line, and scattered parcels of the Smith Trust lands and adjacent Flying M Ranch. Most parcels had relatively high suitability for most factors, except for some parcels on the edges of the study area that are currently agricultural or are zoned for development and those that are influenced by canals or paved roads. The two criteria that had the most influence on the ratings were the vernal pool ratings and the potential trespass factors. Generally the parcels north of La Paloma Road tend to have lower suitability as a prime example of vernal pool complexes because the density of pools is lower with a single parent soil material.



Map of truth values for vernal pool site suitability for the Stage 3 assessment region. The bold line indicates the tentative boundary of the UC Merced campus site.

The addition of a new campus in Merced provides an opportunity to fill the gaps in NRS representation in the Great Valley and the Sierra Nevada in sites that are reasonably close to the campus for class field trips and well suited in terms of the other NRS guidelines. While the three-stage assessment does not guarantee that other good sites were not overlooked because they are embedded in assessment units that do not appear suitable of the coarsest scale, it gave them a reasonable opportunity to be detected. Final selection of a new reserve, if such a decision is made, will still require a more in-depth evaluation of the leading contenders, followed by a reserve design process to combine an appropriate set of contiguous parcels.

The general procedure proposed here as Stage 1 could be used for assessing suitability of new NRS reserves for any UC campus. The assessment unit boundaries either exist (planning watersheds) or can be readily derived (townships) for any region of the state. The GIS data for Stage 1 currently exist statewide as well. The more specific assessments in Stage 2 and 3 would need to be adapted for other locations depending on the availability of local data. Similar knowledge bases could also be developed for other habitat types near Merced that are not well-represented in the NRS, such as Sierran mixed conifer. Our logic network is designed to support the substitution of habitat-specific factors as a separate network in Stage 2. The Stage 3 knowledge base could then be tailored for that habitat type. In fact, we view this as an opportunity to establish a series of reserves along an ecological transect over several thousand meters of elevation range in the central Sierra Nevada, which could be especially valuable to support global change studies. There are several nearby sites currently managed by other agencies for conservation or research purposes that could be considered for NRS use or to complement an NRS reserve without additional university management.

Introduction

Many programs designate networks of nature reserves for a variety of purposes. The IUCN Commission on National Parks and Protected Areas classifies reserves designated for scientific research, education, and environmental monitoring as "scientific reserves" (Category Ia) with the most stringent management for preservation of ecosystems and maintenance of ecological processes (IUCN Commission on National Parks and Protected Areas 1994). In the United States, national programs of research sites include the Long-Term Ecological Research network funded by the National Science Foundation (Franklin et al. 1990), the Man and the Biosphere program (Batisse 1982), research natural area programs of several federal agencies (USDA Forest Service 1994), and the National Estuarine Research Reserve program of the US Fish and Wildlife Service, biodiversity observation sites (Mervis 1998), coral reef reference sites (Jameson et al. 1998), global change monitoring sites (Bailey 1991) and teaching and research reserves operated by academic institutions. The University of California Natural Reserve System (UC-NRS) (Norris 1968, Cheatham et al. 1977, Ford and Norris 1988) is the world's most extensive example of the latter, with 33 natural reserves (encompassing nearly 50,000 ha) affiliated with its eight of its nine campuses.

While these programs have developed qualitative criteria for evaluating the suitability of sites as research reserves, they generally lack a formal, explicit procedure for comparing candidate sites (Stoms et al. 1998). In practice site selection inevitably involves a trade-off between conflicting goals. For example, sites that are more readily accessible to researchers and students are also likely to have experienced greater human impacts and are more prone to trespass. Use of a formal, explicit approach to selection is especially important in the presence of conflicting goals or objective.

Approaches used for selecting additional sites may be usefully divided into "bottom-up" versus "top-down" types. In the bottom-up approach, a specific site or set of sites is nominated for consideration and then evaluated against the criteria. One could say that a site is suitable if it meets the minimal criteria, but one cannot say, without additional evidence, that it is the "best" site for addition to the network. The top-down approach, in contrast, rates all potential sites in an assessment region and selects those that best meet the criteria. Obviously, the data and information needed for top-down selection among a set of sites is far greater than for bottom-up evaluation of a single site, and the former tends to use coarser information than the latter.

In planning for a new University of California (UC) campus near Merced (Figure 1), the UC Office of the President is considering establishing one or more additional NRS research and teaching reserves in the neighboring Sierra Nevada or the San Joaquin Valley. To support this planning process, we developed a generic top-down decision support tool for selecting new sites to expand the NRS based on University guidelines (University of California 1984). The tool was then applied specifically to assess site suitability for establishing an NRS reserve in vernal pool/grassland habitat. The NRS guidelines include a combination of scientific, academic, and administrative criteria that are not always compatible. Our approach explicitly deals with these potentially conflicting objectives and with the issue of the availability and resolution of data. Existing decision support software was adapted to formulate and solve the former problem by exploiting a fuzzy logic network model for combining evidence of suitability. To address the lack of detailed site-level information across the entire planning region, we developed a three-staged assessment process involving the use of relatively coarse data to successively screen the set of candidate sites in the first two stages before preparing a more detailed assessment of finalist sites in Stage 3.

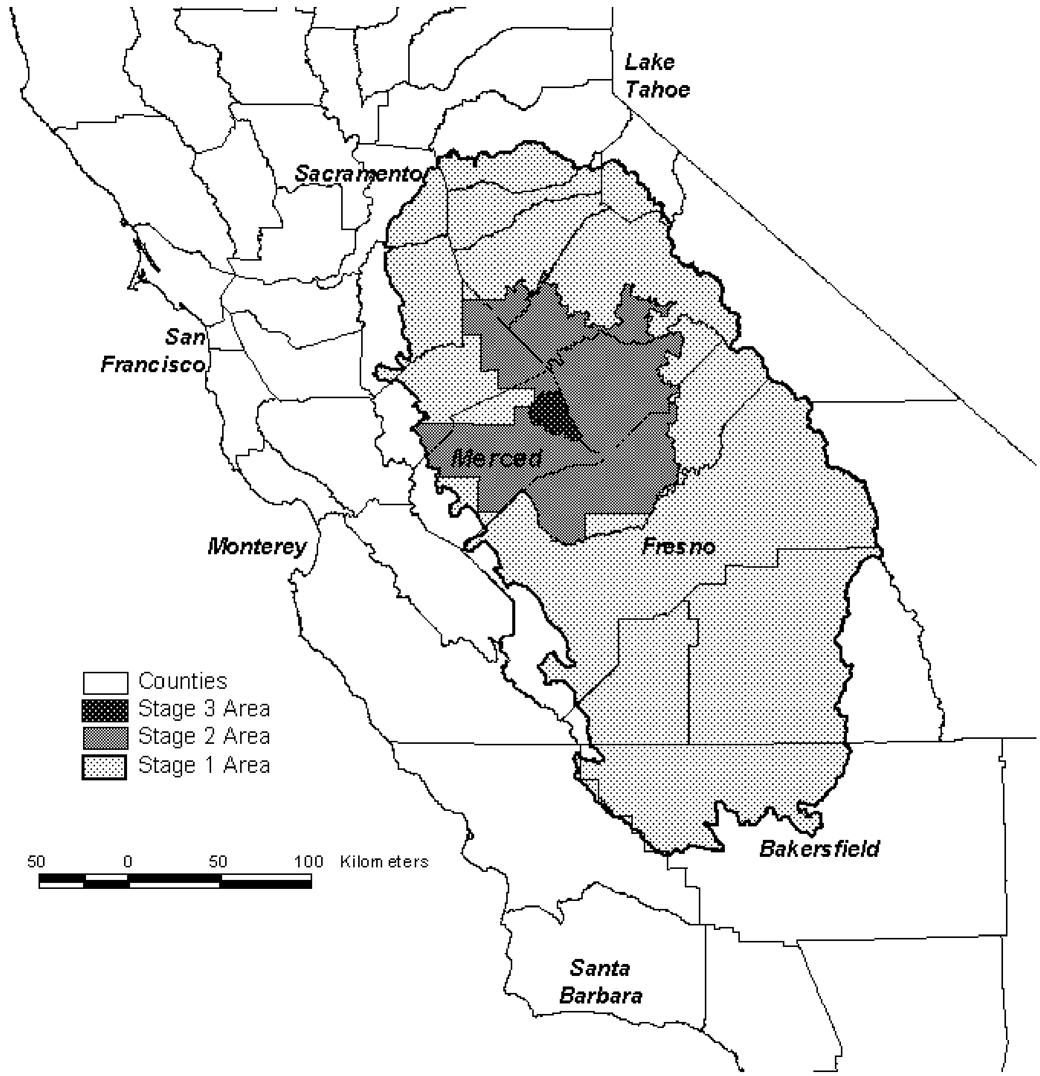


Figure 1. Study area surrounding the proposed UC Merced campus site.

The project had several objectives:

1. To develop a generic top-down decision-support modeling tool, based on the established guidelines, that could be used to rate the suitability of sites in future UC-NRS assessments.

2. To apply the knowledge base to assess the suitability of existing NRS reserves and their contribution to representativeness of California's environmental diversity in the network.

3. To apply the knowledge base to assess the suitability of lands within the San Joaquin Valley and southern Sierra Nevada as potential NRS reserves.

4. To adapt the generic knowledge-base network to assess the suitability for the vernal pool/grassland habitat type that might be represented in the NRS at the Merced campus, using a multistage approach of successively smaller assessment regions with increasing spatial resolution.

5. Apply the model to an assessment region around the proposed Merced campus to identify the most suitable parcels for a vernal pool reserve according to our interpretation of the UC guidelines.

Suitability Assessment

Suitability assessment is a context-dependent concept in which the attributes of a site are compared against the desired attributes of an ideal site for a specific purpose. There is no independent measure of suitability that can be observed directly, and thus no ground truth for validating spatial models. Instead, experts define the most desirable attributes in terms of measurable factors, the optimum values of those factors, and their relative importance weights in a multi-criteria evaluation (Jiang and Eastman 2000). Seldom are there sites that score at the highest level for all factors. Thus some means is developed by which the scores of the individual factors are combined into an overall ranking. The means of determining overall suitability have traditionally involved weighted linear combination (Pereira and Duckstein 1993) or Boolean algebra, in which sites are screened through a series of logical filters (Hall et al. 1992). Geographic information systems serve this multi-criteria evaluation function well, providing the attribute values for each location and both the arithmetic and logical operators for combining attributes (Jiang and Eastman 2000).

These approaches to suitability assessment can be problematic (see review in (Jiang and Eastman 2000). Relations in weighted linear combination approaches may not be truly linear, such as where a limit is approached asymptotically or with a step function. In Boolean methods, it is possible that no sites pass all the evaluation criteria. Sites may be eliminated from consideration on the basis of even one poor rating, or even one in which the factor score barely is outside the acceptable range. At the least, Boolean approaches may make it difficult to visualize the interaction of criteria in assessing sites and to modify the procedure in response to preliminary results (Ray et al. 1998). Fuzzy logic has been effectively applied as an alternative to Boolean logic, weighted linear combination, maximum limitation, and other methods of suitability assessment in a number of recent applications (Liang and Wang 1991, Hall et al. 1992, Davidson et al. 1994, Van Ranst et al. 1996, Charnpratheep et al. 1997, Ray et al. 1998). Rather than the crisp set approach of Boolean methods, fuzzy methods apply a measure of the degree of membership in a fuzzy set, such that a factor can be partly true. Furthermore, fuzzy set theory contains a well formulated group of mathematical set operations, such as AND and OR, for combining factors in a multi-criteria evaluation (Reynolds et al. 2000). Expert knowledge is still required to represent the logic of suitability assessment in a given domain, but the formal logic representation makes the process explicit and transparent to stakeholders.

As pointed out by (Colwell et al. 1999), both crisp and fuzzy knowledge bases have their problems, notably that they focus on single assertions rather than evaluating alternative choices and can become cumbersome if the rules set grow too large. However, their flexibility makes them attractive for siting analyses involving disparate quantitative and qualitative criteria, as is the case here. Most applications of fuzzy suitability assessment to date have been for crop or forest production (Davidson et al. 1994, Van Ranst et al. 1996, Kollias and Kalivas 1998, Ray et al. 1998) or facility siting (Charnpratheep et al. 1997). (Bourgeron et al. 2000) developed a fuzzy knowledge base to assess land suitability for conservation reserves. Our analysis is similar to theirs as an exercise in conservation planning, however in addition to biodiversity conservation goals we are also concerned with academic and administrative goals that are associated with scientific research reserves.

Knowledge-base of Assessment Criteria

The University of California's Natural Reserve System (NRS) employs a set of guidelines for evaluating and selecting new reserves (See Appendix, (University of California 1984). These guidelines are organized hierarchically. The topmost level is organized in three categories of criteria—scientific, academic, and administrative suitability. Scientific criteria refer to the biological significance of the site as well as the integrity ("viability") of its ecosystems. Academic criteria include the number of disciplines that could use the site for teaching or research and the accessibility to the campus for those purposes. The third category deals with administrative criteria of filling "gaps" in representation of California's natural ecosystems and the costs and manageability of the site. All these criteria are only general guidelines, however, and do not specify variables with threshold values as minimum (or maximum) acceptable levels. It is left to each assessment committee to determine how the guidelines will be interpreted, whether with precisely measured variables or with a qualitative estimate of condition.

The selection criteria have several characteristics worth noting. First, they are organized hierarchically. The overall measure of the suitability of a site as a new reserve is based on three logical antecedents of the scientific, academic, and administrative criteria. More specific antecedents similarly define each of these criteria. Second, many of the criteria are semantically imprecise, such as "*close* to a campus" and "include *typical* samples of *widely distributed* habitat types" [italics added]. Such criteria are poorly represented by crisp threshold values. For example, it would be illogical to consider sites 24.9 kilometers from campus as suitable but those 25.0 kilometers as unsuitable.

These characteristics suggested the use of a fuzzy, knowledge-based approach in which the decision rules are formulated as a series of propositions (Reynolds et al. 2000). The propositions are evaluated not as "true" or "false" in a Boolean fashion (e.g., distance from campus = 25 km from campus) but as continuous truth values in which distance from campus is mapped into membership values in the set "close to campus." The result is a map of truth-values for every proposition in the network, including the overall proposition that "the site has high suitability for an NRS reserve." Formulating the problem in a knowledge base both formalizes the set of criteria and the linkages to actual data, and provides insights about what factors are critical in determining the truth-value for a site. The knowledge base also provides a flexible decision-support environment in which the analyst can manipulate the criteria and their weightings.

The task of assessing the suitability of sites as potential new UC reserves was undertaken using the Ecosystem Management Decision Support (EMDS) system from the U. S. Forest Service (Reynolds et al. 2000). EMDS consists of three components: a knowledge base development tool (Netweaver), a GIS application framework, and an assessment system. Netweaver allows developers to encapsulate knowledge about the system of interest, in this case the characteristics of a good research and teaching reserve according to the UC guidelines. It allows the analyst to build the hierarchy of networks of propositions using graphical tools. The assessment system enables the end-user to evaluate the knowledge base for a specific spatial database and to display and interact with the results in the GIS environment. Truth-values in EMDS range from -1.0 (completely false) to +1.0 (completely true) with the degree of partial truth in between. In contrast, Boolean logic only allows completely true or false values. EMDS also allows analysts to assess individual portions of the logic network, for instance to determine which subordinate or antecedent conditions caused a site to receive a low overall suitability score.

The NRS guidelines were interpreted into a logic network (Figure 2), starting with the three primary criteria of scientific, academic, and administrative suitability. To be rated as highly suitable as a potential reserve, an assessment unit must score reasonably high in all of the scientific, academic, and administrative suitability categories, because the top network uses an AND node. AND nodes are similar to a MINIMUM operator, but in EMDS is based on a complex formula in which the minimum value strongly influences the result. Thus a site that rates poorly in one of these three criteria will receive a low overall truth-value (but not necessarily completely false). The scientific criterion was subsequently represented as a combination of both the viability of ecosystems and the significance of the habitat in a site. Academic suitability was represented by the level of potential academic use and proximity to a campus. Administrative suitability was a product of the ability of an assessment unit to fill representation gaps, to add balance to the NRS network, and have favorable acquisition terms. Because the guidelines do not identify quantitative variables to use for evaluation (data links in EMDS terminology), this general logic network was adapted for each of the three stages used in the UC-Merced case study.

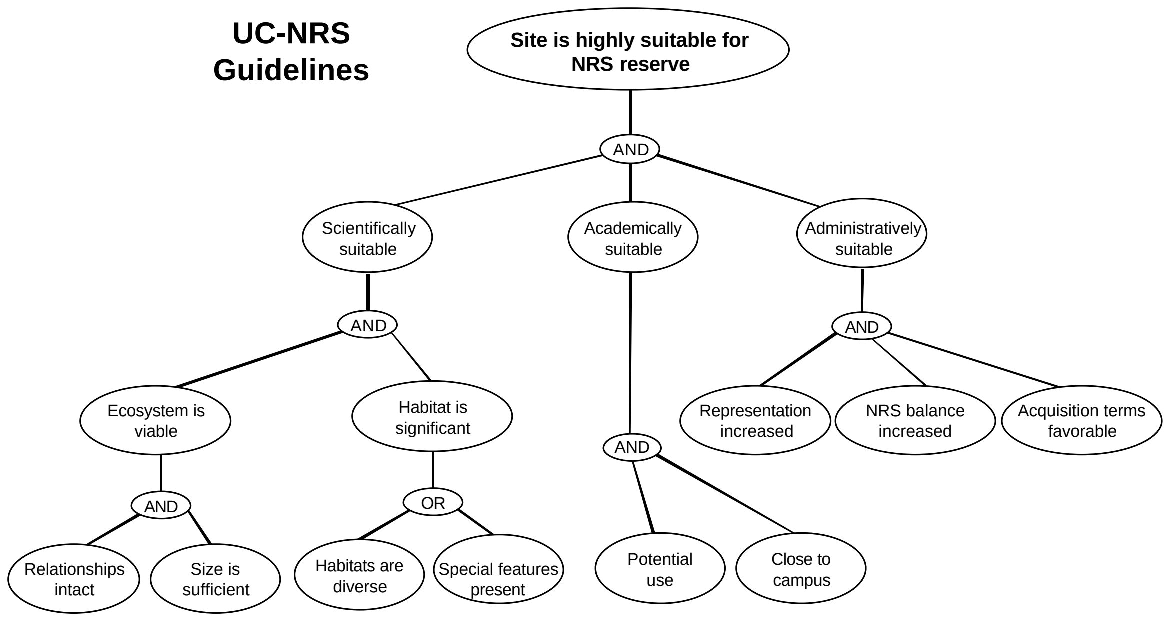


Figure 2. The UC-NRS guidelines represented as a knowledge-based network of propositions. The overall proposition asserts that the "site highly suitable for an NRS reserve." It consists of three sub-networks, joined by an "AND" node, which evaluates the degree to which the assessment unit is scientifically, academically, ***AND*** *administratively suitable.*

Assessment of Representativeness of Existing NRS Reserves

One of the overarching aims of the NRS program is to provide representation of California's environmental diversity. Representativeness is important for providing comprehensive opportunities for teaching and research. In addition, it is more efficient to design a network of reserves that is representative so that research results are relevant over the greatest spatial extent (Burke and Laurenroth 1993). Because the concept of representativeness is so fundamental yet so imprecise, we focus in this section in greater detail how this criterion of administrative suitability was measured for our assessment of suitability of sites for NRS designation.

Measuring representativeness of a set of sites is not a trivial problem, however, and many different methods have been proposed. Some researchers have arbitrarily divided the primary environmental gradients into segments and classified the combinations of factors (Engelking et al. 1994, Pressey et al. 1996). Others have used continuous data sets but clustered them into classes using statistical techniques (Mackey et al. 1988, Kirkpatrick and Brown 1994, Belbin 1995). Nominally, the NRS uses an unpublished habitat classification from Cheatham and Haller in 1975 and hopes to have 70% of these types ultimately represented (Ford and Norris 1988). The reserve descriptions on the NRS web site (http://nrs/ucop.edu) and published brochures often (but not always) list the habitat types or plant communities that occur, but we found that the classification of habitats and communities did not appear to be consistent between reserves or with recognized classification systems.

Thus we developed an alternative method of assessing representativeness of the NRS. We prefer to maintain a continuous data space with a measure of environmental distance (Faith and Walker 1996). Thus, the environmental variability of California was characterized by a principal components analysis (PCA) of biophysical data sets, covering climate, topographic, and soil productivity factors. The principal components analysis transformed biophysical data on mean annual precipitation, January and July mean temperature and seasonal difference, solar irradiance, degree-day heat and cool sums, equivalent elevation (elevation adjusted for latitude), and soil productivity into a revised data space that eliminated the correlation between factors. The input data sets were scaled to a common range of 0-255 prior to PCA. Of the nine principal components, the first four accounted for 91% of the variance. The first component primarily contrasted mean January and July temperatures with soil productivity and elevation. Solar irradiance and seasonal temperature difference versus soil productivity mostly determined the second component. Soil productivity, degree-day heat sum, and seasonal temperature difference contrasted with annual precipitation in the third component. The fourth component contrasted degree-day heat and cool sums. Finding the multivariate Euclidean distance of each 1 km grid cell in California from its nearest site represented by the NRS provides a quantitative measure for locations with environments that are not well-represented by the existing set of NRS reserves.

The measure of representativeness is directly related to the representation of California's diversity by the existing reserves. It was necessary to calculate environmental distance of every assessment unit in the region from each existing reserve. We also generated a measure of representativeness contributed by each existing reserve, by assessing its environmental distance from all other reserves.

As the assessment of representativeness and suitability for the Stage 1 UC-Merced assessment region used small watersheds or townships as assessment units, we also used the watershed or township that contains the reserve as units for this assessment. The reserve locations are shown in Figure 3. The island reserves (Santa Cruz and Ano Nuevo) were not included in our assessment because the database only covered the mainland.

#	Name
1	Stunt Ranch Santa Monica Mountains Reserve
2	Landels-Hill Big Creek Reserve
3	Angelo Coast Range Reserve
4	Hans Jenny Pygmy Forest Reserve
5	Chickering American River Reserve
6	Bodega Marine Reserve
8	Hastings Natural History Reservation
9	Stebbins Cold Canyon Reserve
10	Burns Pinon Ridge Reserve
11	San Joaquin Freshwater Marsh Reserve
12	Box Springs Reserve
13	Motte Rimrock Reserve
14	Dawson Los Manos Canyon Reserve
15	Elliot Chaparral Reserve
16	Kendall-Frost Mission Bay Marsh Reserve
17	Scripps Coastal Reserve
18	Sierra Nevada Aquatic Research Laboratory
19	Valentine Camp
20	Sedgwick Reserve
21	Coal Oil Point
22	Carpinteria Salt Marsh Reserve
23	James San Jacinto Mountain Reserve
24	Emerson Oaks Reserve
25	Boyd Deep Canyon Desert Research Center
26	Sweeney Granite Mountains Desert Research Center
27	Sacramento Mountains Reserve
28	Fort Ord Natural Reserve
29	Younger Lagoon Reserve
30	McLaughlin Reserve
31	Jepson Prairie Reserve
32	Eagle Lake Field Station
33	Quail Ridge Reserve

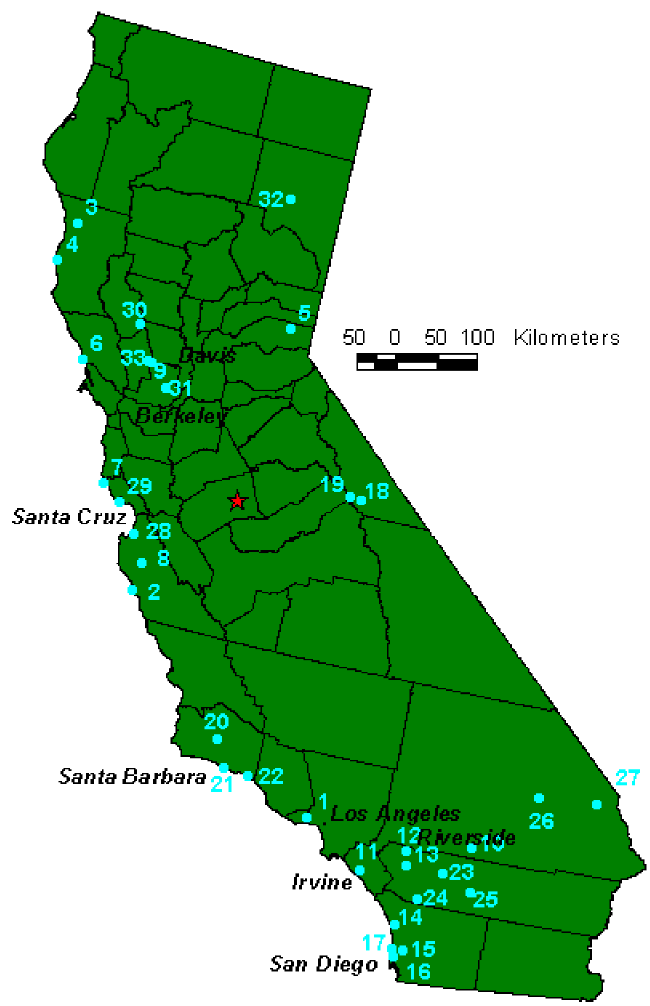


Figure 3. Map of existing NRS reserves (cyan numbers) and UC campuses (names in black).

The Euclidean distance (in the first four dimensions of the PCA data space) for each pixel was calculated from every NRS reserve. The value for each assessment unit to the nearest NRS site (excluding itself) in the PCA space was calculated by finding the mean value of the pixels in the assessment unit.

We also assessed representation by calculating the proportion of the NRS network by two stratifications of environmental variation. The first stratification was by the ten ecoregions defined by topography, climate, and general vegetation types (Hickman 1993). The second classified a digital elevation model into seven zones at 500-meter intervals. Proportions of the area of the NRS network for each category were calculated and compared to the comparable proportion of the state of California to indicate the degree of bias in representation.

Our analysis of the representativeness of the NRS network found that the current reserves tend to cluster together in biophysical properties (Figure 4). There is one cluster of reserves representing higher elevation environments near the Sierra Nevada crest (toward upper left quadrant) and a larger cluster (lower right quadrant) containing most of the remaining reserves in near-coastal and desert environments. The upper right quadrant, representing the hottest locations with moderately productive soils, corresponds to much of the Great Central Valley and the lowlands of the desert regions. The two UC NRS reserves in the Mojave Desert just barely represent this quadrant of the plot. In general the deserts have large minimum distances from existing reserves (Figure 5). This appears to be the result of differences in soil productivity between the mountainous locations of the reserves and the more productive desert valleys. The middle of the plot contains a large number of Forest Service Research Natural Areas from the Sierra Nevada (higher on y-axis) and the north Coast Ranges (lower y-axis). UC does not currently have any reserves that represent these bioenvironments (Figure 4). The reserve closest to this bioenvironment is the James Reserve in the San Jacinto Mountains of southern California. As can be seen in Figure 5, there are no NRS reserves in the Stage 1 assessment region.

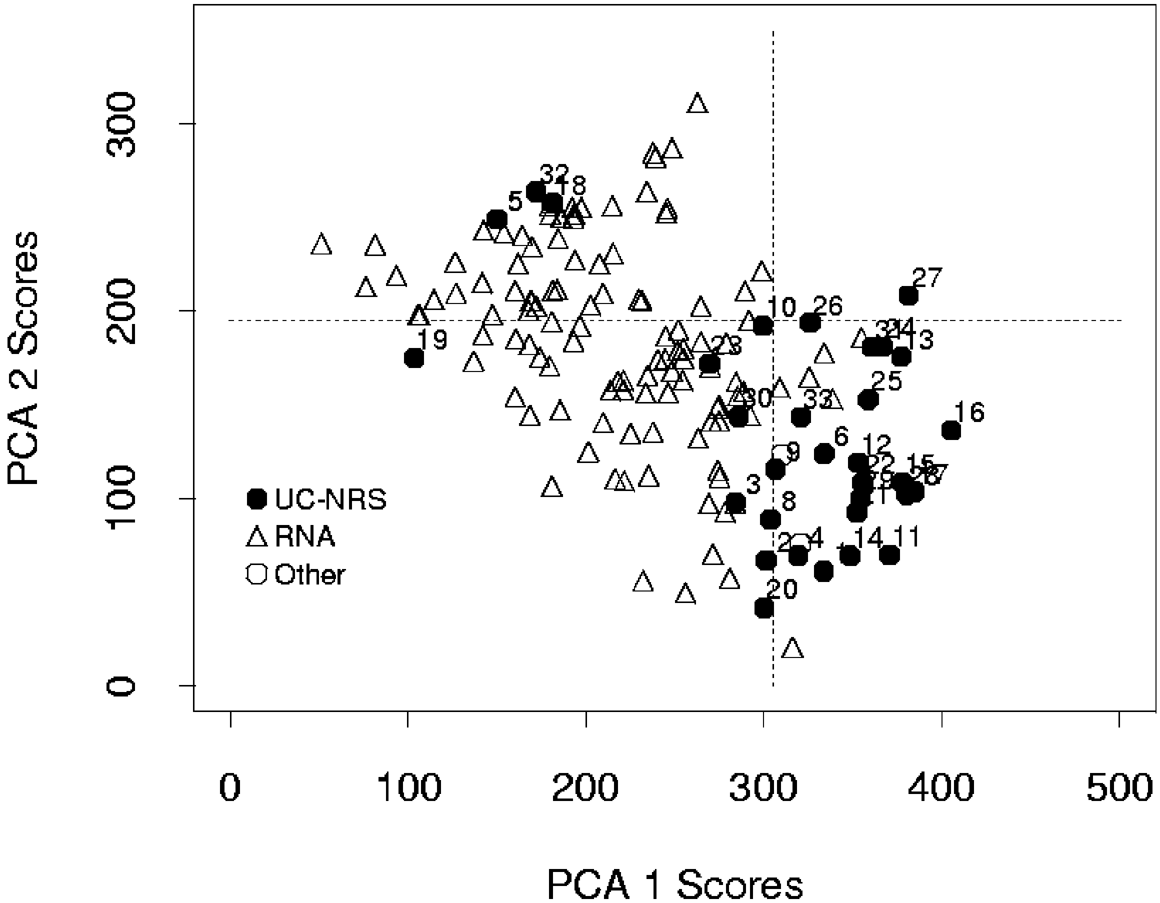


Figure 4. Scatterplot of NRS and other reserves along the first two principal component axes scores. Dashed lines indicate mean values. The upper left quadrant generally corresponds to cool, subalpine or Great Basin environments. The upper right tends to be environments in desert regions. The lower right quadrant contains the near-coastal reserves. The lower left quadrant, containing many of the Forest Service Research Natural Areas represent montane conifer environments.

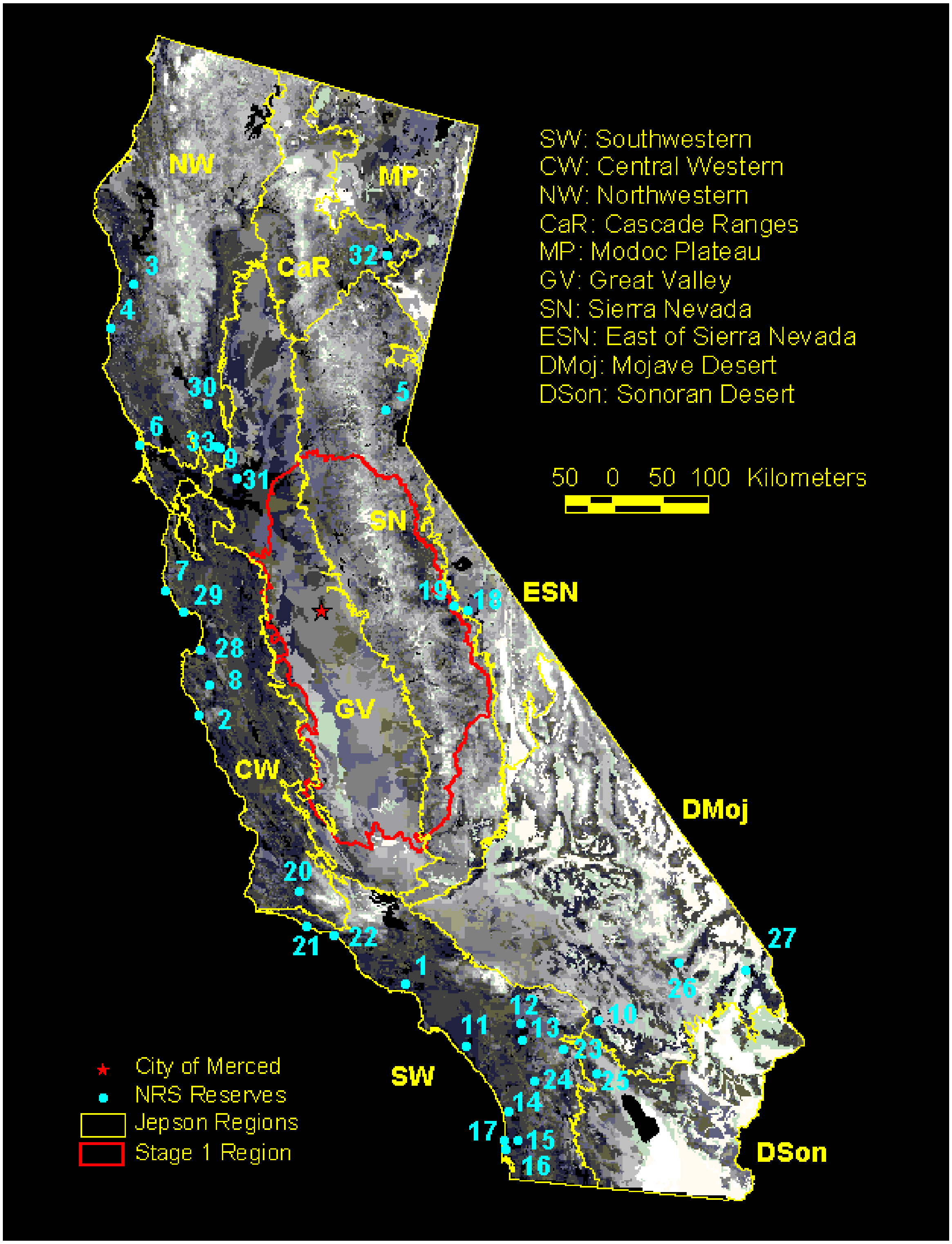


Figure 5. Map of the minimum Euclidean distance from each 1-km grid cell to the nearest NRS site in the dimension principal component space. Lighter shades indicate larger "distances" or environments that are less well represented by the existing NRS network (shown as cyan dots).

The NRS has reserves in nine of the ten ecoregions of California (Figure 6). Only the Modoc Plateau in the sparsely populated northeastern corner of the state has no reserves. The Cascade Ranges ecoregion is represented solely by the Eagle Lake Field Station, and the Great Central Valley's only representative is the Jepson Prairie. In the bar chart in Figure 6, balanced representation would appear if the green NRS bars were virtually identical in height to the cyan bars showing the entire state. The Central Western and Northwestern California regions are over-represented in the sense that they contain a larger share of the reserve system than they do of the state as a whole. The environments least well represented in the previous analysis—the Sierra Nevada, the Northwest, and the deserts—appear to have close to proportional representation of the corresponding ecoregions as a whole.

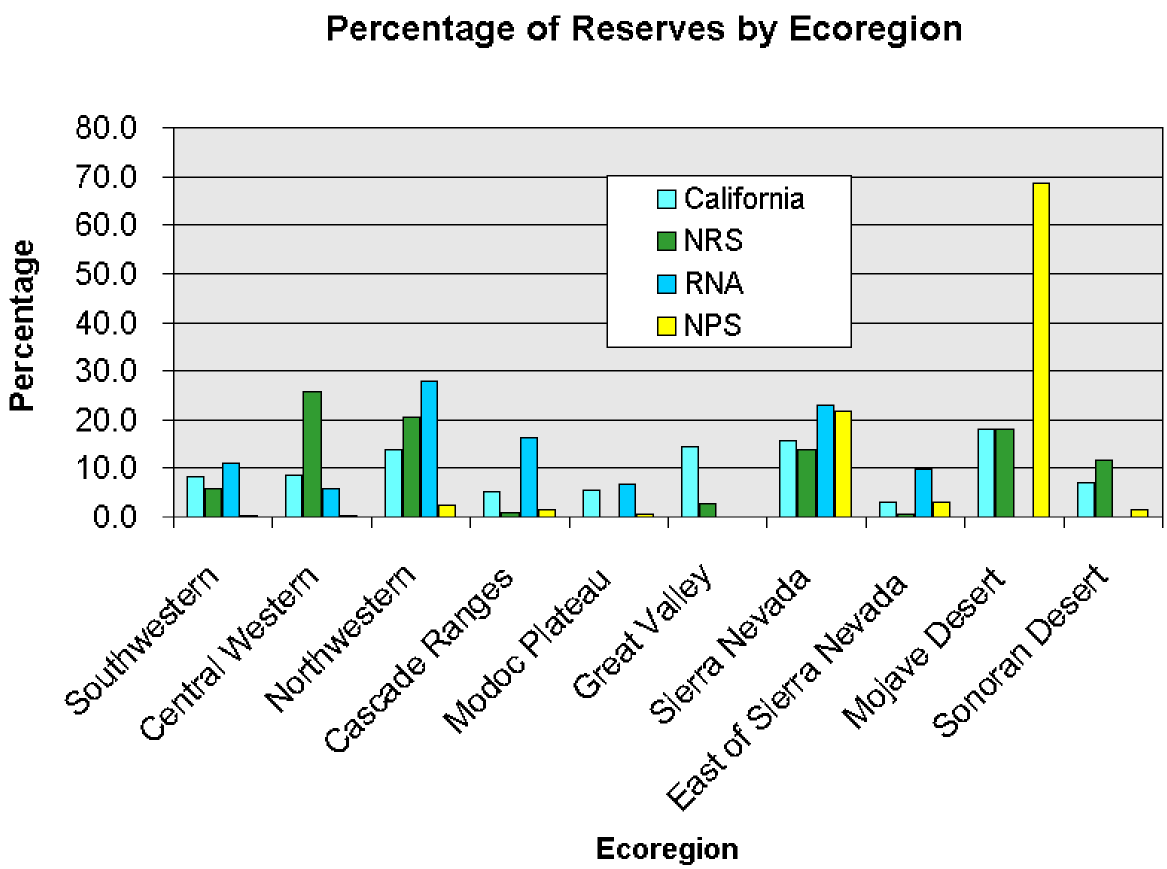


Figure 6. Bar chart of the proportional representation of reserves managed by the NRS, USFS Research Natural Areas, and National Park units in comparison with the state as a whole by the ten ecoregions.

The NRS also has reserves in every elevation zone of California below 2,500 meters (Figure 7). Over 1/3 of the NRS area is in reserves in the lowest elevation zone. Below 2,000 meters, the proportion of area in NRS reserves very closely matches the proportion of the state as a whole. In the 2,000-2,500 meter zone, the NRS actually has a higher proportion. While the NRS has no reserves at the highest elevations, these zones constitute a relatively small proportion of the state and are well represented by research natural areas and national park units.

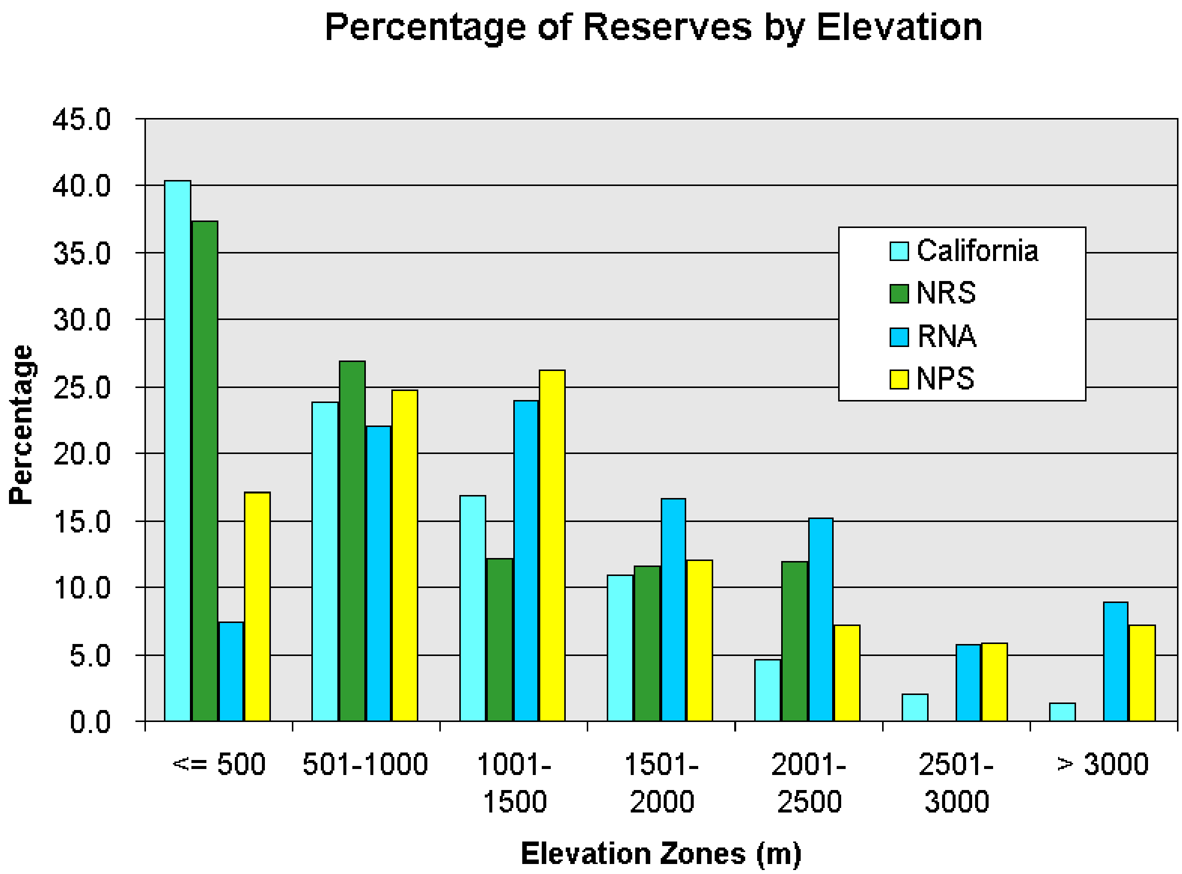


Figure 7. Bar chart of the proportional representation of reserves managed by the NRS, USFS Research Natural Areas, and National Park units in comparison with the state as a whole by elevation zones.

From this assessment of representativeness, we conclude that some regions of the state, particularly the south and central coast near UC campuses, are relatively well represented. Regions that are less well-represented by the NRS include subalpine environments, some desert environments, the mid-elevation conifer zone in the Sierra and northern ranges, the Central Valley, and the Modoc Plateau. In the context of habitats that might best be represented by new reserves for the UC-Merced campus, we delineated an assessment region for Stage 1 that included most of the San Joaquin Valley and the westside of the central and southern Sierra Nevada (Figure 1).

Assessment of Suitability of Existing NRS Reserves

Before assessing suitability of sites for potential NRS reserves at the UC-Merced campus, we tested the knowledge base on the network of existing reserves. This allowed us to do two things. First, it gave an indication of how well existing reserves meet the selection criteria (as interpreted and assessed in our model) and second, how the values for potential sites in the UC-Merced Stage 1 area compare to sites previously identified as highly suitable by less formal means. In other words, it provides a calibration of truth-values that are not in any verifiable units.

As a first step, the general knowledge base (Figure 2) was adapted to the set of spatial data that were available statewide for reserves and the entire Stage 1 assessment region. The guidelines were not specific about how to measure ecosystem integrity or habitat significance. In view of the types of data available, we selected two sources for each criterion. Integrity was characterized by a measure of the area affected by roads (Stoms 2000) and the area of undeveloped habitat in an assessment unit. Significance was a combination of number of plant community types and number of rare elements. Academic suitability was limited to a single criterion based on travel time from the new campus, because the level of current and potential use could not be determined for the Stage 1 area. Administrative suitability was a product of the ability of an assessment unit to fill representation gaps and to add balance to the NRS network. The representation subnetwork was defined as either being distinct from the environments represented by the other NRS reserves (as described above) or filling gaps from other programs or agencies (in this case from the California Gap Analysis Project; (Davis et al. 1998). The full logic network and terminal data nodes are listed in Table 1 and represented graphically in Figure 8. These terminal nodes, called data links in EMDS, correspond to attribute data of assessment in the GIS database. For this assessment stage we elected to use small "planning watersheds" (mean size of approximately 3,300 ha) as the assessment units (Menning 1997). Where planning watersheds have not been delineated, 6x6 mile townships (approximately 9,400 ha each) from the Public Land Survey were used instead. All spatial information was aggregated to the planning watersheds or the townships. Thus these assessment units are larger than the actual NRS reserves to be comparable to the Stage 1 assessment described below.

Table 1. Outline of knowledge-based network of propositions defining suitability of sites as potential NRS reserves. Final data links are in italics, while propositions are in plain text or bold; data link names are in parentheses. Explanations of the data links are listed in the Table 2.

Site Is Highly Suitable For An NRS Reserve

- **Scientifically suitable**
  - <u>Ecosystems have integrity</u>
    - *Road-effect zone is small (ROAD)*
    - *Native habitat is sufficiently large (SIZE)*
  - <u>Habitat is significant</u>
    - *Number of CNDDB communities (DIVERSE)*
    - *Rare elements are present (RARENUM)*
- **Academically suitable**
  - *Research accessible (TRAVEL)*

Administratively suitable

Representation increased

Fills NRS PCA gaps (NRSMINPCA)

Fills other gaps (VULNCOM)

NRS balance increased

Far from other NRS reserves (NRSDIST)

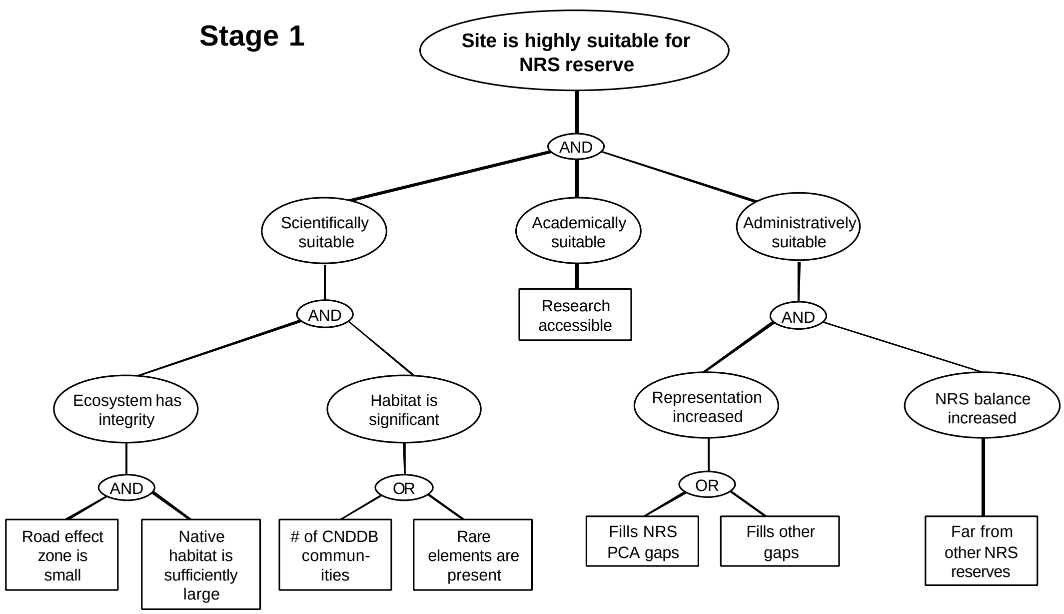


Figure 8. The network for the Stage 1 proposition that the "site highly suitable for an NRS reserve." Networks are shown as ovals and data links are rectangles.

Table 2. Data links in the Stage 1 knowledge base and how they were derived. Variable names correspond to names of propositions in Table 1, and are shown here in alphabetical order.

Variable name (Alias)	Assumption or explanation	Data source	GIS processing steps	Range of values
DIVERSE	Greater diversity makes a site better.	California Gap Analysis Project	Sum number of unique plant community types in each assessment unit	0-17 communities

NRSDIST	Maximizes geographic distribution of reserves	Locations of NRS reserves	EUCDISTANCE to calculate euclidean distance from all reserves; then determine minimum distance to each assessment unit	0-184 km
NRSMINPCA	Greater environmental distance from a reserve means site is less-well represented.	Biophysical factors, various sources	Principal components analysis of 9 biophysical factors, compute multivariate euclidean distance from each NRS reserve, find minimum value for each pixel, average values for each assessment unit	0-123
RARENUM	Site has added value if it also possesses special features such as rare or endangered species/habitats.	California Natural Diversity Data Base, California Fish and Game	Sum number of unique elements in each assessment unit from 1992 version of California Natural Diversity Data Base	0-11 elements
ROAD	Areas with higher index of roadedness have less ecological integrity.	California Gap Analysis Project using TIGER roads	Buffer roads to width related to their class, summarize percentage of area in assessment units within the "road effect zone" relative to the area of the unit.	0-100%
SIZE	Size should be sufficient so that the natural balance of the community may be maintained with the survival of the plant and animal elements assured.	California Gap Analysis Project	Sum area of native vegetation in each assessment unit	0-9,834 ha
TRAVEL	Maximum travel time allowed is 1 hour, based on 50 km/hr average speed on roads for teaching, and is a continuous function for research needs.	TIGER roads	Travel time estimated from road class in each segment, then a 'cost' distance surface is created in grid. Total time is the minimum travel time to each assessment unit.	0-5.8 hours, assign 20 hrs to units with no road access
VULNCOM	Site gets added value if it also contributes to representation goals of other institutions.	California Gap Analysis Project	Score of assessment unit as weighted by vulnerability and area of all plant community types	0-100

Truth values for the proposition that existing NRS reserves are highly suitable for that purpose range from–1.000 (totally false) to 0.519 (moderately true) with a mean value of -0.087. Within the second level of networks, the maximum values for assessment units were higher. The range for Scientifically suitable was -1.000 to 0.974 (mean 0.223); Academically suitable was -0.119 to +1.000 (mean 0.547); and Administratively suitable was -1.000 to +1.000 (mean -0.109). Thus at least some assessment units scored very high for individual sets of criteria, compared to the lower maximum truth-value for the overall ranking. In fact, even the lowest scoring assessment units tended to score very high in one or two of the three main criteria, but they all had one or two criteria on which they scored very low (Table 3). These reserves would therefore appear to have been selected because they excelled in meeting some criteria while accepting or overlooking their limitations in other respects.

Table 3. Truth-values of the lowest scoring NRS reserves (assessment units) for top-level criteria in ascending order.

	Suitability Truth Values			
Reserve Name	**Overall**	**Scientific**	**Academic**	**Admini-strative**
Scripps Coastal Reserve	-1.000	-1.000	1.000	-1.000
Kendall-Frost Mission Bay Marsh Reserve	-1.000	-1.000	1.000	-0.985

Boyd Deep Canyon Desert Research Center	-0.701	0.582	0.000	-0.780
Quail Ridge Reserve	-0.615	0.416	1.000	-0.741
Stebbins Cold Canyon Reserve	-0.604	0.564	1.000	-0.737

On the other hand, the highest scoring reserves did not necessarily have very high scores for every suitability criterion, but were characterized by the absence of extremely low scores (Table 4). In addition, sites with near-average scores for all three suitability criteria tended to score higher overall than sites with extreme values. No reserves scored very high in all three criteria. Some degree of trade-off between criteria is always present.

Table 4. Truth values of the highest scoring NRS reserves (assessment units) for top-level criteria in descending order.

	Suitability Truth Values			
Reserve Name	**Overall**	**Scientific**	**Academic**	**Admini-strative**
Jepson Prairie Reserve	0.519	0.655	1.000	0.287
Stunt Ranch Santa Monica Mtns Reserve	0.466	0.268	1.000	0.475
McLaughlin Reserve	0.430	0.650	0.353	0.398
Fort Ord Natural Reserve	0.339	0.193	0.886	0.231
Sedgwick Reserve	0.295	0.401	0.966	0.078

For example, compare the truth-values for the highest rated (Jepson Prairie) and the second lowest rated (Kendall-Frost Mission Bay) NRS reserves (Figure 9 and 10). Jepson Prairie rated as partially true in all three subcriteria, which generated a high overall suitability. Kendall-Frost Mission Bay, in contrast, was outstanding in academic suitability, being close to the UC San Diego campus, but rated poorly in the other criteria. The suitability truth values for all NRS reserves are given in Table 5.

We need to be cautious in this interpretation because the logic and data used in our assessment were not identical to those used in selecting these reserves initially. Further, our truth values correspond to the assessment unit containing the reserves, not the specific parcel, which may have special properties not represented in our regional-scale database. The most common criteria that caused the low scores was the fact that reserves were close to one another and therefore did not contribute highly to the ecological and geographic diversity of the state. They also tended to be located in urban areas (with low ecological integrity as measured by roadedness and native habitat area) and as a result had average to poor scientific suitability values. Most assessment units scored moderately high for the Academic suitability criterion, which was based solely on travel time from the sponsoring campus. The key point is that the lowest scoring reserves were not poor in all aspects, but instead were excellent in some aspects and poor in others.

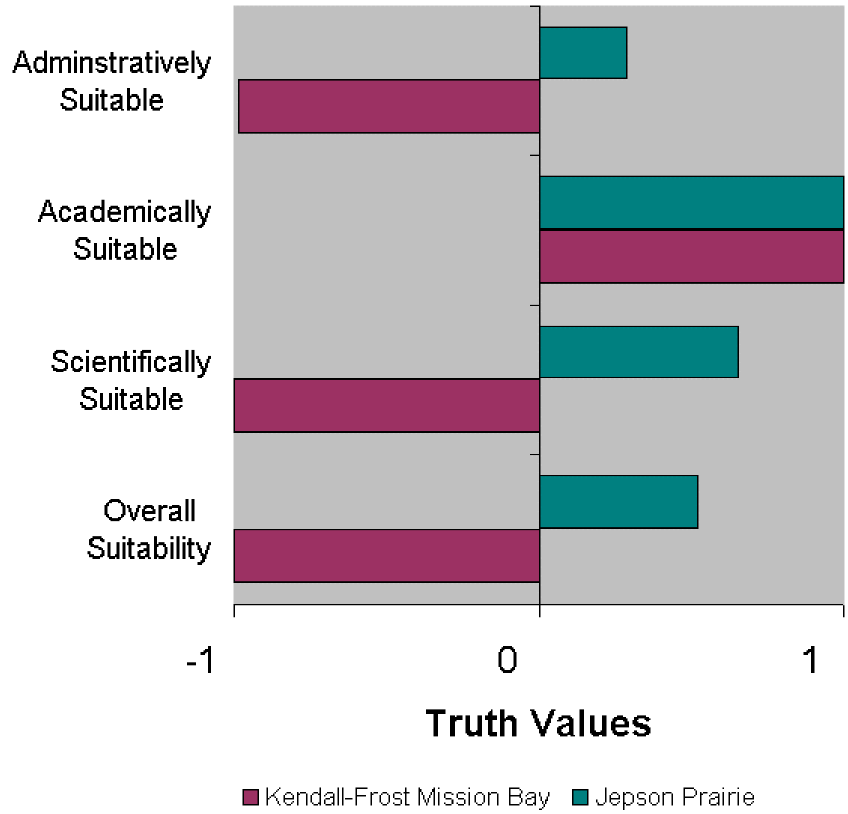


Figure 9. Bar chart of the truth-values for the suitability networks and overall suitability for the highest scoring reserve (Jepson Prairie) and one of the lowest scoring (Kendall-Frost Mission Bay).

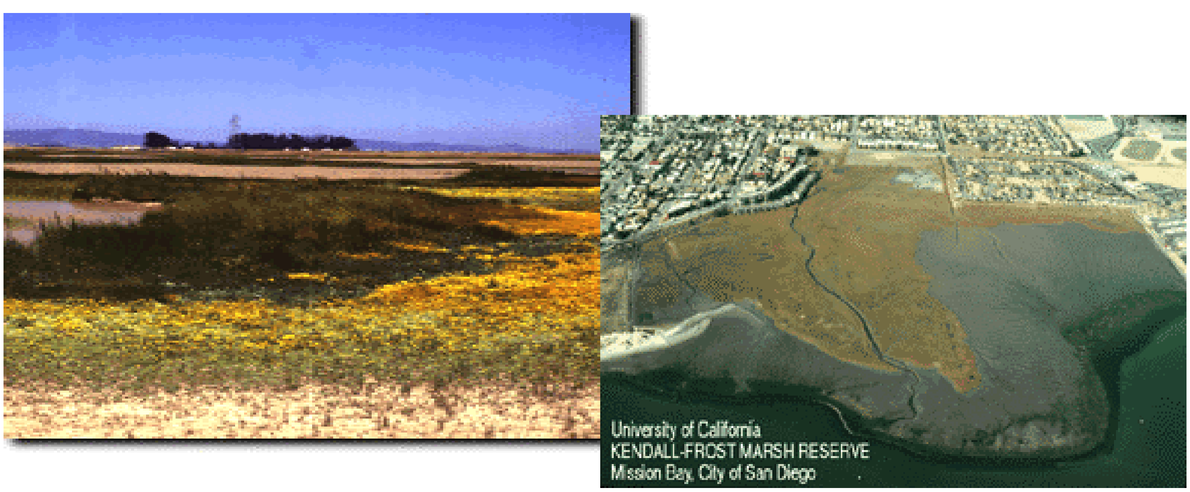


Figure 10. Photos of Jepson Prairie (left) and Kendall-Frost Marsh (right) NRS reserves. Source for photos: http://nrs.ucop.edu)

Table 5. Truth-value of the all NRS reserves (assessment units) for top-level criteria in alphabetical order.

#	Name	Overall suitability	Scientifically suitable	Academically suitable	Administratively suitable
3	Angelo Coast Range Reserve	0.125	0.466	0.000	0.284
6	Bodega Marine Reserve	0.169	0.168	0.000	0.845
12	Box Springs Reserve	0.135	0.083	1.000	-0.053
25	Boyd Deep Canyon Desert Research Center	-0.701	0.582	0.000	-0.780
10	Burns Pinon Ridge Reserve	-0.222	0.056	0.000	-0.298
22	Carpinteria Salt Marsh Reserve	-0.597	-0.349	1.000	-0.700
5	Chickering American River Reserve	0.189	0.974	0.000	0.157
21	Coal Oil Point	-0.437	-0.424	1.000	-0.561
14	Dawson Los Manos Canyon Reserve	-0.100	-0.114	1.000	-0.273
32	Eagle Lake Field Station	0.247	0.482	0.000	1.000
15	Elliot Chaparral Reserve	0.121	0.255	1.000	-0.097
24	Emerson Oaks Reserve	0.015	0.071	0.737	-0.141
28	Fort Ord Natural Reserve	0.339	0.193	0.886	0.231
4	Hans Jenny Pygmy Forest Reserve	0.091	0.176	0.000	0.372
8	Hastings Natural History Reservation	0.109	0.421	0.000	0.233
23	James San Jacinto Mountain Reserve	0.013	0.543	0.755	-0.214
31	Jepson Prairie Reserve	0.519	0.655	1.000	0.287
16	Kendall-Frost Mission Bay Marsh Reserve	-1.000	-1.000	1.000	-0.985
2	Landels-Hill Big Creek Reserve	-0.475	0.922	0.000	-0.613
30	McLaughlin Reserve	0.430	0.650	0.353	0.398
13	Motte Rimrock Reserve	0.015	-0.160	1.000	-0.069
33	Quail Ridge Reserve	-0.615	0.416	1.000	-0.741
27	Sacramento Mountains Reserve	0.081	0.198	0.000	0.290
11	San Joaquin Freshwater Marsh Reserve	0.153	-0.050	1.000	0.183
17	Scripps Coastal Reserve	-1.000	-1.000	1.000	-1.000
20	Sedgwick Reserve	0.295	0.401	0.966	0.078
18	Sierra Nevada Aquatic Research Laboratory	-0.092	0.546	-0.085	-0.207
9	Stebbins Cold Canyon Reserve	-0.604	0.564	1.000	-0.737
1	Stunt Ranch Santa Monica Mountains Reserve	0.466	0.268	1.000	0.475
26	Sweeney Granite Mountains Desert Research Center	-0.570	0.650	0.000	-0.678
19	Valentine Camp	-0.076	0.199	-0.119	-0.124
29	Younger Lagoon Reserve	0.179	0.292	1.000	-0.041
	Average	**-0.087**	**0.223**	**0.547**	**-0.109**
	Minimum	**-1.000**	**-1.000**	**-0.119**	**-1.000**
	Maximum	**0.519**	**0.974**	**1.000**	**1.000**

Assessment in the Stage 1 UC-Merced Assessment Region

The Stage 1 region for assessing suitability was derived from our assessment of representativeness of the existing NRS network. It includes the westside of the central and southern Sierra Nevada ecoregion plus a portion of the San Joaquin Valley surrounding the proposed UC Merced campus. This region contains many environments not well represented by the existing NRS network, does not contain any reserves, and does not overlap with any other UC campuses. The combined areas total over 63,000 km² (Figure 11).

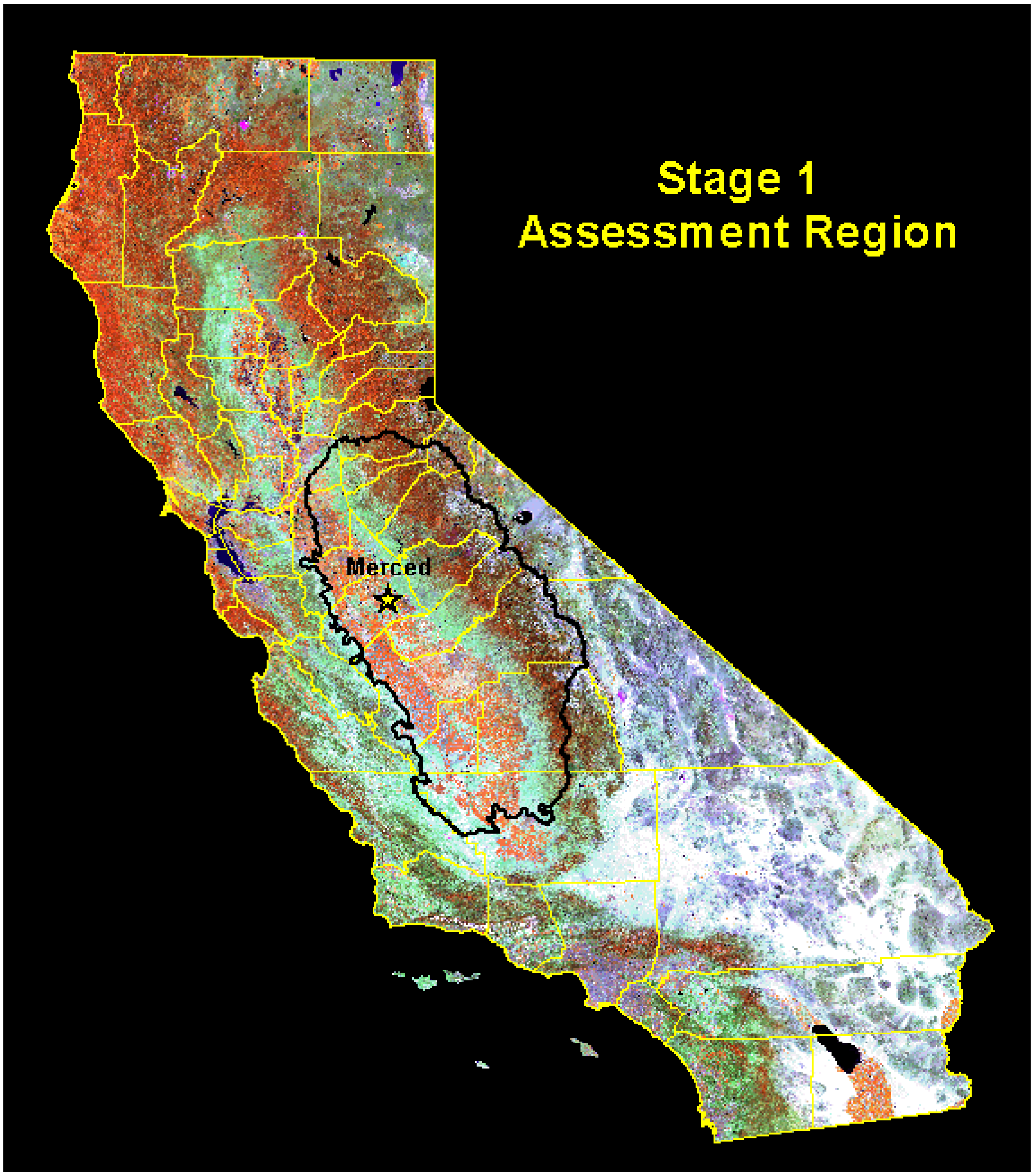


Figure 11. Landsat mosaic image showing Stage 1 assessment region. Counties are shown as yellow lines. The city of Merced is a yellow star.

As this stage screens a large geographical region, the analysis must be at a coarse scale. Finer detail will be used in the second and third stages when more specific sites are being evaluated (Figure 12). For this initial stage, therefore, we elected to use small "planning watersheds" (mean size of approximately 3,300 ha) as the planning units in the Sierra Nevada (Menning 1997). For the San Joaquin Valley, where planning watersheds have not been delineated, 6x6 mile townships (approximately 9,400 ha each) from the Public Land Survey were used instead. All spatial information was aggregated to the planning watersheds or the 468 townships. These assessment units are larger than a typical UC NRS site, but they are compatible with the resolution of the regional data on biological, environmental, and administrative factors (Stoms et al. 1998). Even at this low resolution, this number of assessment units puts a serious computational load on a decision support system.

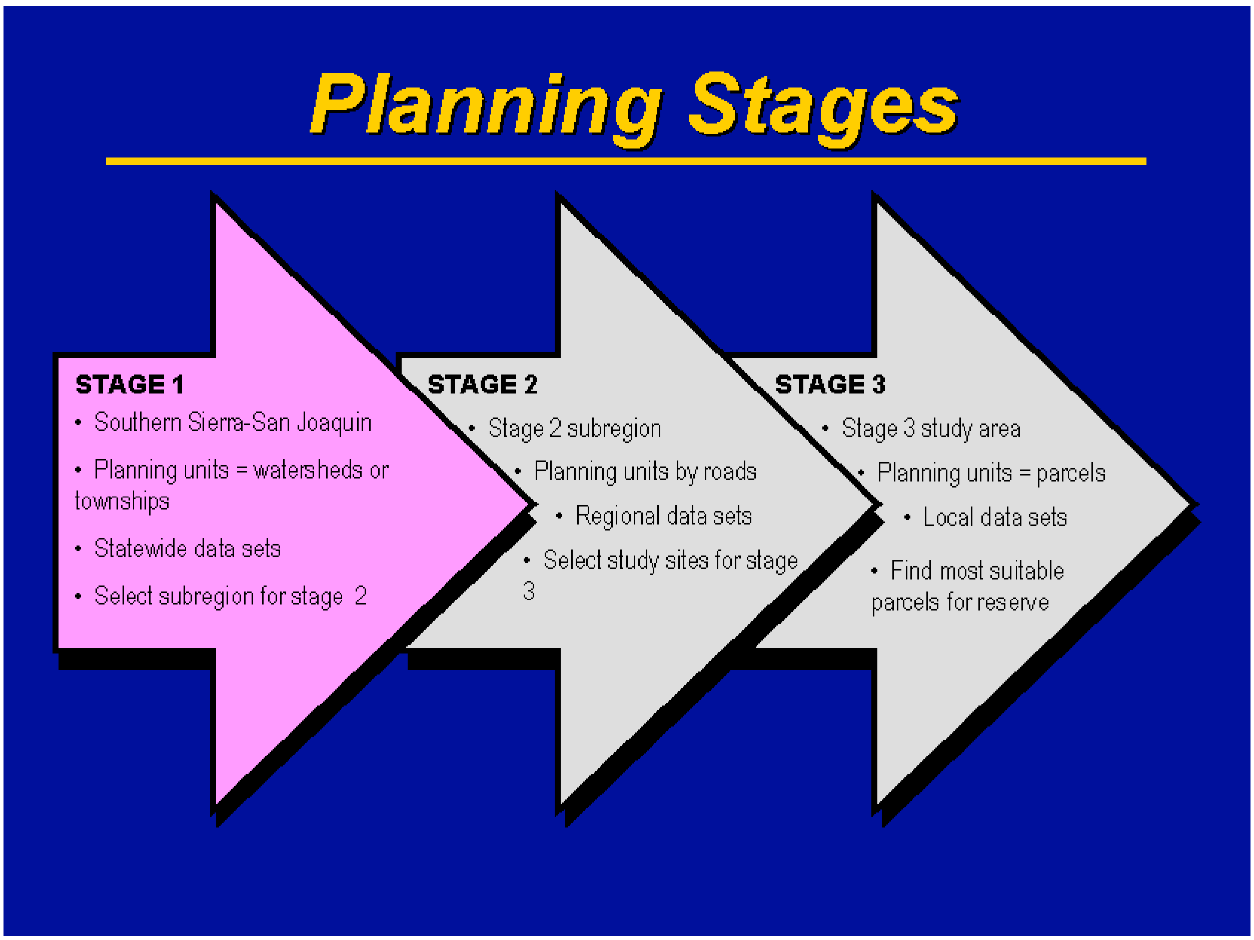


Figure 12. Relationship between Stage 1 and the other two stages of the suitability assessment.

A GIS database was compiled for the data links needed by the knowledge base (Table 1, Figure 8) for each of the approximately 1,400 assessment units. Most of the information to calculate data links for the knowledge-based network came from the California Gap Analysis Project (CA-GAP). The CA-GAP (Davis et al. 1998) was a statewide conservation assessment that mapped land cover, land management and ownership, and other factors. These and additional data were interpreted by various GIS analyses as described in Table 2 to generate the data for assessment units used for the data links at the bottom level of the logic network. Travel time was estimated from the city of Merced rather than one of the existing campuses.

Applying the knowledge-base logic network to the data links from the GIS database generated truth-values for every assessment unit in the study area (Figure 13). No units absolutely met the suitability proposition (i.e., truth-value = +1.000). One unit had a value of 0.815, but the next highest had values between 0.6 and 0.7. Travel time from campus was a very strong constraint on the rankings, such that the highest ranked assessment units fall within a 2-hr driving distance. Within that radius, there are some units that score above 0.6 because they meet some other combination of criteria. Beyond that circle around the campus, most assessment units in the Sierra Nevada and at the southwestern corner of the study area scored with low positive values. Most units in the agricultural Central Valley had negative scores as a result of a combination of ecosystem integrity and representation criteria. Assessment units in the highest elevation zone of the Sierra Nevada scored very high on ecosystem integrity but low for travel time (many units are not accessible by road) and representativeness. The latter criterion was low for these alpine sites because they are already well represented in existing managed areas and in the NRS. So again we see where sites meet part of the criteria exceptionally well but fail on one of the others.

The range of suitability truth-values for the Merced assessment region is very similar compared to the range for the existing reserves (Table 6). The mean suitability score for the existing reserves is slightly higher than the mean suitability of all assessment units in the assessment region. That is, existing NRS reserves are on average more suitable than the average assessment unit in our assessment region. Existing reserves do slightly better on scientific criteria, on average, than the assessment region, but relatively worse for administrative criteria. The scientific results can be explained by the large number of assessment units that are highly impacted by urban and agricultural land uses in the assessment region. This administrative result appears to be related to the distinctiveness of the study area, in both ecological and geographical distance, from existing reserves. By these measures of similarity, the existing reserves tend to be relatively redundant among themselves while the assessment region tends to be dissimilar to the existing network. By the academic suitability criterion, the existing reserves score much higher on average than the assessment region, because existing reserves are generally close to their sponsoring campus. Most of the assessment units for the Merced campus reserve siting project lie beyond a 2-hr travel time and therefore have low truth values for academic suitability. These results indicate that there are some assessment units in the Stage 1 assessment region that are comparably suitable to existing NRS reserves as defined by the logic network based on the NRS guidelines.

Table 6. Truth-values of the assessment units in the study area for top-level criteria.

	Suitability Truth Values			
	Overall	**Scientific**	**Academic**	**Administrative**
Minimum	-1.000	-1.000	-1.000	-1.000
Maximum	0.815	1.000	1.000	1.000
Mean	-0.197	0.163	-0.004	0.217
Mean for existing reserves	-0.087	0.223	0.547	-0.109

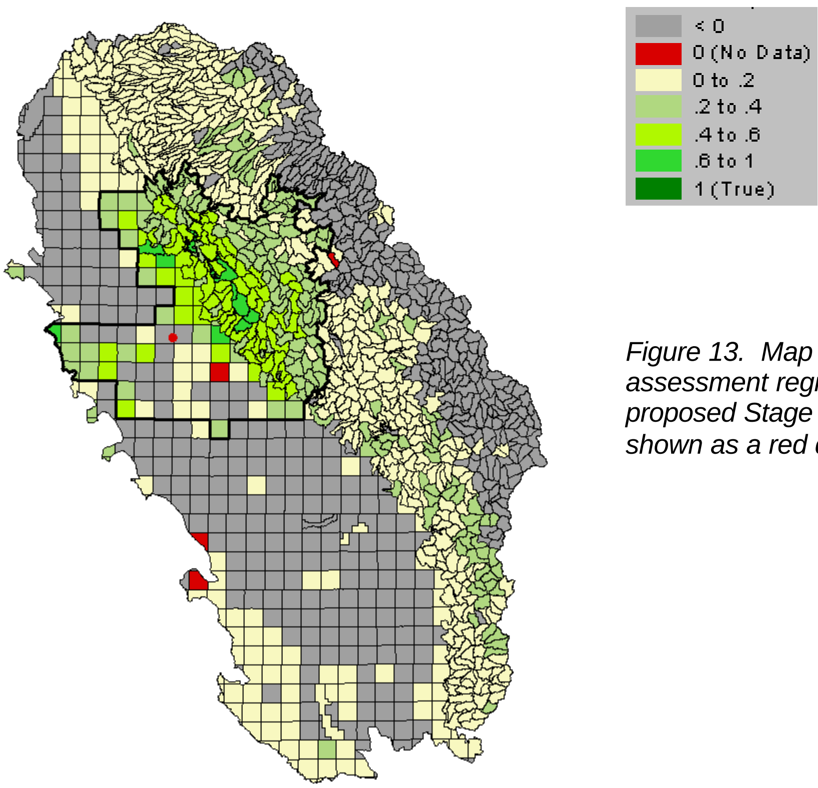


Figure 13. Map of suitability in the Stage 1 assessment region with the outline (bold) of the proposed Stage 2 region. The city of Merced is shown as a red dot.

The Stage 1 suitability assessment ranked large assessment units in a large study region based on moderate-resolution data that were available for the entire region. This represents only an initial screening of sites to focus a more-detailed (Stage 2) assessment. Stage 2 will examine more specific criteria that were unavailable regionally, using the same general structure of our knowledge-based approach.

The suitability assessment identified a distinct region in the Sierra Nevada with a roughly circular outline where ratings of assessment units were consistently greater than 0.2, and mostly greater than 0.4 (Figure 13). There is also a small cluster of assessment units with similar scores west of Merced near the wetland areas of the San Joaquin Valley. We limited the Stage 2 assessment to an area that encompasses these two clusters of assessment units.

The Stage 2 assessment region will be approximately bounded by Highway 41 on the east, Highway 120 across the northeast, Highway 4 on the north for the Sierra Nevada group, and Interstate 5 on the west for the Central Valley group. Boundaries were adjusted where appropriate to accommodate ancillary information. This Stage 2 region spans a large environmental gradient (Figure 14) including wetlands in the San Joaquin Valley, foothill oak woodlands and mid-elevation conifer forest up to the boundary of Yosemite National Park (Figure 15). Most of the valley floor is privately owned, with lands managed by various federal agencies in the Sierra Nevada (Figure 16). There are several sites currently managed for conservation or research purposes within the Stage 2 assessment region that could be considered for NRS use or to complement an NRS reserve without additional university management (Figure 17 and Table 7). In fact, we view this as an opportunity to establish a series of reserves along an ecological transect over several thousand meters of elevation range, which could be especially valuable to support global change studies (Zhang et al. 1997). The Stage 2 assessment region includes portions of Tuolumne, Stanislaus, Merced, Mariposa, and Madera counties. The goal of the second stage will be to narrow the selection of potential NRS reserves to identify a small number of specific parcels for further evaluation.

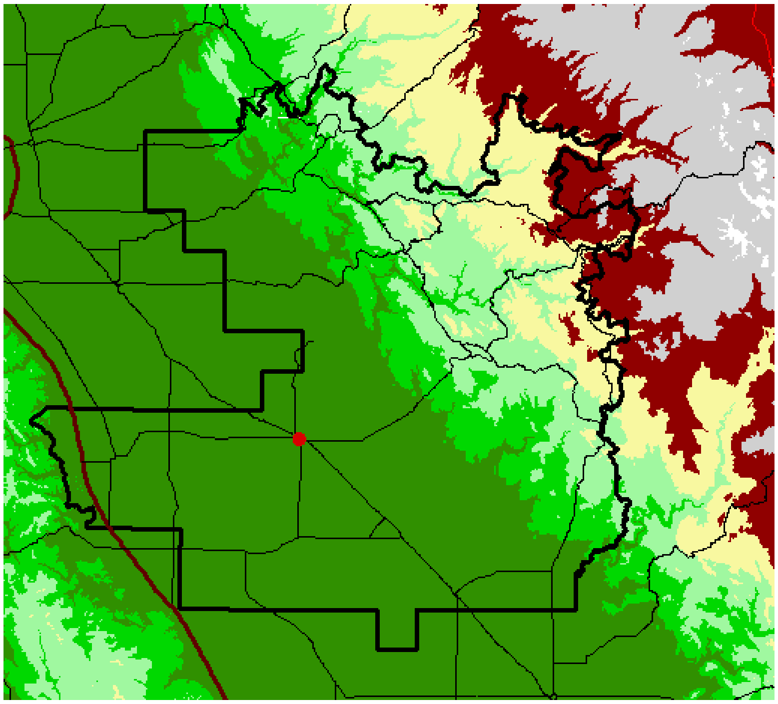


Figure 14. Map of Stage 2 assessment region showing elevation zones in meters. The city of Merced is shown as a red dot.

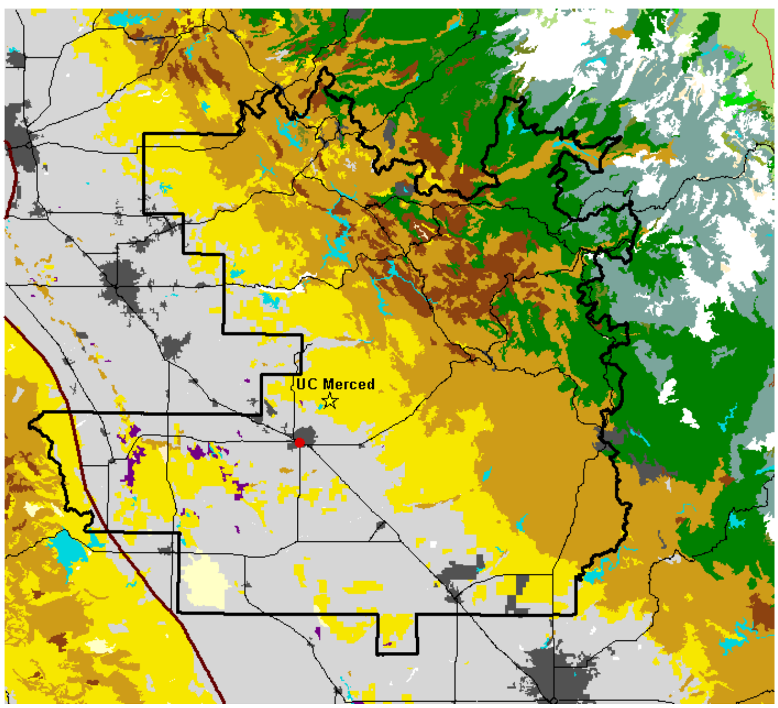


Figure 15. Map of Stage 2 assessment region showing patterns of major habitat types. The city of Merced is shown as a red dot.

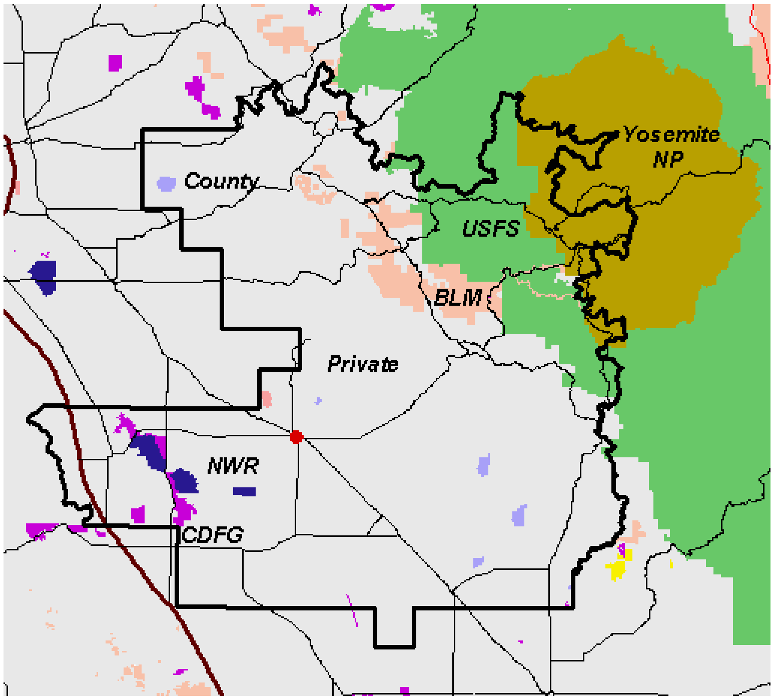


Figure 16. Map of Stage 2 assessment region showing patterns of land ownership. The city of Merced is shown as a red dot.

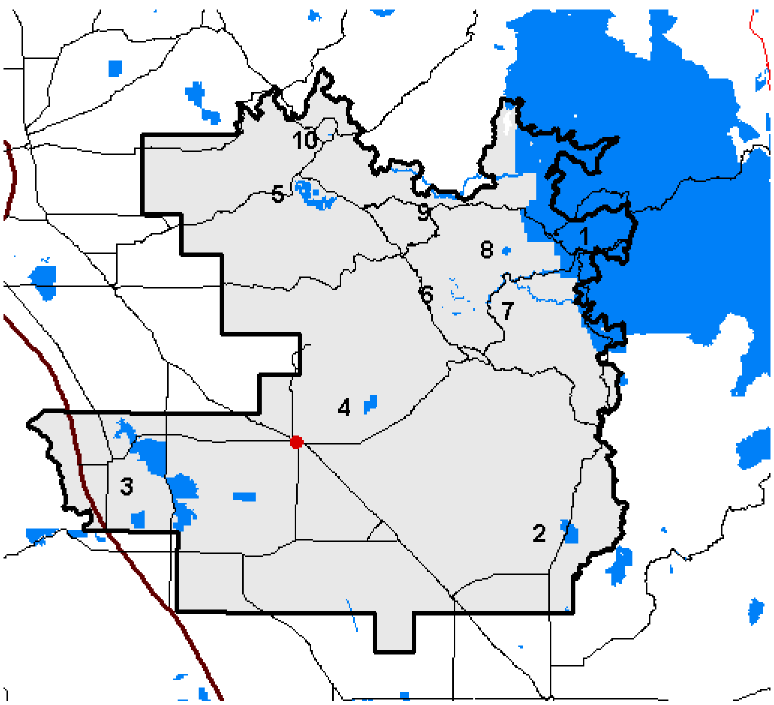


Figure 17. Map of Stage 2 assessment region showing existing nature reserves (see Table 6). The city of Merced is shown as a red dot.

Table 7. Existing reserves in Stage 2 assessment region.

#	Site Name	Agency
1	Yosemite NP	NPS
2	San Joaquin Exp. Sta.	USFS
3	Various wildlife refuges	FWS/ CDFG
4	Flying M Ranch easement	TNC
5	Red Hills ACEC	BLM
6	Limestone Salamander ACEC	BLM
7	Merced W&S River	USFS
8	Big Grizzly Mountain RNA	USFS
9	Jawbone Ridge RNA	USFS
10	El Dorado Manzanita ACEC	BLM

Assessment in the Stage 2 UC-Merced Assessment Region

For the second stage of assessment for the highest ranking assessment units, we envisioned a more detailed set of criteria within the same logical framework (Figure 18). That is, the higher levels of the logic network would be the same, but the data for characterizing ecosystem integrity and so on will be more specific. In addition, the assessment units for the second stage were smaller in extent, but still larger than individual land tenure parcels, for which we could not obtain adequate digital maps. The suitability of assessment units was performed for the vernal pool/grassland habitat type, whereas in Stage 1, only a generic suitability was considered. This allowed us to consider the best sites for particular habitats to be represented in the NRS. We focused on vernal pool and grassland ecosystems specifically because of their regional ecological significance and their close association with the proposed location for the new campus. Similar assessments could be conducted for Sierran foothill woodlands and Sierran mixed conifer, but have not been performed.

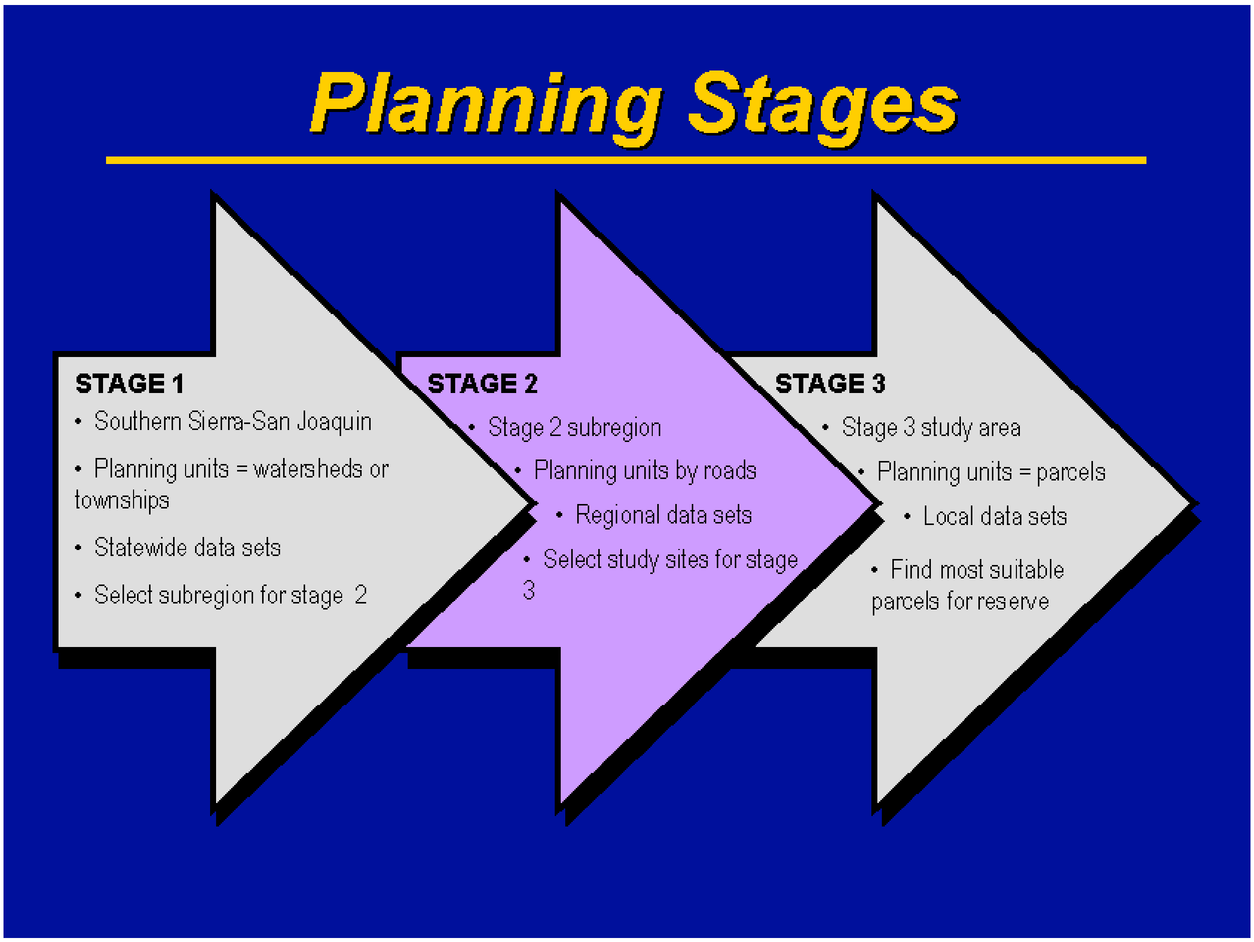


Figure 18. Relationship between Stage 2 and the other two stages of the suitability assessment.

Vernal pools are considered one of the most threatened ecosystems in California, with a significant proportion of their distribution lost to cultivation or urbanization (Jones and Stokes Associates 1987). These seasonal pools form during winter rains in small depressions above an impermeable layer and then dry up in the long summer drought. Vernal pools are associated with many rare and endangered species that have evolved on the unusual soil chemistry and highly fluctuating hydrology (Mead 1996, Holland 2000). Some vernal pool community species also use associated upland habitats for part of their life history requirements (Mead 1996). Large, dense vernal pool complexes are more likely to contain a diversity of pool size, depth, duration of inundation, and therefore support more species than sites with small or less dense complexes (Mead 1996). Vernal pool landscapes also provide opportunities for pedological studies of soil-forming processes and climate history, opportunities that are increasingly rare in these environments due to grading and cultivation (Amundson 1998).

There are many types of vernal pools that are associated with different landforms, geologic formations, and soils [Smith, 1996 #884; Holland, 2000 #888; (Reiner and Swenson 2000). The Merced campus vicinity is underlain by hummocky Pleistocene alluvial terraces with extensive hardpan that supports a Northern hardpan vernal pool community type (Holland 2000). The area is considered the largest region of dense vernal pool habitat in California (Holland 2000). Northern Claypan vernal pool complexes occur on lower alluvial terraces across the Central Valley, west of Merced. The NRS' Jepson Prairie Reserve between San Francisco and Sacramento contains claypan vernal pools, but the type of pool complex near Merced is currently unrepresented in the NRS. The vernal pool/grassland habitat near Merced has also been identified as critical to the recovery of several endangered species (U. S. Fish and Wildlife Service 1998).

In Stage 2 the NRS guidelines were interpreted into a logic network that was similar to Stage 1, starting with the three primary criteria of scientific, academic, and administrative suitability. There were three primary differences in Stage 2. First, because we wanted the ability to evaluate the suitability of potential sites for specific habitat types, we added a fourth network specifically to test the assertion that "vernal pool/grassland habitat is suitable", based on vernal pool quality and density (Holland 1998). In a sense, the "habitat significance" criterion has been detached from the scientific suitability network and promoted to a top-level network that is defined specifically for each habitat type (Figure 15). Second, the smaller size of the assessment region permitted more detailed information to be included in the logic networks. For instance, information about the number of landowners and size of largest parcel was used to estimate the degree of difficulty in acquiring parcels for a new reserve. The assumption behind these criteria was that it would be less desirable to assemble a reserve from many small parcels with different owners. The statewide data from the California Gap Analysis Project that were used in Stage 1 were generally replaced with more detailed maps of land use/land cover. The third change was that not all Stage 1 criteria were continued into Stage 2. The criteria not carried over were those that all assessment units presumably already satisfied, such as environmental distance from existing NRS reserves.

Scientific suitability was characterized by the integrity of the ecosystem in terms of the area affected by roads (Stoms 2000) and land use conversion from photo-interpreted maps of farmland use. We defined academic suitability solely by travel time from the proposed campus site as modeled over the road network. Because of the large size of the assessment region, data on individual parcels were not available. Instead, we interpreted the potential ease of acquisition by the number of landowners and size of largest parcel in a unit. The risk of development as it may impact compatible uses in neighboring units and therefore the ease of management was based on a simple model of future urban growth (Stoms 2000). We also included information on site importance for the San Joaquin Endangered Species Recovery Plan (U. S. Fish and Wildlife Service 1998). The full logic network and terminal data nodes are listed in Table 8 and shown graphically in Figure 19.

Table 8. Outline of Stage 2 knowledge-based network of propositions defining suitability of sites as potential NRS reserves for vernal pool/grasslands. Final data links are in italics, while propositions are in plain text or bold; data link names are in parentheses. Explanations of the data links are listed in the Table 9.

Site Is Highly Suitable For NRS

Vernal Pool Habitat is suitable

Vernal pool density is high (VP DENSITY INDEX calculated from weighted sum of percentage area of three density classes)

Scientifically suitable

Ecosystems have integrity

Road-effect zone is small (ROAD)

Little native habitat has been lost (PCT_CONVERT)

Academically suitable

Accessible for field trips (TRAVEL)

Administratively suitable

Representation increased

Important for San Joaquin Endangered Species Recovery Plan (SJESRP calculated from weighted sum of percentage areas of three plan elements--linkages, continuous zones, and special preserves)

Easy to acquire and manage

Acquisition terms favorable

Few owners involved (NUM_OWNERS)

Large parcel exists (PCT_OWN1)

Easy to maintain/manage

Risk of development is low (THREAT)

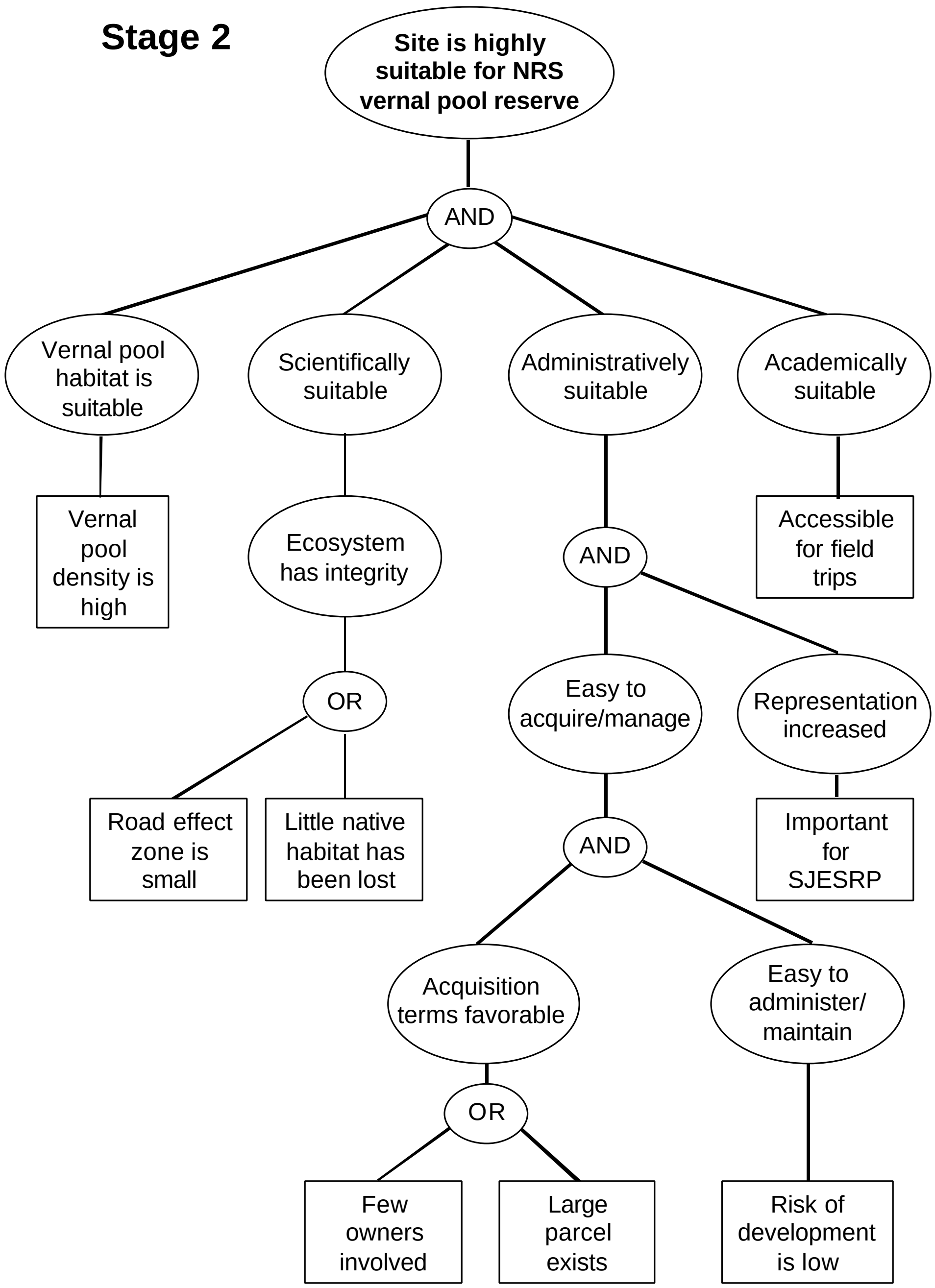


Figure 19. The network for the Stage 2 proposition that the "site highly suitable for an NRS vernal pool reserve." Networks are shown as ovals and data links are rectangles.

Table 9. Data links in the Stage 2 knowledge-base and how they were derived. Variable names correspond to names of propositions in Table 8, and are shown here in alphabetical order.

Variable name (Alias)	Assumption or explanation	Data source	GIS processing steps	Range of values
NUM_OWNERS	Greater number of owners makes assembling parcels into a reserve more difficult; also could be harder to manage a reserve with more neighbors	Echoe-Map Publishing Co.--Property Ownership Maps, Plat Book & Guide for available counties (ca. 1997)	Rough count of unique owners in assessment unit from paper maps and categorize as follows: code # of owners 1 1-5 2 6-10 3 11-25 4 26-50 5 >50 -9 MISSING DATA	1-5, -9
PCT_CONVERT	Less land use conversion in assessment unit means higher integrity	Farmland Mapping and Monitoring Program maps (ftp://ftp.consrv.ca.gov/pub/fmmp/), 1996, where available; else Gap Analysis land cover map	Sum area of D, L, S, U, and P (i.e., urban and farmland) classes, convert to percentage of assessment unit; where unit mapped as "Z", assign -9; where not mapped by FMMP, assign -7	0-100%, or -7.0 -9.0 for missing data
PCT_OWN1	It would be easier to design a reserve from a large parcel than from several smaller ones.	Echoe-Map Publishing Co.--Property Ownership Maps, Plat Book & Guide for available counties (ca. 1997)	Visually estimate proportion of assessment unit owned by largest landowner from paper maps and categorize as follows: code % of unit owned by largest owner 1 <10 2 10-25 3 25-50 4 >50 -9 MISSING DATA	1-4, -9
ROAD	Areas with higher index of roadedness have less ecological integrity.	California Gap Analysis Project using TIGER roads	Buffer roads to width related to their class, summarize percentage of area in assessment units within the "road effect zone" relative to the area of the unit.	0-100%
SJESRP	Beneficial opportunities to achieve representation goals of other programs, such as the San Joaquin Endangered Species Recovery Program	SJESRP plan elements (US Fish and Wildlife Service 1998)	Overlay assessment units on coverage of each plan element--linkages, continuous zones, and special preserves; sum area in assessment unit and convert to percentage of assessment unit; index is weighted sum of these	0-33.3
THREAT	Sites in path of potential urban sprawl more likely to be harder to manage as reserve--pets, lights, noise, fire management, etc.	Gap Analysis map of potential urban growth areas (Stoms 2000)	Overlay map of potential urban growth with assessment units and summarize area as percentage. The campus assessment unit and the adjoining university village unit to the east were outside these growth buffers but were arbitrarily assigned a value of 60%	0-100%
TRAVEL	Less travel time is desirable for teaching/research reserves	TIGER roads, 1995	Assume travel speed for each road class; travel time estimated from road class speed and length in each segment, then a 'cost' distance surface is created in grid. Total time is the minimum travel time to each assessment unit.	0-146 minutes, assign 200 to units with no road access
VP DENSITY INDEX	Greater proportion of unit with high density (i.e., higher index value) of vernal pools is better.	Vernal pools coverage (Holland 1998)	FREQUENCY of area in assessment unit by 3 density classes converted to percentages; index is a weighted sum of these	0-60

The Stage 2 assessment region encompassed over 12,628 km² (Figure 1), or 20% of the Stage 1 assessment region. To allow finer resolution of the Stage 2 assessment, the assessment units were redefined. Although not explicitly stated in the UC guidelines, we assumed that potential reserves should not be bisected by major roads. Thus, most assessment units were delineated as blocks of unroaded area bounded by roads. Where the size of unroaded units was excessively large, they were further subdivided by watershed or township boundaries. All roads from the 1995 TIGER files that were named were selected from all roads. This subset was intersected with the Stage 1 boundaries. Further manual editing of assessment units was required to aggregate units considered too small or unmanageable. Where watershed and road lines were in close proximity, the road was used as a boundary as the more visible feature. Following discussions with Patrick Kelly of the San Joaquin Endangered Species Recovery Program, additional assessment units were added in the southwest corner of Madera County to the San Joaquin River. Although these sites did not score particularly high in Stage 1, they include some relatively undisturbed lands containing habitat for a number of endangered species. This process delineated 623 assessment units, ranging in size from 136 to 12,285 hectares, with a mean size of 2,027 hectares (slightly less than half the size of Stage 1 assessment units). These assessment units are still larger than many UC NRS sites, but they are compatible with the resolution of the regional data on biological, environmental, and administrative factors (Stoms et al. 1998).

A GIS database was compiled for the data links needed by the knowledge-base for each of the 623 assessment units. The information to calculate data links for the knowledge-based network came from photo-interpreted maps of farmland use and vernal pool quality and density (Holland 1998), the 1995 TIGER road files, the San Joaquin Endangered Species Recovery Plan (U. S. Fish and Wildlife Service 1998), and parcel maps (Echoe-Map Publishing Company, ca. 1997 editions where available). These data were interpreted by various GIS analyses as described in Table 9 to generate the data for assessment units used for the data links at the bottom level of the logic network.

Applying the knowledge-base logic network to the data links from the GIS database generates truth values for every assessment unit in the study area (Figure 20). From the map of vernal pool density (Holland 1998), the best areas for Northern Hardpan vernal pools occur along the grassy base of the Sierra Nevada in hummocky, old alluvial terraces. A secondary zone of smaller and less dense Northern Claypan vernal pool complexes occurs on lower alluvial terraces along Sandy Mush Road across the Central Valley and in the wetlands near the various wildlife refuges west of Merced. The large extent of dense vernal pool complexes in these assessment units are more likely to contain a diversity in pool size, depth, duration of inundation, and therefore the number of species than sites with small or less dense complexes (Mead 1996). These same locations also tend to be of importance for the San Joaquin Endangered Species Recovery Plan (U. S. Fish and Wildlife Service 1998). The travel time from campus criterion favored assessment units closer to the proposed campus site, which also contain some of the highest suitability vernal pool sites. The criteria relating to ease of acquisition and management, where such information was available, likewise rated the ranchlands in the vernal pool zone among the highest suitability sites. The overall suitability, therefore, gave the highest truth values (0.601 to 0.924) to a small set of contiguous assessment units surrounding, and including, the proposed campus site. A few additional assessment units had moderately high scores just north or south of the most highly-rated units. In addition, some units along Sandy Mush Road had low to medium suitability but tended to be rated lower because of relatively high levels of agricultural land uses and roadedness and in some cases small parcel sizes. There may be individual parcels within these assessment units that could still offer suitable sites for vernal pool reserves. Assessment units in the Sierra Nevada rated very low to low positive values because of high integrity, despite having few or no vernal pools. Otherwise, assessment units tended to have negative truth values, i.e., were very unsuitable for a new NRS vernal pool habitat reserve.

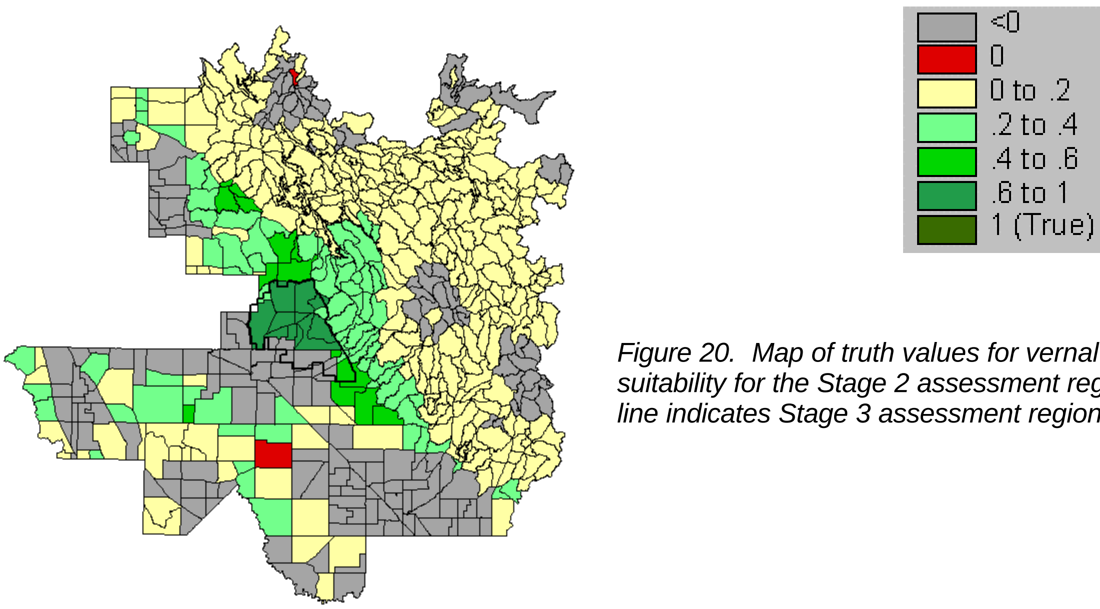


Figure 20. Map of truth values for vernal pool site suitability for the Stage 2 assessment region. Bold line indicates Stage 3 assessment region boundary.

None of the planning units absolutely met the suitability proposition (i.e., truth value = +1.000). The highest scoring assessment unit had a truth value of 0.924 (Table 10). It scored high in all criteria. Other high-scoring sites scored only moderately well on either vernal pool or administrative suitability. Another unit scored moderately high overall because it had moderate suitability in all the individual criteria, but was not outstanding in any of them. One of the best scoring sites under the vernal pool suitability criteria was assigned a negative score solely because it was within the potential urban growth area as modeled by the California Gap Analysis Project. Consequently, it was scored very low for administrative suitability. This is perhaps the least certain criterion, and so this assessment unit should be carried over into the Stage 3 assessment.

Table 10. Truth values of the assessment units in the study area for top-level criteria.

	Suitability Truth Values				
	Overall	**Scientific**	**Academic**	**Admini-strative**	**VP Habitat**
Minimum	-1.000	-0.957	-1.000	-1.000	0.000
Maximum	0.924	1.000	0.997	1.000	0.991
Mean	-0.107	0.593	0.224	-0.067	0.045
Mean for recommended assessment units	0.650	0.934	0.879	0.704	0.646

The truth values from Stage 2 were compared with those from Stage 1 to assess the effects of a change in scale and of criteria. The truth values in the two stages were based on different spatial assessment units and had to be standardized to the Stage 2 units. Stage 1 units were gridded into 100 m cells and assigned their truth values. The Stage 1 truth values were then assigned as an areally-weighted average to the Stage 2 assessment units. The corresponding values are shown in a scatterplot of assessment units (Figure 21). Points above the red line indicate higher truth values in Stage 2 than in Stage 1. These units tended to have moderately good suitability in the coarser resolution assessment of Stage 1 but emerged as highly suitable when assessed at finer spatial scale and specifically for vernal pool habitat suitability. These are generally the units recommended for further assessment in Stage 3. It should be noted that the red line is for ease of visualization. The truth values in Stage 1 and 2 were derived independently and are not necessarily scaled the same. The majority of assessment units occur below the red line in the scatterplot because they had overall high suitability in Stage 1 but have habitats other than vernal pools. In the extreme case, a number of assessment units had positive values in Stage 1 but were assessed with -1.0 values (completely false) in Stage 2 because of lack of vernal pool habitat or other desirable qualities.

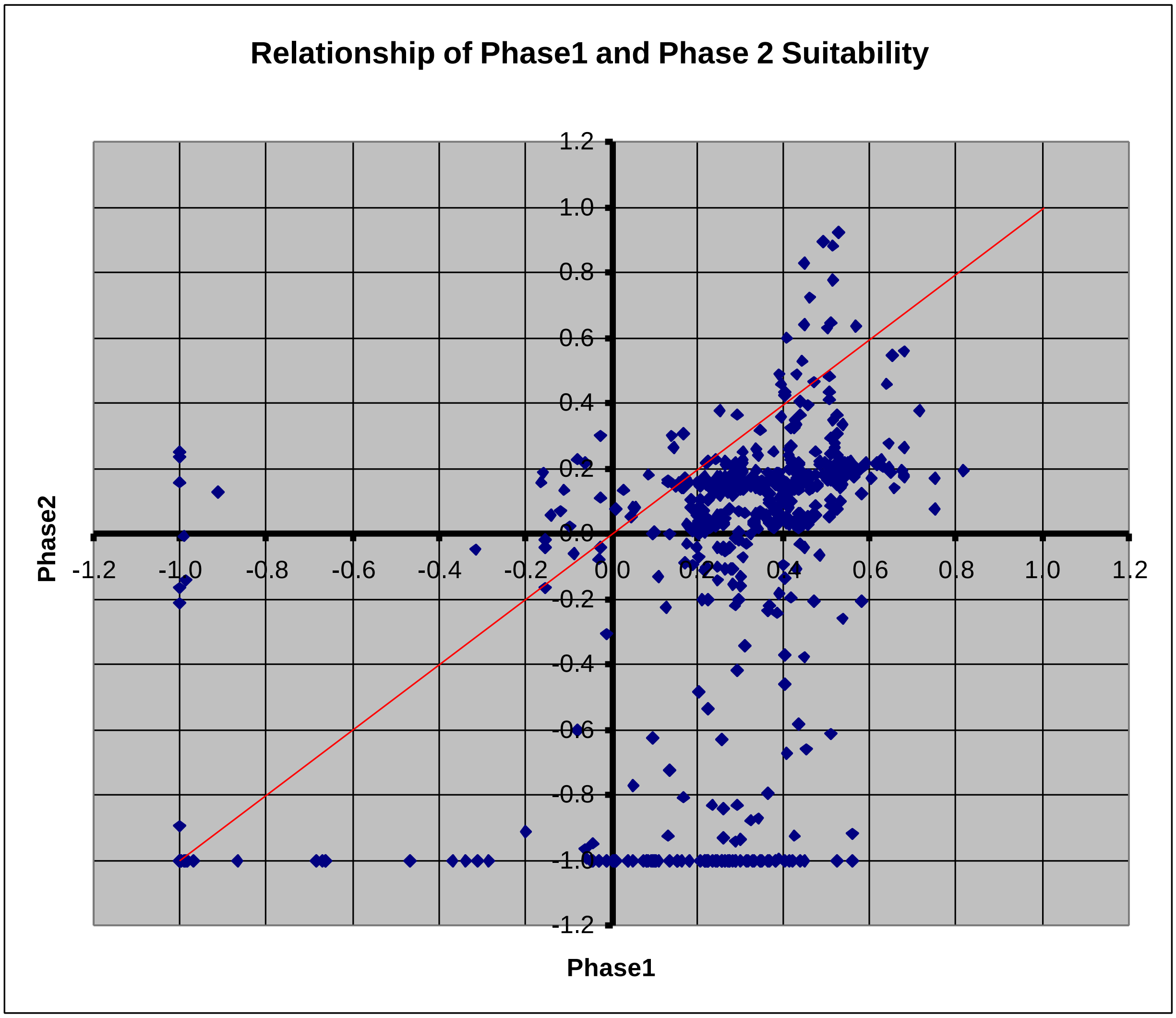


Figure 21. Map of truth values for site suitability for the Stage 2 assessment units (vernal pool habitat) in relation to their overall Stage 1 suitability truth values. The red line indicates equivalent values in both stages.

As is well-known, the area containing and surrounding the proposed UC Merced campus contains a very dense complex of vernal pools, among the best examples remaining in the Central Valley (Holland 2000). By following the guidelines for evaluating potential UC NRS reserves, we found that the lands in these assessment units also achieve a high level of concurrence with these guidelines for their scientific, academic, and administrative suitability as well. These sites tend to be relatively intact ecologically, with few roads or converted lands, be the larger ranches rather than small farms or rural residential lots, and are within easy commute for class field trips. There are other vernal pool complexes in the Stage 2 assessment region that perhaps rival those near the campus in size and density, such as along Sandy Mush Road west of Merced or further south along the base of the Sierra Nevada. These sites do not meet the other University guidelines as well as those closer to the campus site, however. Thus we recommend only the assessment units in the vicinity of the proposed campus (Figure 22) for further consideration in Stage 3. Other vernal pool sites need not be evaluated further unless no suitable and available parcels can be found among the Stage 3 sites.

The recommended assessment region for Stage 3 can be described as the undeveloped lands between Highway 59 on the west to the Merced-Mariposa county line on the east, and south from the Merced River to Bellevue Road (and a line extending this road to the county line). The proposed campus site, labeled 'UCM' in Figure 22, is roughly in the center of this smaller assessment region. La Paloma Road approximately bisects the assessment region from southwest to northeast. Rangelands extending south of South Bear Creek Drive and Highway 140 were also included although their larger assessment units did not score highly in Stage 2. The Nature Conservancy has already purchased a conservation easement on part of the Flying M ranch (easement labeled on Figure 22 as of 1995) to protect some of the vernal pool resources of the area.

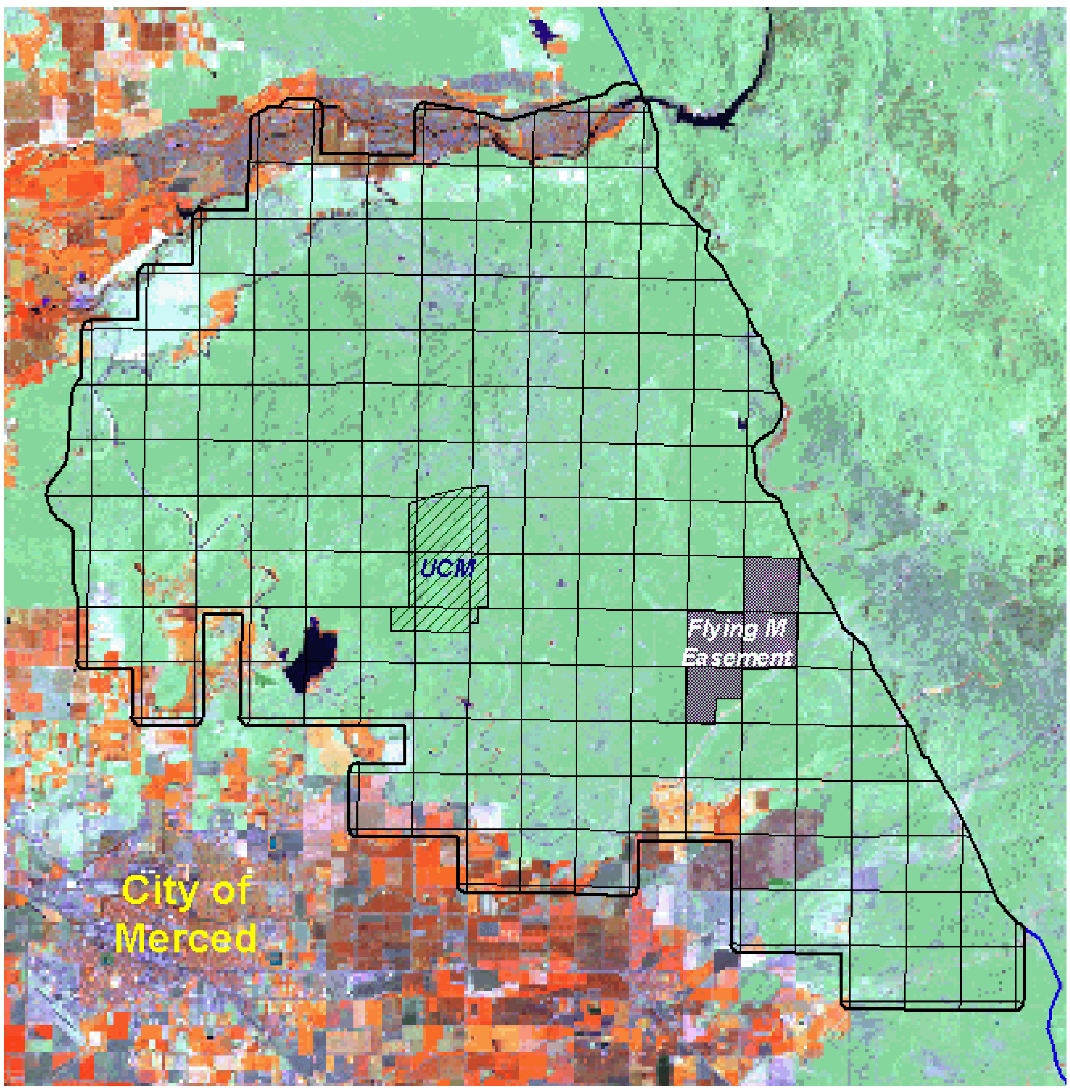


Figure 22. Landsat scene of assessment units selected for detailed assessment in Stage 3 (outlined in bold line). Blue line is Merced-Mariposa county line.

Most of the Stage 3 region is undeveloped and uncultivated, except for some parcels on the fringes (Figure 22). Not all assessment units in the Stage 3 area have the same suitability for vernal pool management, however. Figure 23 shows the variation in pool density from Holland's map (1998). The gold areas represent low-density vernal pool complexes, which predominate in the northern portion of the campus site and the next assessment unit north of La Paloma Road. Medium density complexes are represented in orange and are primarily in the northeastern-most unit near the Merced River. There are some lands with no vernal pools along ridges. The metadata for the Holland vernal pool map, however, cautions that "the density ratings should not be the sole basis for identifying high priority preserve areas, especially at the local assessment level. At the local level, this layer is probably best used for suggesting new areas for regional preserves, areas which may never have been considered because of a lack of information". Final reserve siting and design will require more explicit rating of vernal pool habitat quality through field and high-resolution aerial photo interpretation.

The purpose of the UC NRS is to manage reserves that represent the diversity of California's landscapes in support of the university's teaching and research mission. The NRS normally does not involve itself in habitat restoration, and consequently we have not assessed suitability of sites for restoration of vernal pool habitat. The criteria for prioritizing sites for restoration would be different than those for preservation. Restoration suitability would require assessment of the likelihood of successful restoration and current site condition, which would involve an understanding of hydrologic function. There are two reasons why restoration may be an attractive option for an NRS assessment. First, vernal pool habitat has been severely reduced in the Central Valley and would benefit significantly from restoration. Second, the development of a large university and affiliated facilities will undoubtedly disturb some of the highest-quality vernal pool habitat that does remain. This impact creates an opportunity for mitigation through restoration of comparable habitat in the vicinity of the campus. Paired vernal pool research sites, one intact (for documenting reference conditions) and one being restored, could support useful comparative studies. The disturbed site could also support valuable research on restoration methods.

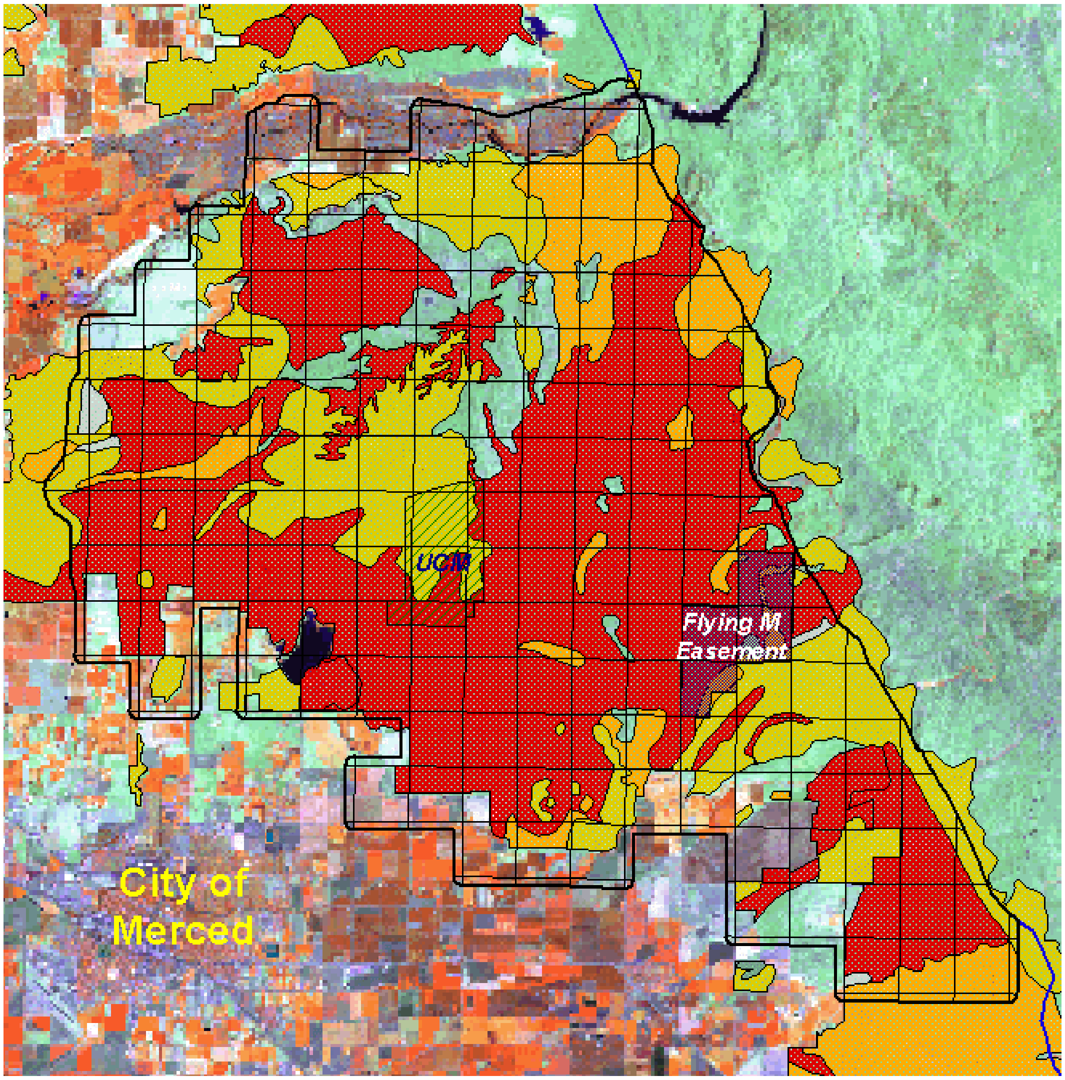


Figure 23. Map of vernal pool density (Holland 1998) in Stage 3 assessment region (outlined in bold line). Red areas are high-density vernal pool complexes, orange is medium density, and gold is low density. Areas where the Landsat TM image shows through were not mapped as vernal pool complexes.

Assessment in the Stage 3 UC-Merced Assessment Region

Following the screening process in Stages 1 and 2, Stage 3 of the hierarchical process ranks the suitability of individual parcels as potential new NRS reserves. The handful of parcels identified in Stage 3 would need to be reviewed according to standard UC procedures, including a field visit, recommendation by a campus committee, a visit and recommendation to the UC Merced chancellor by a University-wide committee, and a recommendation from the chancellor to the UC president. Ultimately, any negotiations for acquisition would have to be approved by the UC regents.

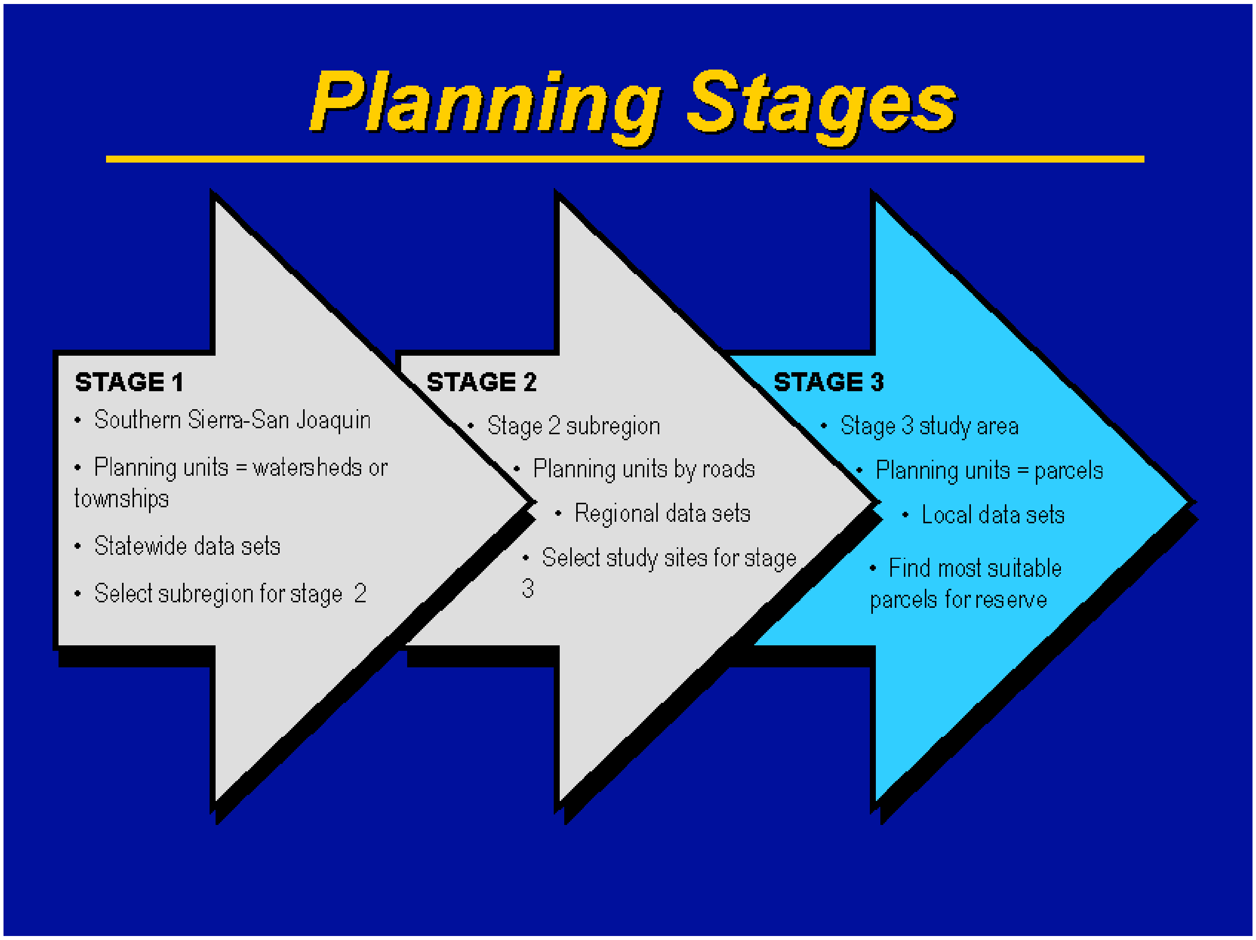


Figure 24. Relationship between Stage 2 and the other two stages of the suitability assessment.

For the third stage of assessment for the highest ranking assessment units, we envisioned a more detailed set of criteria within the same logical framework (Figure 24). That is, the higher levels of the logic network would be the same, but the data for characterizing ecosystem integrity and so on would be more specific. For instance, the Academic Suitability criterion in Stage 2 was based entirely on travel time from the campus site. Virtually all parcels in the Stage 3 area fall within an acceptable travel time, and so this criterion was dropped in Stage 3. In addition, the assessment units for the third stage are smaller in extent, using boundaries of actual assessor's parcels. The suitability of assessment units was assessed only for vernal pool/grassland habitat in Stage 3.

We recognize the need for consideration of other Sierran habitats as potential NRS reserves in the future. In fact, a future research direction is to assess suitability for reserves to represent all the major habitats in a transect from the Central Valley to the Sierra crest. A research transect would undoubtedly involve lands managed by state and federal agencies and non-governmental organizations. The University of California could contribute toward the realization of such a noble research goal.

In Stage 3 the NRS guidelines were interpreted into a logic network that was similar to Stages 1 and 2, starting with the three primary criteria of scientific and administrative suitability (academic suitability, based on travel time from campus, was considered uniform across all parcels and therefore not included). There were two primary differences in Stage 3. First, the basic logic network was modified to assess the suitability of assessment units as representative of vernal pool/grasslands. We applied logic similar to that of previous studies that incorporated vernal pool diversity and density, potential threat of development, parcel size, and condition and defensibility of the site (Mead 1996, Reiner and Swenson 2000). In particular, we attempted to address the importance of representing the diversity of pool communities, which differ significantly among landforms and parent soil materials (Smith and Verrill 1996, Holland 2000, Reiner and Swenson 2000). In the absence of biological inventory data, we relied instead on soil mapping (Arkley 1954) to infer biophysical environmental heterogeneity and associated biological diversity. Second, the smaller size of the assessment region permitted more detailed, parcel-level information to be included in the logic networks. For instance, information on actual and potential land use was used to estimate the existing capital investment and land value that determines the degree of difficulty in acquiring parcels for a new reserve. The full logic network and terminal data nodes are listed in Table 11 and shown graphically in Figure 25.

Table 11. Outline of Stage 3 knowledge-based network of propositions defining suitability of sites as potential NRS reserves for vernal pool/grasslands. Final data links are in italics, while propositions are in plain text or bold; data link names are in parentheses. Explanations of the data links are listed in the Table 12.

Site Is Highly Suitable For NRS

- **Scientifically suitable**
  - <u>Ecosystems have integrity</u>
    - *Upstream is intact (UPSTREAM_INTACT)*
    - *Land use is compatible (COMPATUSE)*
  - <u>Excellent vernal pool example</u>
    - *Parcel is large (GIS_HA)*
    - *Parcel has diverse parent material (NUMPARENT)*
    - *Vernal pool density is high (VP DENSITY INDEX calculated from weighted sum of percentage area of three density classes)*

- **Administratively suitable**
  - <u>Acquisition terms favorable</u>
    - *Capital investment is small (INVEST)*
    - *Potential use is same as current (SAMEUSE)*
  - <u>Easy to aminister/maintain</u>
    - *Number of encumbrances is low (NUMENCUMB)*
    - *Neighboring use is same as parcel (COMPNEIGH)*
    - <u>Parcel is safe from trespass</u>
      - *Number of border roads is low (BORDERRDS)*

Number of access points is low (ACCESSPTS)

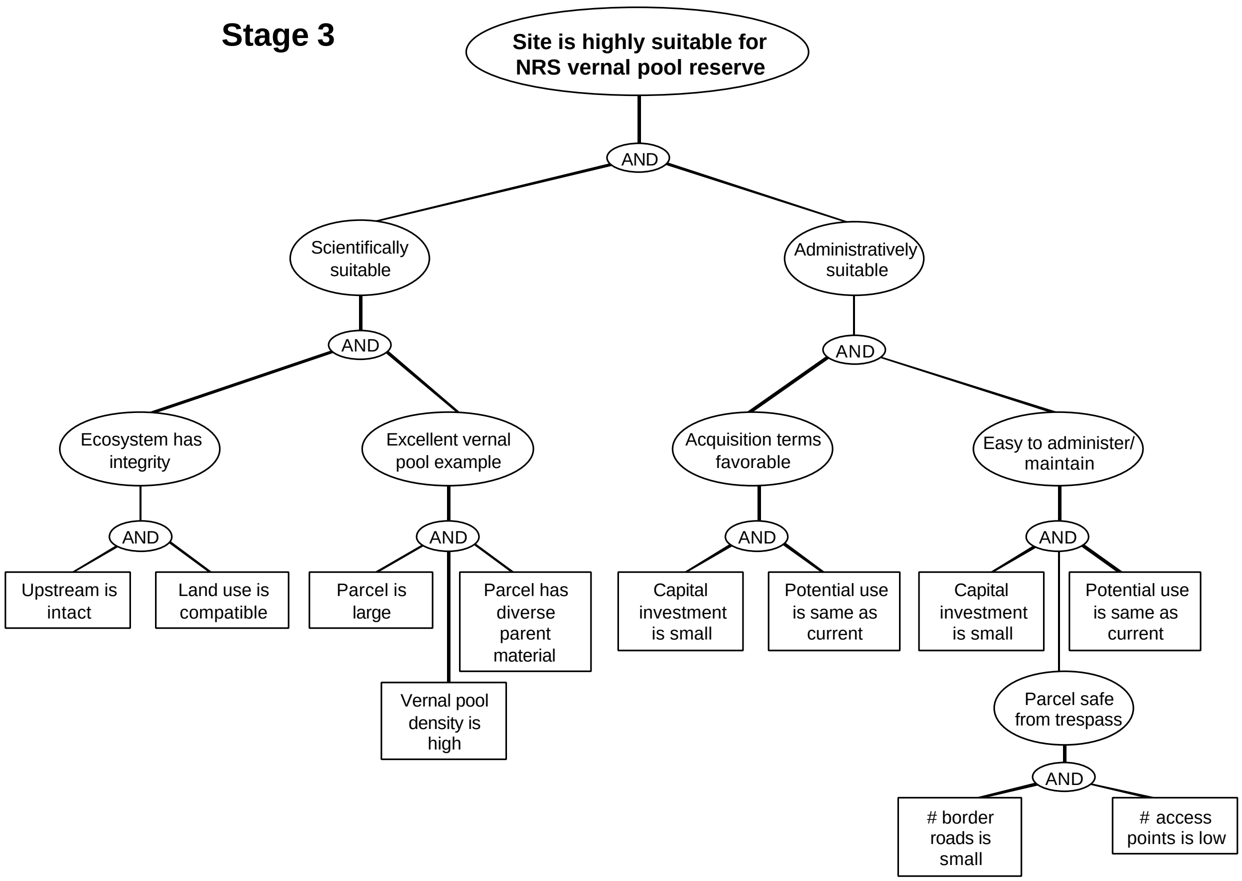


Figure 25. The network for the Stage 3 proposition that the "site highly suitable for an NRS vernal pool reserve." Networks are shown as ovals and data links are rectangles.

Table 12. Data links in the Stage 3 knowledge-base and how they were derived. Variable names correspond to names of propositions in Table 21, and are shown here in alphabetical order.

Variable name (Alias)	**Assumption or explanation**	**Data source**	**GIS processing steps**	**Range of values**
ACCESSPTS	Parcels with more entry	USGS topo maps	Visually count the number of	0-7

	points will be harder to protect from trespass.	in Digital Raster Graphic format	places a road crosses each parcel boundary	
BORDERRDS	Parcels bordered by roads will be harder to protect from trespass.	USGS topo maps in Digital Raster Graphic format	Visually count the number of borders of a parcel that is defined by a road.	0-3
COMPATUSE	Parcels that do not have current uses compatible with reserve management do not have high ecological integrity.	Assessors database of land use by parcel (Merced County Association of Governments)	Crosswalk from Usename field in parcel coverage to an index of compatibility with hydrologic integrity of vernal pool complexes. code Usename 1 Agriculture, Orchard 3 Dairy, Poultry, Vacant 5 Grazing, Government	1, 3, 5
COMPNEIGH	Parcels that have neighbors with more intense land uses will be harder to manage as reserves.	Assessors database of land use by parcel (Merced County Association of Governments)	Assign yes or no to parcel based on visual inspection of Usename of surrounding parcels, or with evident land use types on Landsat image.	y/n
GIS_HA	Larger parcels contain a greater abundance of vernal pools with greater diversity and typically contain more associated upland habitats.	Parcel coverage from Merced County Association of Governments	Sum area of by Assessors Parcel Number (APN) and convert to hectares	0 - 545 ha
INVEST	Parcels with greater capital investments will be more costly to acquire.	Assessors database of land use by parcel (Merced County Association of Governments)	Crosswalk from Usename field in parcel coverage to an index of capital investment. code Usename 1 Agriculture, Orchard, Dairy, Poultry 4 Grazing, Government 5 Vacant	1, 4, 5
NUMENCUMB	Parcels that have more easements and rights of way will be harder to manage as reserves.	Parcel coverage from Merced County Association of Governments and USGS topo maps in Digital Raster Graphic format	Visually count the number of encumbrances of a parcel, including the canals, roads, and power transmission line. For canals and roads, it only counts as an encumbrance splits a single parcel, not if it forms a border of a parcel.	0-2
NUMPARENT	Vernal pools on different soil parent materials will contain different flora and fauna, so that diversity is greatest for parcels with the most parent materials.	Soils of Eastern Merced County (Arkley 1954)	This map has not been digitized, so we colored the soil units by the parent material (basic, sedimentary, granitic, or mixed alluvium) for all hardpan soils. The presence of each of the four types was recorded for each parcel and then the number of unique types present was summed.	0-3
SAMEUSE	Parcels zoned for future development, even if currently undeveloped, will generally have greater land value and be more expensive to acquire.	Assessors database of land use, zoning and general plan designation by parcel (Merced County Association of Governments)	No parcels are considered developed currently. Therefore all parcels with Agricultural-Residential zoning or with a General Plan designation that included LD, LMD, CO, PK, or RRC were considered to be a different use.	y/n
UPSTREAM_ INTACT	The hydrologic system will be disrupted where watersheds are transected by canals or larger roads.	USGS topo maps in Digital Raster Graphic format	Visually interpret which parcels are not downstream from a canal or a paved road that bisects a watershed. If a road bisects a watershed but there is no stream on the topo map, the downstream parcels are considered intact (i.e.,	y/n

			= yes)	
VP DENSITY INDEX	Greater proportion of unit with high density (i.e., higher index value) of vernal pools is better.	Vernal pools coverage (Holland 1998)	FREQUENCY of area in assessment unit by 3 density classes converted to percentages; index is a weighted sum of these	0-60

The Stage 2 assessment region encompassed over 12,628 km² (Figure 1), or 20% of the Stage 1 assessment region. Stage 3 has been narrowed to 430 km², or 3% or Stage 2 and less than 1% of Stage 1 (Figure 1). To allow finer resolution of the Stage 3 assessment, the assessment units were redefined. Thus a GIS coverage of assessors parcels was obtained from the Merced County Association of Governments to use as assessment units (Figure 26). These parcels largely represent units of the original public land survey, either full sections (approximately 640 acres or 259 hectares) or some smaller division of sections. Roads or canals in the study area have divided some sections, creating irregular shapes. The coverage contained some parcels that were subdivided by roads, canals, or streams. In such cases, the assessment was made for parcels, that is for all polygons with the same assessors parcel number (APN). This created 298 separate parcels for assessment, although the number of unique landowners is much less because some individuals own multiple parcels in the larger ranches of the region.

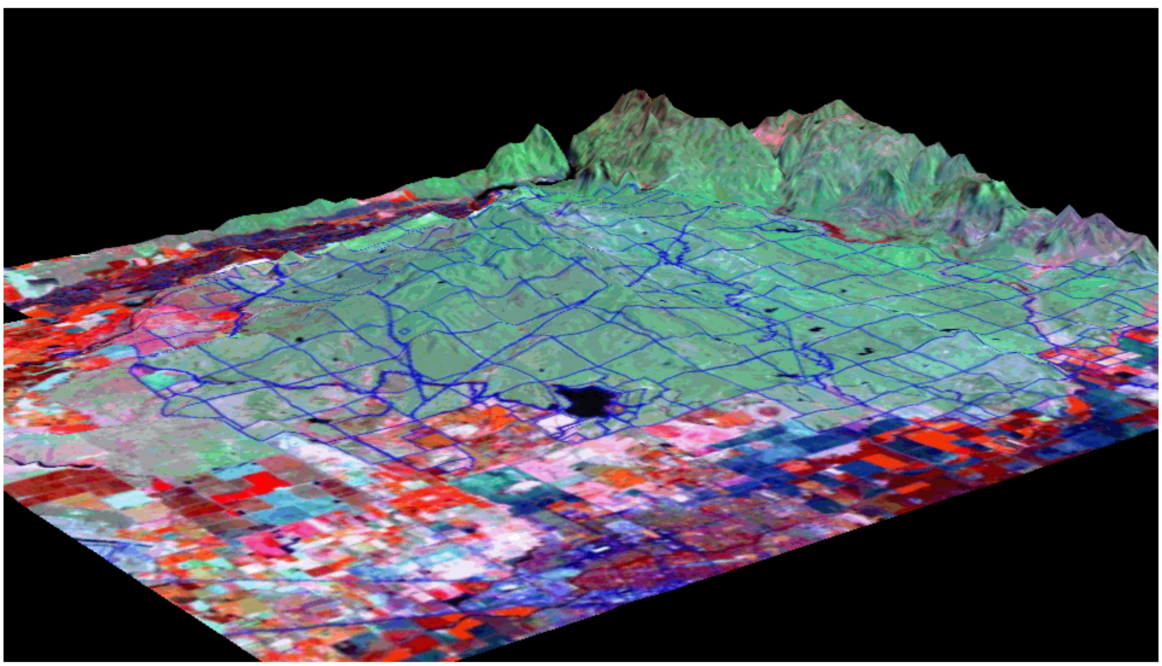


Figure 26. Three-dimensional view of the Stage 3 assessment region. The blue lines are the boundaries of the parcel-based assessment units.

The parcel coverage contained attribute data about current use, zoning and general plan designation, and owner information. These data were interpreted as needed for the knowledge base of suitability. Other attributes were interpreted by visual comparison of the parcels with USGS topographical maps in digital raster graphic format and with an analog soils map. The parcel database included the assessed value. Because of the way parcels are assessed in California following the passage of Proposition 13, it was not possible to normalize the values to a base year that could be used to quantify land value. Consequently we used an index of expected capital investment and the zoning information to classify acquisition costs.

A GIS database was compiled for the data links needed by the knowledge-base for each of the 298 assessment units. The information to calculate data links for the knowledge-based network came from the GIS parcel coverage and database from the Merced County Association of Governments, photo-interpreted maps of vernal pool quality and density (Holland 1998), soil type maps (Arkley 1954), and the 1:24,000 scale USGS topographic quadrangle maps in digital raster graphic format. These data were interpreted by various GIS analyses as described in Table 2 to generate the data for assessment units used for the data links at the bottom level of the logic network.

Applying the knowledge-base logic network to the data links from the GIS database generated truth values for every assessment unit in the study area (Figure 27, Table 13). Three clusters of parcels had the highest overall suitability (greater than 0.9): the lands south of Highway 140 between Owens and Miles Creeks, the east end of La Paloma Road near the county line, and scattered parcels of the Smith Trust lands and adjacent Flying M Ranch. Most parcels had relatively high suitability for most factors, except for some parcels on the edges of the study area that are currently agricultural or are zoned for development and those that are influenced by canals or paved roads. The two criteria that had the most influence on the ratings were vernal pool ratings and trespass factors. The majority of the study area had only a single parent material type in each parcel and therefore relatively low diversity. A few parcels at lower elevations around Burns, Miles, and Owens Creeks tended to have two or three soil types and presumably greater biological diversity. Also, the density of pools was greatest across the middle of the study area and around Highway 140. Generally the parcels north of La Paloma Road tended to have lower suitability as a prime example of vernal pool complexes because of lower pool density and soil diversity. The areas that rated highest for ease of administration and maintenance were those with fewer roads in the northeast part of the study area, south of Highway 140, some of the Smith Trust lands, and elsewhere in the Burns and Black Rascal Creek drainages. Some parcels were assessed as completely unsuitable (truth value = -1.0) because they were unsuitable for a single lower level criterion. In the fuzzy logic, a false value for any link in an AND network propagates that false value up the network.

The three highest-ranking parcels are found in the southeastern corner of the assessment region, south of Highway 140 (on the Cunningham Ranch and adjacent parcels). One of these had a truth value of 1.000, that is, it perfectly fulfilled the proposition that it was suitable for a vernal pool nature reserve according to the UC guidelines. The other two adjacent parcels had scores of at least 0.968. All three had high density pool complexes on diverse parent soil materials, were not degraded by roads or canals, were zoned for low intensity use, and had low trespass issues. Quite to the contrary, the complete absence of roads within these parcels could be viewed as a problem for reserve management and access. Also, with sites this small there is a real trade-off between the diversity of soils and the area in each soil type.

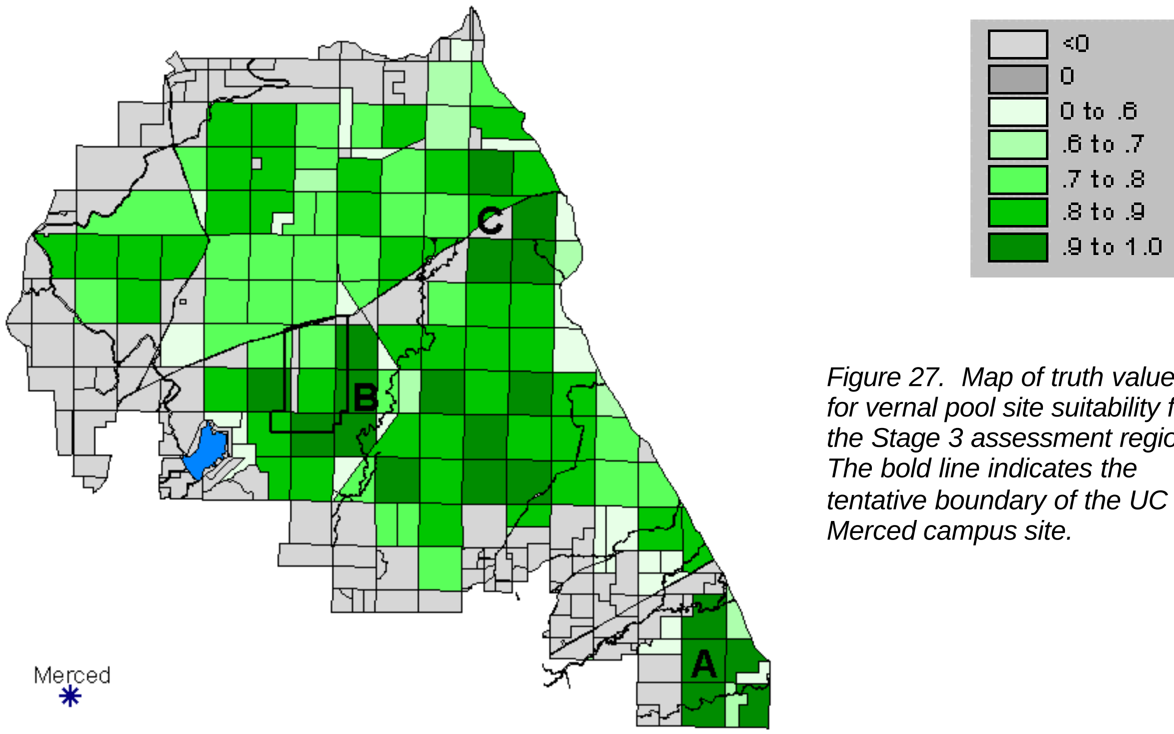


Figure 27. Map of truth values for vernal pool site suitability for the Stage 3 assessment region. The bold line indicates the tentative boundary of the UC Merced campus site.

Table 13. Truth values of the assessment units in the study area for top-level criteria.

	Suitability Truth Values		
	Overall	**Scientific**	**Admini-strative**
Minimum	-1.000	-1.000	-1.000
Maximum	1.000	1.000	1.000
Mean	-0.209	-0.135	0.327
Mean for top 20 parcels	**0.931**	**0.890 (min = 0.823)**	**0.980 (min = 0.819)**

The proposed campus site (Cluster B) scored moderately high as a potential reserve, and the Smith Trust parcels surrounding it generally scored in the top 10 percentile (greater than 0.9). Pool density is high, road access is limited, and current zoning is compatible with a reserve. The primary factor that lowered their suitability slightly relative to the Miles/Owens Creek site was the presence of only one type of soil parent material--high terrace/mixed alluvium. Another highly rated area on the Flying M Ranch just east of the tentative campus site and Smith Trust lands is considered an outstanding vernal pool site (Holland 2000) and is already partially included in a conservation easement held by The Nature Conservancy.

Several highly-rated parcels at the east end of La Paloma Road (Cluster C) with scores greater than 0.9 had high pool density, were appropriately zoned, and had relatively low road access. One of the parcels contained two soil parent materials as well. Other than the Smith Trust lands, this area would probably be the easiest to access from the tentative campus site because of its proximity to La Paloma Road. The road actually bisects the cluster of highly-ranked parcels, which thus could not be managed as a contiguous reserve.

Most of the parcels in the assessment region rated at least moderately high (greater than 0.7) for their suitability as an NRS natural reserve to represent vernal pool ecosystems. The only parcels with low suitability tended to be those around the perimeter of the region where there are conflicts with road access/trespass or with land uses of the parcels or their neighbors. The parcels south of La Paloma Road in general showed high suitability. The most highly rated parcels had scores too close to confidently select one or more as the appropriate site for a reserve, given the nature of our methods and quality of the data. What this suggests is that there are many locations that would potentially make excellent reserves. Thus there is a good deal of flexibility to negotiate with landowners to identify lands within this set of suitable parcels that could be made available to the University by acquisition or management agreement.

Discussion

As is well-known, the Stage 3 area containing and surrounding the proposed UC Merced campus contains a very dense complex of vernal pools, among the best examples remaining in the Central Valley (Holland 2000). By following the guidelines for evaluating potential UC NRS reserves, we found that the lands in these assessment units also achieve a high level of concurrence with these guidelines for their scientific, academic, and administrative suitability as well. These sites tend to be large ranches that are relatively intact ecologically, with few roads or converted lands, and are within easy commute for class field trips. There are other vernal pool complexes in the larger Stage 2 assessment region that perhaps rival those near the campus in size and density, such as west of Merced or further south along the base of the Sierra Nevada. These sites do not meet the other University guidelines as well as those closer to the campus site, however.

Most of the parcels in the Stage 3 assessment region rated at least moderately high for their suitability as an NRS natural reserve to represent vernal pool ecosystems. The only parcels with low suitability tended to be those around the perimeter of the region where there are conflicts with road access/trespass or with land uses of the parcels or their neighbors. The southern half of the Stage 3 assessment region in general showed high suitability. The most highly rated parcels had scores too close to confidently select one or more as the appropriate site for a reserve, given the nature of our methods and quality of the data. This suggests that there are many locations that would potentially make excellent reserves. Thus there is a good deal of flexibility to negotiate with landowners to identify lands within this set of suitable parcels that could be made available to the University by acquisition or management agreement.

Without specific design criteria from the University, we could not assess the suitability of aggregations of parcels that may be more or less suitable than the individual parcels within them. For instance, many ranches in the region consist of several contiguous parcels. An entire ranch might contain a greater diversity of soil parent material than the individual parcels. The roads that cross parcels that we considered a risk for trespass may all be contained within a single ranch. In that case, the roads could be an asset for access within a reserve rather than a trespass liability from outside. Small parcels were downweighted as representing vernal pool complexes because of their size, but they may still contribute to a reserve consisting of several contiguous parcels. Further, it may be possible to acquire portions of parcels to omit the part from a reserve that lowered the suitability, such as where a road splits a parcel or neighboring land use is potentially in conflict with reserve management. Consequently, any decision about reserve boundaries will need to consider the interrelation and complementarity of parcels beyond the assessment criteria that we used here.

It might appear from the results on vernal pool suitability that a formal process was unnecessary. Looking at the vernal pool map (Holland 1998) and the location of the campus site would make an obvious set of sites for evaluation. We contend, however, that the criteria for reserve selection in the University of California guidelines are sufficiently complex, and potentially conflicting, that it is worthwhile to conduct a more systematic assessment. In fact, several other potential sites had been suggested as valley reserve sites that scored relatively low by our implementation of the university guidelines. Issues such as land ownership patterns, level of ecological integrity, travel time, and threat of future development are also important factors to consider. Although there were differences in the specific variables used, our approach captured the same basic factors of site condition and defensibility as the established program of the U. S. Fish and Wildlife Service for determining credits for vernal pool preservation banks (Mead 1996). Having completed a systematic assessment, we can defend the recommendations against other contending sites that did not meet the full set of guidelines as well.

We relied on 1954 soil mapping (Arkley 1954) to determine the diversity of parent soil material within parcels. The Natural Resources Conservation District has not digitized this map because it "does not meet requirements of modern soil survey" (web page updated May 4, 2000 at http://www.ca.nrcs.usda.gov/mlra/sstatus.html). Our assessment of the proposition that a parcel is an excellent example of a vernal pool complex was based on the interpretation of the soil map, which may be substantially revised in the next generation of mapping. Some inventory has occurred for specific locations, but none is available for the entire assessment region.

Conclusions

Selection of research reserves tends to be opportunistic, where one or a few known sites are compared to formal or informal criteria. The UC-NRS guidelines define a general set of qualities reserves should possess but provide little specific guidance for a quantitative, systematic, and repeatable protocol for selecting sites for the NRS network. This is not uncommon among organizations that designate lands for reserves. The Forest Service, for instance, has similar guidelines for its network of research natural areas (Stoms et al. 1998). Without a more explicit set of criteria and quantitative measures of suitability, planners are vulnerable to bias in their assessments. There is no standard against which to judge a candidate site. Superior sites may be overlooked when only a single candidate site is considered. While there is a need for flexibility in an assessment protocol to respond to specific circumstances, we suggest that the current guidelines are too flexible. To overcome this limitation, we have developed a GIS-based methodology that interprets the guidelines for systematically evaluating the suitability of all lands in the assessment region.

The fuzzy knowledge base encapsulates all criteria and their relationships in an explicit form that can be critiqued and continually updated as better ecological understanding and data emerge. The process of translating the guidelines into a knowledge base structure also helped identify weaknesses in the guidelines. For instance, the current guidelines encourage representation of the diversity of California's habitats but lack any useful measure of representativeness. By simply splitting categories (or minimal distances) finer and finer, one can always create a measure of this objective that shows that some environment or habitat is not represented. Other terms such as "viability" and "significant" are equally vague. Fuzzy logic was designed specifically to cope with such linguistically imprecise factors. In addition, it automatically casts all factors into a common range of truth (or membership) values. This assignment of membership has great flexibility, accommodating non-linear relationships, Boolean values, and weighted linear combinations of factors. Multicriteria suitability assessments often have criteria that compete with one another. Fuzzy logic provides formal mathematical operations to handle combinations of factors. Analysts can quickly try alternative assessments and visualize the results of the overall network or any individual subnetwork. In this study, we assessed the influence of the "accessible for field trips" factor in Stage 2, which seemed to be constraining the rankings to a small radius from the proposed campus site. Results showed that parcels near the campus site in fact also rated best for the other combination of factors.

The dilemma of spatial extent of the assessment region versus consistency and detail of information about the assessment units was addressed by designing a hierarchical three-stage process. At each stage, the highest resolution data that were comprehensive for the extent of the assessment region were utilized. The finest resolution data were only required for a relatively small area for which it is more practical to compile. In this manner, we were able to identify a relatively few highly suitable parcels within a total region of 63,000 km^2. While this does not guarantee that good sites were not overlooked at the coarser scales, it expedited the analysis and because of its explicitness can be subjected to review by regional experts.

Similar knowledge bases could be developed for other habitat types that are also not well-represented in the NRS, such as Sierran mixed conifer. Our logic network is designed to support the substitution of habitat-specific factors as a separate network in Stage 2. The Stage 3 knowledge base could then be tailored for that habitat type. There are several nearby sites currently managed by other agencies for conservation or research purposes that could be considered for NRS use or to complement an NRS reserve without additional university management.

The current NRS guidelines lack any useful measure of representativeness. By simply splitting categories (or minimal distances) finer and finer, one can always create a measure of this objective that shows that some environment or habitat is not represented. According to the environmental factors used in this analysis, the bioenvironments least represented in California are the Great Central Valley and deserts, the northern interior coastal mountains and the Great Basin. These environments, however, also tend to be the farthest geographically from existing campuses. The mid-elevation conifer zone of the Sierra Nevada is also not represented in the NRS network. The reserve with the most similar environmental conditions is the James Reserve in the San Jacinto Mountains in southern California. The addition of a new campus in Merced provides an opportunity to fill the gaps in the Great Valley and the Sierra Nevada in locations reasonably close to the campus for class field trips.

The general procedure proposed here as Stage 1 could be used for assessing suitability of new NRS reserves for any UC campus. The assessment unit boundaries either exist (planning watersheds) or can be readily derived (townships) for any region of the state. The GIS data for Stage 1 currently exist statewide as well. The more specific assessments in Stage 2 and 3 would need to be adapted for other locations depending on the availability of local data. Similar knowledge bases could also be developed for other habitat types near Merced that are not well-represented in the NRS, such as Sierran mixed conifer. Our logic network is designed to support the substitution of habitat-specific factors as a separate network in Stage 2. The Stage 3 knowledge base could then be tailored for that habitat type. In fact, we view this as an opportunity to establish a series of reserves along an ecological transect over several thousand meters of elevation range in the central Sierra Nevada, which could be especially valuable to support global change studies (Zhang et al. 1997). There are several nearby sites currently managed by other agencies for conservation or research purposes that could be considered for NRS use or to complement an NRS reserve without additional university management.

Other research reserve programs (LTER, RNA, MAB, BON) use similar guidelines to characterize a good site but do not specify systematic procedures for assessing suitability of all potential sites in an assessment region (Stoms et al. 1998). Although the specifics of the criteria may be slightly different, we believe such programs could benefit from hierarchical structuring of the analysis and construction of a knowledge-base fuzzy logic linked to a GIS database. Highly suitable potential sites are less likely to be neglected, and the entire process becomes more explicit and transparent to critics.

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Literature Cited

Amundson, R. 1998. Do soils need our protection? *Geotimes* 43: 16-20.

Arkley, R. J. 1954. *Soils of eastern Merced County, California.* Soil Survey No 11. Berkeley, University of California. College of Agriculture. Agricultural Experiment Station.

Bailey, R. G. 1991. Design of ecological networks for monitoring global change. *Environmental Conservation* 18: 173-175.

Batisse, M. 1982. The Biosphere Reserve: A tool for environmental conservation and management. *Environmental Conservation* 9: 101-111.

Belbin, L. 1995. A multivariate approach to the selection of biological reserves. *Biodiversity and Conservation* 4: 951-963.

Bourgeron, P. S., H. C. Humphries and K. M. Reynolds. 2000. Conducting large-scale conservation evaluation and conservation area selection using a knowledge-based system. Pages in *Proceedings of 4th International Conference on Integrating GIS and Environmental Modeling*, Banff, Canada. http://www.Colorado.EDU/research/cires/banff/upload/326/.

Burke, I. and W. K. Laurenroth. 1993. What do LTER results mean? Extrapolating from site to region and decade to century. *Ecological Modelling* 67: 19-35.

Charnpratheep, K., Q. M. Zhou and B. Garner. 1997. Preliminary landfill site screening using fuzzy geographical information systems. *Waste Management & Research* 15: 197-215.

Cheatham, N. H., W. J. Barry and L. Hood. 1977. Research natural areas and related programs in California. Pages 75-108 in *Terrestrial Vegetation of California*. M. G. Barbour and J. Major. New York, John Wiley & Sons.

Colwell, R. G., A. P. Dawid, S. L. Lauritzen and D. J. Spiegelhalter. 1999. *Probabilistic networks and expert systems*. New York, Springer.

Davidson, D. A., S. P. Theocharopoulos and R. J. Bloksma. 1994. A land evaluation project in Greece using GIS and based on Boolean and fuzzy set methodologies. *International Journal of Geographical Information Systems* 8: 369-384.

Davis, F. W., D. M. Stoms, A. D. Hollander, K. A. Thomas, P. A. Stine, D. Odion, M. I. Borchert, J. H. Thorne, M. V. Gray, R. E. Walker, K. Warner and J. Graae. 1998. *The California Gap Analysis Project-Final Report.* Santa Barbara, University of California, Santa Barbara.

Engelking, L. D., H. C. Humphries, M. S. Reid, R. L. DeVelice, E. H. Muldavin and P. S. Bourgeron. 1994. Regional conservation strategies: Assessing the value of conservation areas at regional scales. Pages 208-223 in *Eastside Forest Ecosystem Health Assessment*. M. E. Jensen and P. S. Bourgeron. Portland, U S Forest Service General Technical Report PNW. Volume II: Ecosystem management: Principles and applications.

Faith, D. P. and P. A. Walker. 1996. Environmental diversity: On the best-possible use of surrogate data for assessing the relative biodiversity of sets of areas. *Biodiversity and Conservation* 5: 399-415.

Ford, L. D. and K. S. Norris. 1988. The University of California Natural Reserve System. *BioScience* 38: 463-470.

Franklin, J. F., C. S. Bledsoe and J. T. Callahan. 1990. Contributions of the Long Term Ecological Research Program: An expanded network of scientists, sites, and programs can provide crucial comparative analyses. *BioScience* 40: 509-523.

Hall, G. B., F. Wang and Subaryono. 1992. Comparison of Boolean and fuzzy classification methods in land suitability analysis by using geographical information systems. *Environment & Planning A* 24: 497-516.

Hickman, J. C., Ed. 1993. *The Jepson Manual: Higher Plants of California*. Berkeley, California, University of California Press.

Holland, R. F. 1998. Great Valley vernal pool distribution, Second edition. 1:24000 map. U. S. Fish and Wildlife Service. Sacramento.

Holland, R. F. 2000. The Flying M Ranch: soils, plants, and vernal pools in eastern Merced County. *Fremontia* 27/28: 28-32.

IUCN Commission on National Parks and Protected Areas. 1994. *Guidelines for protected area management categories*. Cambridge, UK, IUCN Commission on National Parks and Protected Areas with the assistance of the World Conservation Monitoring Centre.

Jameson, S. C., M. V. Erdmann, G. R. G. Jr. and K. W. Potts. 1998. *Development of Biological Criteria for Coral Reef Ecosystem Assessment*. Washington, DC, USEPA, Office of Science and Technology, Health and Ecological Criteria Division.

Jiang, H. and J. R. Eastman. 2000. Application of fuzzy measures in multi-criteria evaluation in GIS. *International Journal of Geographical Information Science* 14: 173-184.

Jones and Stokes Associates. 1987. *Sliding towards extinction: The state of California's natural heritage*. San Francisco, California Nature Conservancy.

Kirkpatrick, J. B. and M. J. Brown. 1994. A comparison of direct and environmental domain approaches to planning reservation of forest higher plant communities and species in Tasmania. *Conservation Biology* 8: 217-224.

Kollias, V. J. and D. P. Kalivas. 1998. The enhancement of a commercial geographical information system (ARC-INFO) with fuzzy processing capabilities for the evaluation of land resources. *Computers and Electronics in Agriculture* 20: 79-95.

Liang, G. S. and M. J. J. Wang. 1991. A fuzzy multi-criteria decision-making method for facility site selection. *International Journal of Production Research* 29: 2313-2330.

Mackey, B. G., H. A. Nix, M. F. Hutchinson, J. P. MacMahon and P. M. Fleming. 1988. Assessing representativeness of places for conservation reservation and heritage listing. *Environmental Management* 12: 501-514.

Mead, D. L. 1996. Determination of available credits and service areas for ESA vernal pool preservation banks. Pages 274-281 in *Proceedings of Ecology, Conservation, and Management of Vernal Pool Ecosystems*, Sacramento, California, California Native Plant Society.

Menning, K. M., D. C. Erman, K. N. Johnson, and J. Sessions. 1997. Modeling aquatic and riparian systems, assessing cumulative watershed effects, and limiting watershed disturbance. Pages 33-51 in *Sierra Nevada Ecosystem Project, Final Report to Congress*. Davis, California, University of California, Centers for Water and Wildlands Resources. Addendum.

Mervis, J. 1998. NSF Eyes Biodiversity Monitoring Network. *Science* 281: 1935 - 1936.

Norris, K. S. 1968. California's Natural Land and Water Reserve System. *BioScience* 18: 415-417.

Pereira, J. M. C. and L. Duckstein. 1993. A multiple criteria decision-making approach to GIS-based land suitability evaluation. *International Journal of Geographical Information Systems* 7: 407-424.

Pressey, R. L., S. Ferrier, T. C. Hager, C. A. Woods, S. L. Tully and K. M. Weinman. 1996. How well protected are the forests of north-eastern New South Wales? Analyses of forest environments in relation to formal protection measures, land tenure, and vulnerability to clearing. *Forest Ecology and Management* 85: 311-333.

Ray, D., K. Reynolds, J. Slade and S. Hodge. 1998. A spatial solution to ecological site classification for British forestry using Ecosystem Management Decision Support. Pages in *Proceedings of Third International Conference on GeoComputation*, Bristol, UK. http://www.fsl.orst.edu/emds/geocomp/geopap3.htm .

Reiner, R. and R. Swenson. 2000. Saving vernal pools in the Cosumnes River watershed. *Fremontia* 27/28: 33-37.

Reynolds, K. M., M. Jensen, J. Andreasen and I. Goodman. 2000. Knowledge-based assessment of watershed condition. *Computers and Electronics in Agriculture* 27: 315-334.

Smith, D. W. and W. L. Verrill. 1996. Vernal pool-soil-landform relationships in the Central Valley, California. Pages 15-23 in *Proceedings of Ecology, Conservation, and Management of Vernal Pool Ecosystems*, Sacramento, California, California Native Plant Society.

Stoms, D. M. 2000. GAP management status and regional indicators of threats to biodiversity. *Landscape Ecology* 15: 21-33.

Stoms, D. M., M. I. Borchert, M. A. Moritz, F. W. Davis and R. L. Church. 1998. A systematic process for selecting representative Research Natural Areas. *Natural Areas Journal* 18: 338-349.

U. S. Fish and Wildlife Service. 1998. *Recovery Plan for Upland Species of the San Joaquin Valley, California.* Portland, Oregon, Region 1.

University of California. 1984. *NRS Acquisition Guidelines*. Oakland.

USDA Forest Service. 1994. *Forest Service Manual, FSM 4000-Research.* 4000-94-2. Washington, D. C.

Van Ranst, E., H. Tang, R. Groenemans and S. Sinthurahat. 1996. Application of fuzzy logic to land suitability for rubber production in peninsular Thailand. *Geoderma* 70: 1-19.

Zhang, X.-S., Q. Gao, D.-A. Yang, G.-S. Zhou, J. Ni and Q. Wang. 1997. A gradient analysis and prediction on the northeast China transect (NECT) for global change study. *Acta Botanica Sinica* 39: 785-799.

Appendix.

University of California Natural Reserve System--NRS Acquisition Guidelines June 1984

Scientific Criteria

General. The objective of the Natural Reserve System (NRS) is to develop and maintain, for educational and scientific study, a system of natural reserves broadly representing California's diversity of natural environment. A site with many habitat types will make a bigger contribution to the NRS than one with only a single habitat type. However, there may be occasions when a feature of special interest will override the usually important requirement for diversity. Ecosystems totally free of man's influence are no longer to be found, and in reality, units of a system of natural reserves will fall within a spectrum with undisturbed ecosystems on the one hand and ecosystems heavily influenced by man on the other hand. With care and good judgment, the reserves will be bunched as closely as possible to the undisturbed end of the spectrum with samples of selected ecosystems of significant merit elsewhere along the spectrum.

Criteria. (1) Viable ecosystem: Ecosystem viability is a prime requisite in establishing a natural reserve. The natural relationships should be essentially intact (i.e., an ecosystem operating as much as possible under its own influences), and the reserves should be of sufficient size so that the natural balance of the community may be maintained with the survival of the plant and animal elements assured. Boundary configuration is an important contributor to viability. The boundaries must be located so as to encompass the critical landscape features necessary to maintain the ecosystem. An ideal reserve will be buffered from the detrimental impact of adjacent land uses. In some instances, a disturbed ecosystem will revert to its formerly undisturbed condition and may be considered as a candidate natural reserve. In other instances, a candidate natural reserve will be a remnant ecosystem not meeting the test of viability, but with value for study during whatever time is left before the natural reserve value is lost.

(2) Habitat significance: Reserves should possess exceptional value in illustrating, interpreting, and protecting examples of the major habitat types of California. The most desirable situation is a reserve with a large diversity of habitats. This maximizes the academic yield for its acquisition cost by providing a large variety of things to see and do on a given field trip as well as maximizing the variety of research possibilities at a given location. It is easy to become enamoured with the unusual and overlook the common. Therefore, it is important that the NRS guard against unbalancing its system in favor of unusual values and take care to include typical samples of widely distributed habitat types. However, a reserve has added value if it also possess special features, such as:

- important variations of the common habitat types, such as different successional stages (including important man-induced successional stages) or variations in soil parent material.
- significant gene pools, such as isolated populations or populations at extreme limits of the range of a species or habitat type.
- "type localities," for example, the location where a species, soil type, geological type, etc. are first described.
- transition zones (ecotones) and interfaces between adjacent habitat types.
- the presence of a rare or an endangered habitat type or the presence of a rare or endangered species.
- the presence of a feature of geological, archaeological, or paleontological importance.

In some cases, unusual features will be deliberately acquired because they are judged to have special value to the NRS.

Academic Criteria

General. There is an increasing awareness of the need for establishing natural reserves. Federal, state, and private agencies involved are stepping up their levels of participation allowing the NRS to concentrate on its special ability to serve the needs of higher education. Worthy sites lacking a high degree of academic usefulness can be left to the other agencies to protect.

Criteria. Of particular importance is acquisition of sites enjoying current academic use, but not yet in the system. Some sites are not presently being used because of budget stringencies or other reasons which, if eliminated, would result in future academic use. This potential for future use is an important criterion. The larger the variety of disciplines that can be accommodated, the more useful the reserve will be. This is somewhat a matter of degree, since most reserves will be useful for more than the one biological science, but only in special cases will a reserve also be useful for such other disciplines as geology, paleontology, and archaeology. Extended field trips and studies in remote locations play an important role in field biology and these needs should be met by the NRS, but the backbone of undergraduate education is the normal three-hour laboratory period. Sites close to a campus will naturally receive more use and make a correspondingly high contribution to the NRS.

Administrative Criteria

General. Once the scientific and academic value of a candidate reserve is established, there are a number of administrative criteria that help to establish acquisition priorities.

Criteria. Since it is an NRS objective to have samples of as many habitat types as possible, there is importance in filling NRS habitat voids. There is special importance if a potential acquisition will also fill a habitat void in natural reserves programs administered by other agencies. This is not to imply that the opposite situation -- protection "in depth" -- is to be avoided. On the contrary, there are advantages to be gained in this. An additional criterion is the balanced growth of the NRS. It is important that the NRS be distributed geographically around the state as well as among the various campuses of the University. Favorability of the terms of acquisition is, of course, an important criterion. Responsiveness to this criterion affects the ability to build the best system with the resources available. Similarly, the ease in administering a site (trespass, maintenance of facilities, etc.) and the availability of maintenance funds will influence its relative priority.