Ecological Research Reserve Planning

David M. Stoms

Abstract Guidelines for assessing sites as potential reserves for scientific study tend to be very general. Translating these imprecise qualities into measurable ranking criteria in a large landscape can be particularly challenging. Here, we evaluate the usefulness of the Ecosystem Management Decision Support (EMDS) system to assess suitability of sites to serve as a potential new reserve to support the research and teaching mission of the University of California Merced campus. The assessment was performed iteratively at three geographic scales, narrowing the spatial scope but increasing the detail of the criteria at each subsequent stage. The products of the assessment were the identification of a small number of high suitability parcels to be field inspected, and a flexible, transparent framework for assessing new areas in the future. Although the criteria might vary among reserve systems, our basic approach and use of EMDS could be readily adapted to other reserve systems in the U.S. and abroad.

Keywords Ecological reserve · Reserve planning · Spatial decision support · EMDS

1 Introduction

Many programs establish protected areas for a variety of purposes such as conservation of biodiversity and natural ecosystems. One specialized form of this is the protection of areas dedicated to scientific research and monitoring of environmental conditions and processes. In the United States, programs that designate scientific

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reserves (hereafter, ecological reserves) include the U.S. Forest Service (research natural areas, Lugo et al. 2006), the National Oceanic and Atmospheric Administration (National Estuarine Research Reserves, http://www.nerrs.noaa.gov/), and teaching and research reserves operated by academic institutions (Ford and Norris 1988). Such sites are known by many names: e.g., research natural areas, research reserves, natural reserves, experimental forests, biological stations, and field stations. I will refer to sites dedicated to protection for scientific study as *ecological research reserves*. In addition to supporting the research needs of the managing institution, ecological research reserves are often aggregated into networks of sites to facilitate comparative studies between ecoregions or to monitor phenomena across a greater range of conditions than is contained in any one institution's system. Examples include the Long-Term Ecological Research network funded by the National Science Foundation (Franklin et al. 1990; Hobbie et al. 2003) and the National Ecological Observatory Network (Keller et al. 2008). Similar programs and networks can be found throughout the world, and indeed there are proposals for international networks of research reserves (Peters et al. 2008).

Ecological research reserves provide many valuable services. They provide irreplaceable training opportunities for the next generation of scientists. Greater understanding of the natural world and its response to management practices is created, both directly from experimental studies but also from analysis of data archives collected at reserves. As Michener et al. (2009) observed, many of these discoveries would not be possible from isolated field studies, but only through the existence over time of a dedicated site with infrastructure, protection from incompatible uses, and a critical mass of creative minds. Further, findings from ecological research reserves may be incorporated into management policy for other lands in similar landscapes (Burke and Lauenroth 1993).

A thoughtful selection of sites is required to achieve these purposes. Land uses on the site and its neighborhood should be compatible with the mission of the reserve. If the mission is to isolate effects of management treatments, the ideal site would be relatively undisturbed. The ecosystems at the site should be important to study, either due to their rarity, their sensitivity to management practices or regional/global change, or the degree to which they represent biophysical environments that lack coverage by another reserve. In the context of significant climatic change, biophysical environment settings move across the landscape and are redefined. In this context, having a broad range of environmental settings represented within research reserve networks becomes especially important to detecting and understanding a variety of ecological and climatic changes.

The costs of initial acquisition and ongoing maintenance and management must also be considered. Setting aside land for a reserve may be politically controversial, either with neighboring landowners, or with other constituencies who had different interests in the site. Although research reserve networks generally have qualitative criteria for evaluating the suitability of individual sites, they usually lack an explicit, operational procedure for comparing and ranking candidate sites (Stoms et al. 1998). Use of a formal, explicit, transparent, and repeatable approach for reserve site selection is especially important where decisions are closely scrutinized.

Approaches used for selecting new reserve sites may be usefully divided into "bottom-up" versus "top-down" types. In the more common bottom-up approach, a specific site 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. A top-down approach, in contrast, rates all potential sites in an assessment region and identifies those that best meet the criteria. Obviously, the top-down process needs information for the criteria for all eligible sites. If the region of interest is large, the information available for all sites will be less detailed than for a single site in a bottom-up process. For example, the ecological condition of a single parcel could be assessed with a field survey, whereas the assessment of a large region may require broad-scale mapped data from remotely sensed or other sources.

The University of California Natural Reserve System (UC-NRS) (Norris 1968; Ford and Norris 1988) is the world's most extensive example of an academic ecological reserve program, with 34 natural reserves affiliated with eight of its ten campuses. In the early 21st century, the University of California (UC) was planning for the development of a tenth campus in the Central Valley near the city of Merced (Fig. 1). Anticipating that UC would establish one or more new NRS research and teaching reserves, a generic top-down decision-support framework was developed for selecting new site(s) based on existing UC guidelines (University of California 1984, published in the Appendix of this chapter). The framework was then adapted for three geographically nested stages (Fig. 1), where the criteria were tailored to the available spatial data appropriate to each scale.

Stage 1 assessed general suitability of the neighboring Sierra Nevada or San Joaquin Valley. Stages 2 and 3 further refined the criteria to assess site suitability for an NRS reserve in vernal pool-grassland habitat, in more detail, and over progressively smaller areas. This chapter describes how EMDS was used to frame the decision using a knowledgebase applied to (1) assessing suitability of the existing NRS reserves and (2) identifying specific land parcels of high suitability for a candidate reserve for the new Merced campus. Readers who wish to learn more about the details of the analyses that populated the data links of the knowledgebase are referred to Stoms et al. (2000, 2002).

2 Case Study

2.1 Assessment of Existing University of California Reserves

The UC-NRS employs a set of guidelines for evaluating the suitability of sites as new reserves (University of California 1984, published in the Appendix of this chapter). These guidelines are organized hierarchically. The topmost level is organized in three categories of suitability—scientific, academic, and administrative.

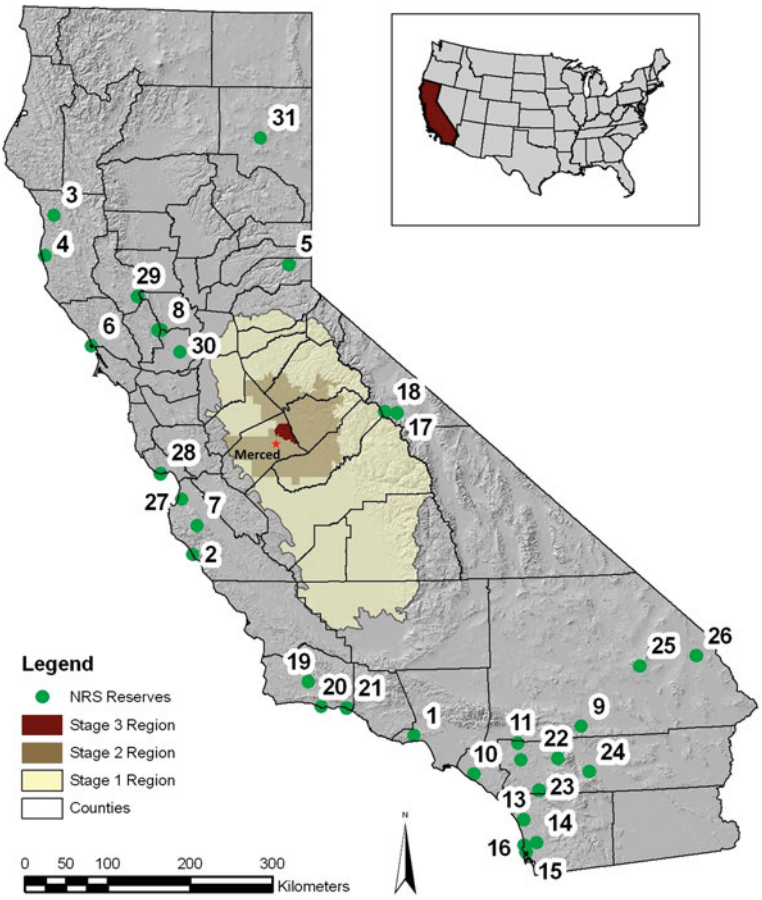


Fig. 1 Map of California showing three hierarchically organized assessment regions. To support a logical and systematic search for a new ecological research reserve with an under-represented ecosystem for the UC Merced campus, three stages of assessment (corresponding with the three mapped regions) were implemented in an hierarchically structured decision support model (see Stages 1–3 in the text). *Numbered points* identify existing NRS reserves at the time of the analysis (see Table 2 for the reserve names)

Scientific guidelines refer to the biological significance of the site as well as the integrity ("viability") of its ecosystems. Academic guidelines include the number of disciplines that could use the site for teaching or research, and the accessibility from the managing campus for those purposes. The administrative guidelines deal with filling gaps in representation of California's natural ecosystems, and the costs and manageability of the site. All these are only general guidelines, however, and do not specify how they should be measured, weighted relative to each other (Malczewski 1999; Jiang and Eastman 2000), or combined into an overall suitability rating (Hopkins 1977). Each assessment committee retains some discretion to determine

how the guidelines will be interpreted, whether with precisely measured variables, or with qualitative estimates of suitability.

The guidelines have several characteristics worth noting. First, they are organized hierarchically. The overall measure of the suitability of a site as a new ecological research reserve is based on three logical antecedents (i.e., the scientific, academic, and administrative criteria). Each of these guidelines is similarly predicated on additional antecedents specific to each criterion. Second, many guidelines are semantically and quantitatively imprecise, such as "close to a campus" and "include typical samples of widely distributed habitat types" Such guidelines are poorly represented by crisp threshold values. For example, it would be unreasonable to consider sites up to 25 km from campus as suitable but totally unsuitable if they are one meter beyond that threshold.

On balance, these characteristics of extant guidelines suggest the use of a fuzzy, knowledge-based approach as highly suited to the problem of reserve selection, wherein decision rules would be formulated as a series of equally applied propositions (Malczewski 2002, Chaps. 1 and 2). The propositions would be evaluated not as "true" or "false", in a strict Boolean sense (e.g., distance from campus $\leq$25 km from campus), but as continuous truth values, in which distance from campus, for example, is mapped into a membership function, in the set "close to campus." Formulating the problem in a knowledgebase both formalizes the relationship of the guidelines and the linkage to actual data, and provides insights into which factors are critical in determining the most suitable sites. The knowledgebase also provides a flexible decision-support environment in which the analyst can manipulate the criteria and their weightings, in a gaming sense, to determine the relative influence of various criteria.

The NRS guidelines were interpreted into a logic network using EMDS for ArcView®. As described earlier, the overall proposition that a site is suitable was decomposed according to the three primary criteria of scientific, academic, and administrative suitability (Fig. 2). A poor rating for any of those criteria should yield a relatively poor overall rating, and an excellent site should rate highly in all three criteria. The top network therefore uses an AND node to combine criteria. An AND node functions similarly to a MINIMUM operator, but in EMDS is based on a complex formula in which the minimum value strongly influences the result. The scientific criterion was represented by two subcriteria—viability of ecosystems and the significance of the habitat in a site. Likewise, academic suitability was represented by two subcriteria—the level of potential academic use and proximity to a campus. Administrative suitability was a product of the three subcriteria—the ability of an assessment unit to fill representation gaps, to add geographic balance to the NRS network, and to have favorable acquisition terms.

To make the logic network operational, EMDS requires that each terminal node of the network connect to an elementary topic at which data are evaluated. However, it is occasionally impractical that all criteria and subcriteria be mapped over large spatial domains. For instance, it is not feasible to assess potential acquisition terms for all properties of an assessment region that is thousands of

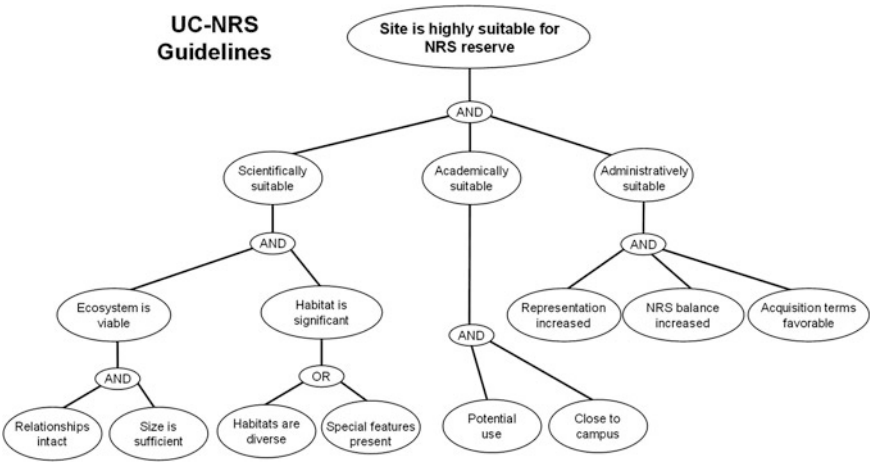


Fig. 2 The UC-NRS guidelines represented as a conceptual network of propositions. The overall proposition asserts that the "site is highly suitable for an NRS reserve." It consists of three subnetworks, joined by an "AND" node, which evaluates the degree to which the assessment unit is scientifically,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

square kilometers. Consequently, the logic network was adapted (Table 1, Fig. 3). The UC guidelines were not specific about how to measure ecosystem integrity or habitat significance. In view of the types of data available for the entire state of California, two sources were selected 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 assessed as the combination—number of plant community types and number of rare elements. Academic suitability was limited to a single criterion based on travel time from the site of the managing campus, because the level of current and potential use for teaching and research could not be determined for all sites. 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 subtopic was defined as either being distinct from the environments represented by the other NRS reserves or filling gaps from other programs or agencies (in this case from the California Gap Analysis Project, Davis et al. 1998). To ensure accurate comparison of existing reserve sites with sites to be considered in Stage 1 for the proposed new campus, the spatial units for the assessment had to be comparable. Thus, 6×6 mile square township areas (approximately 9,400 ha each) from the Public Land Survey were used as assessment units. All spatial information was aggregated to townships. These assessment units are larger than the actual NRS reserves.

The existing system of reserves was then assessed by the knowledgebase to determine (1) how well existing reserves met the selection criteria, as assessed by this knowledgebase and the available data, and (2) to establish a baseline for

Table 1 Data links in the Stage 1 knowledgebase and how they were derived

Data link to proposition (VARIABLE NAME)	Assumption or explanation	Data source	GIS processing steps
Road-effect zone is small (ROAD)	Areas with greater area affected by roads exhibit lower ecological integrity	California Gap Analysis Project (Davis et al. 1998) using TIGER roads layer (US Census)	Apply a buffer on roads, buffer width is related to road class. Summarize percentage of area in assessment units within the "road effect zone"
Native habitat is sufficiently large (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 shapefile (Davis et al. 1998)	Sum the total area with native vegetation in each assessment unit
Number of California Natural Diversity Database communities (DIVERSE)	The more diversity, the better the site is	California Gap Analysis Project (Davis et al. 1998)	Sum the number of unique plant community types in each assessment unit
Rare elements are present (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 the number of unique elements in each assessment unit from 1992 version of California Natural Diversity Data Base
Research accessible (TRAVEL)	Maximum travel time allowed is 1 h at 50 km/h for teaching, but is a continuous decreasing function for research needs	TIGER roads (US Census)	Travel time estimated by road segment, then a 'cost' distance is estimated. Total time is minimum time to each assessment unit
Fills NRS PCA gaps (NRSMINPCA)	Greater environmental distance from a reserve means site is less-well represented	Biophysical factors, various sources	Principal components analysis of nine biophysical factors, compute multivariate Euclidean distance from each NRS reserve. Find minimum value for each pixel, average values for each assessment unit

(continued)

Table 1 (continued)

Data link to proposition (VARIABLE NAME)	Assumption or explanation	Data source	GIS processing steps
Fills other gaps (VULNCOM)	Site gets added value if it also contributes to representation goals of other institutions	California Gap Analysis Project (Davis et al. 1998)	Score of assessment unit as weighted by vulnerability and area of all plant community types
Far from other NRS reserves (NRSDIST)	Maximizes geographic distribution of reserves	Locations of NRS reserves	Calculate Euclidean distance from all reserves; then determine minimum distance to each assessment unit

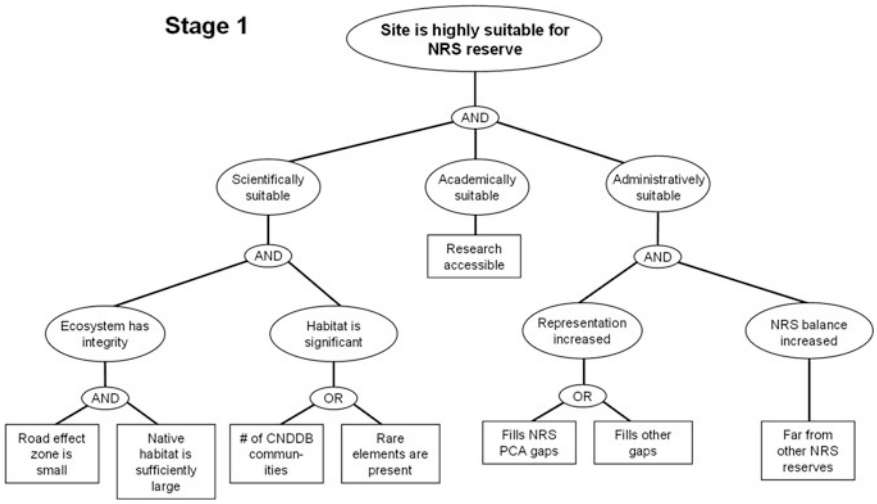


Fig. 3 The knowledgebase as implemented in Netweaver for the top-level proposition that the "site is highly suitable for an NRS reserve." Networks are shown as *ovals* and data links as *rectangles*. This network was used both in the assessment of existing reserves and in screening for Stage 1

comparing potential reserve sites with those previously identified by UC as highly suitable. At the time of this analysis, there were 34 reserves in the NRS; two of these are island reserves (Santa Cruz and Año Nuevo). Because of their uniqueness relative to onshore reserves, they were excluded from this assessment.

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 Lauenroth 1993). Because the concept of representativeness is so fundamental yet imprecise, this section focuses in greater detail on how this criterion of administrative suitability was measured.

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; Hargrove and Hoffman 2004). Nominally, the NRS uses an unpublished habitat classification and hopes to have 70 % of the extant types 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 the classification of habitats and communities are not consistent between reserves or with recognized classification systems.

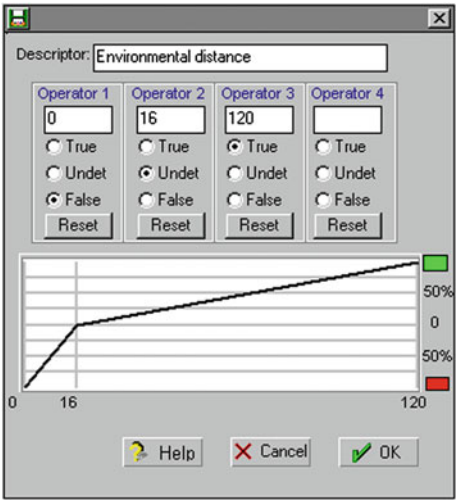


Fig. 4 A fuzzy membership function for the environmental distance of a site from its most similar NRS site

To maintain a continuous data space with measured environmental distance from existing reserves (Faith and Walker 1996), environmental variability of California was characterized via principal components analysis (PCA) of biophysical data sets covering climatic, topographic, and soil productivity factors. The PCA transformed data [on mean annual precipitation, January and July mean temperature and seasonal difference, solar irradiance, degree-day heat and cold sums, equivalent elevation (elevation adjusted for latitude), and soil productivity (Stoms and Hargrove 2000)] into a reduced data space capturing 91 % of the multi-variance. Finding the Euclidean distance of each 1-km^2 grid cell to the most similar research site represented by the NRS provided a quantitative measure of poorly represented environments (Michener et al. 2009). This data value was then transformed into a truth value through a fuzzy membership function defined in NetWeaver (Fig. 4). The resulting evaluation assessed the proposition that each 1-km^2 grid cell was adequately represented by an existing research reserve.

From this representativeness assessment, some regions of the state, particularly the south and central coast (where most of the UC campuses are located), appeared relatively well-represented. In fact, some habitats such as coastal wetlands were over-represented, and these reserves scored relatively low under this criterion. Regions that were less well-represented by the NRS included subalpine environments, some deserts, the mid-elevation conifer zone, and the Central Valley. The UC-Merced campus occurs in the Central Valley, close to mid-elevation Sierra Nevada conifer forests. New reserves for this campus would aid the goal of better representing California's landscapes if placed in Sierra Nevada mixed conifer forest.

To fill this gap, the assessment region for Stage 1 (Fig. 1) included most of the San Joaquin Valley and the west slope of the southern Sierra Nevada. Truth values for the proposition that existing NRS reserves were *highly suitable* for that purpose ranged 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 2). These reserves would appear to have been selected because they excelled at meeting some criteria but displayed limitations in other respects.

On the other hand, the highest scoring reserves did not exhibit very high scores for every suitability criterion; they were instead characterized by the absence of extremely low scores. In addition, sites with near-average scores for all three suitability criteria tended to score higher overall than sites with extreme values. Some degree of trade-off between criteria was always present. For example, compare the truth values for the highest rated (Jepson Prairie) and the second lowest rated (Kendall-Frost Mission Bay) NRS reserves (Table 2). 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 interpretation of these results must be used with caution because the logic and data used in our assessment were not identical to those used in selecting these reserves initially. The truth values describe the assessment unit containing the reserves, not the specific parcel, which may have special properties not represented in our regional-scale database. That is, this assessment is based on what information would be available to a planner looking broadly across the state for new reserves, whereas an evaluation team for a specific parcel of land would typically be privy to more specialized information. The most common criterion that caused the low scores was the fact that reserves were close to one another and therefore did not contribute highly to representing the ecological and geographic diversity of the state. They also tended to be located in urban areas (with low ecological integrity as measured by area affected by roads and lack of native habitats) 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 and poor in others.

Table 2 Truth value of the assessment units containing NRS reserves for top-level criteria in ascending numerical order

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

Numbers preceding the reserve name correspond to the site numbers in Fig. 1. Note that the assessment units are larger than the actual reserves

2.2 Stage 1

With the knowledgebase of ecological reserve suitability guidelines and the assessment of existing reserves in hand, the next task was to perform a three-stage suitability screening assessment specific to identifying potential reserve sites for the proposed UC Merced campus. The Stage 1 region for assessing suitability was derived from our representativeness assessment of the existing NRS network. It included the west side of the central and southern Sierra Nevada, plus a portion of the San Joaquin Valley surrounding the proposed site for the UC Merced campus. This region contains many environments not well-represented by the existing NRS network, does not contain any reserves or overlap with any other UC campus. The combined area totaled over 63,000 km^2 in 15 counties (Fig. 1).

As Stage 1 screened a large geographical region, the analysis needed to be at a coarse scale. For this stage therefore, small "planning watersheds" (mean size of approximately 3,300 ha, Menning et al. 1997) were used as the assessment units in the Sierra Nevada portion of the region. For the San Joaquin Valley, where planning watersheds have not been delineated, 6 × 6 mile townships (approximately 9,400 ha each) from the Public Land Survey were used. All spatial information was aggregated to planning watersheds or townships. These assessment units were larger than a typical UC-NRS site, but 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 knowledgebase (Table 1, Fig. 3) 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 (Davis et al. 1998) that mapped land cover and land ownership for the entire state. These and additional data were interpreted by various GIS analyses, as described in Table 1 and Stoms et al. (2000), to generate the data evaluated in the elementary topics (the lowest level of the logic network).

Applying the knowledge-based logic network to the data links from the GIS database generated truth values for every assessment unit in the Stage 1 region (Fig. 5). 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 assessment units displayed values below 0.7. *Travel time* from campus was a very strong constraint on rankings, such that the highest ranked units fell within a 2-h driving distance. Within that radius, there were units that scored above 0.6. Beyond that time-limited distance from campus, most assessment units in the Sierra Nevada and at the southwestern corner of the study area showed low positive values. Most units in the agricultural Central Valley displayed negative scores as a result of combined low *ecological integrity* and *representativeness* values. Assessment units in the highest elevation zone of the Sierra Nevada scored very high on *ecosystem integrity* but low for *travel time* and *representativeness* (some units were inaccessible by road because they reside in designated wilderness). Thus many sites displayed high truth values for some criteria but low values with at least one other.

The range of *suitability* truth values for the UC Merced assessment region was similar in comparison with the range for the existing reserves (Table 2). That is, existing NRS reserves were on average slightly more suitable than the average assessment unit in the Stage 1 assessment region. Existing reserves fared slightly better on *scientific criteria*, on average, than the assessment region, but relatively poorer for *administrative criteria*. The *scientific criteria* results could be explained by the large number of assessment units that were highly impacted by urban and agricultural land uses. This 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 while the Stage 1 assessment region tends to be dissimilar with the existing network. By the *academic suitability* criterion, the existing reserves scored higher on average than the Stage 1 assessment region, because they were generally closer to their sponsoring campus. Most of the assessment units for the Stage 1 region lie beyond a 2-h travel time and therefore had low truth values for *academic suitability*. These results indicate that at least some assessment units in the Stage 1 region were comparably suitable to existing NRS reserves, based on the NRS guidelines.

2.3 Stage 2

The Stage 1 suitability assessment identified several areas having a roughly circular outline (strongly influenced by *travel time*), where *suitability* truth values of assessment units were consistently greater than 0.2, and mostly greater than 0.4 (Fig. 5). This circular area became the Stage 2 assessment subregion for more detailed application of the logic network. The Stage 2 assessment subregion included portions of five counties (Tuolumne, Stanislaus, Merced, Mariposa, and Madera). Within this area, there are several sites currently managed for conservation or research purposes that could be considered for NRS use or to complement an existing NRS reserve without additional university management. This observation created a potential opportunity to establish a series of ecological research reserves along an ecological gradient over several thousand meters of elevation range, which could be especially valuable to support global change studies (Zhang et al. 1997).

The goal of the Stage 2 assessment was to further narrow the pool of potential sites for NRS reserves and more specifically to assess suitability to represent the vernal pool/grassland habitat type. Vernal pool and grassland ecosystems were targeted because of their regional ecological significance and their close association with the proposed location for the new campus. The vicinity of the proposed Merced campus is considered the largest region of dense vernal pool habitat in California (Holland 2000). Large, dense vernal pool complexes are more likely to contain a diversity of pool sizes, depths, and duration of inundation, and therefore

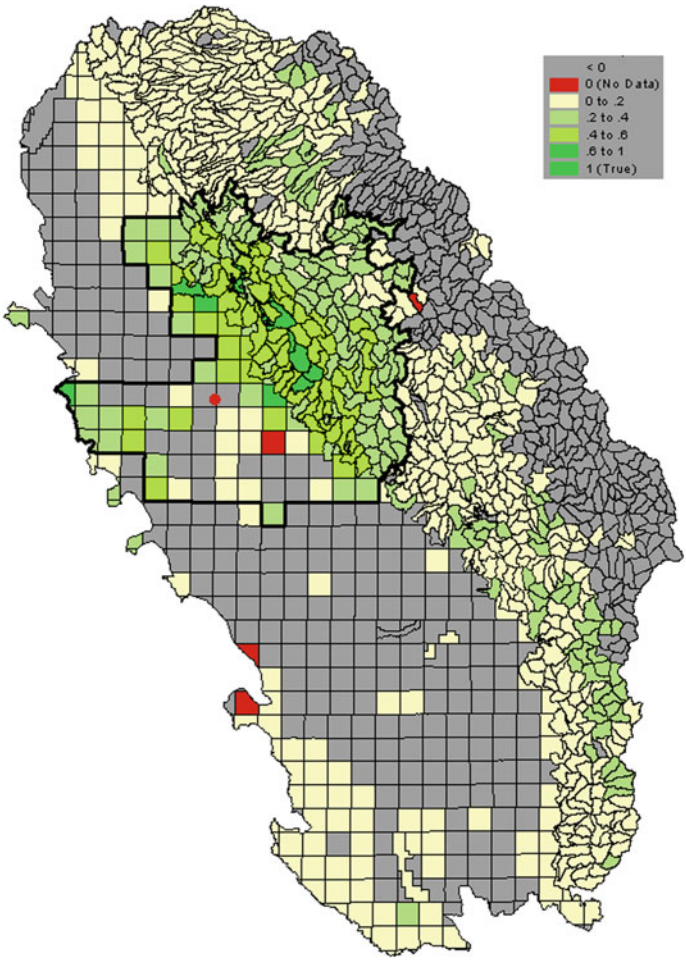


Fig. 5 Map of suitability in the Stage 1 assessment region with the outline (*bold*) of the proposed Stage 2 region. The city of Merced is shown as a *red dot*

support more species than sites with small or less dense complexes (Mead 1996). 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). 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).

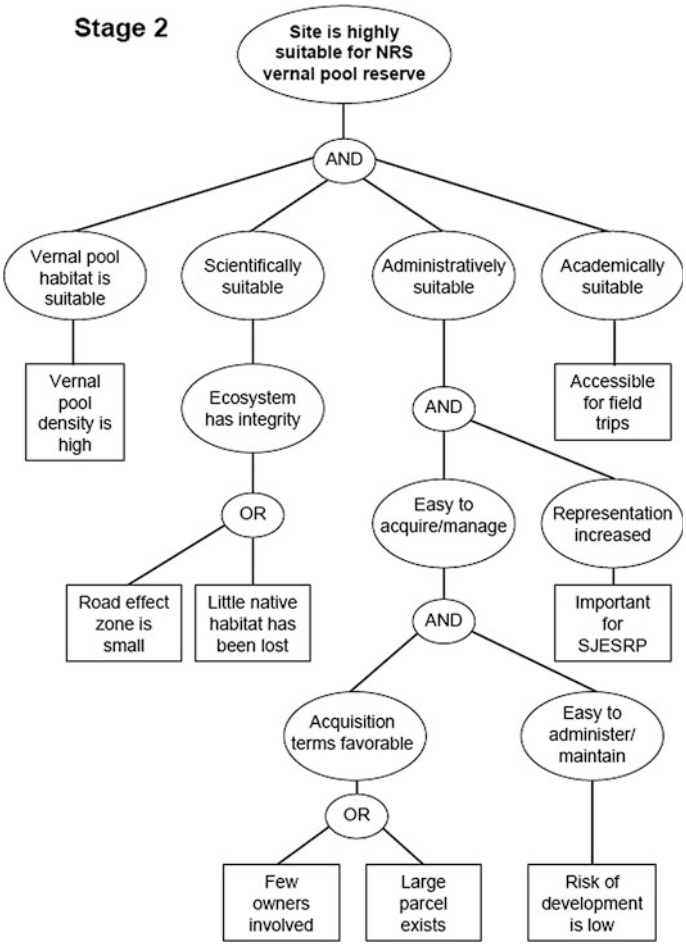


Fig. 6 The network for the Stage 2 proposition that the "site is highly suitable for an NRS vernal pool reserve." Networks are shown as *ovals* and data links as *rectangles*. With kind permission from Springer Science+Business Media (Stoms et al. 2002, p 549, Figure 2)

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* (Fig. 6). There were three primary differences distinguishing Stage 1 from Stage 2. First, because the Stage 2 assessment was focused on a specific habitat type, a fourth network was added to specifically 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 was detached from the *scientific suitability* network and promoted to a top-level network. Second, the smaller size of the Stage 2 assessment subregion permitted more detailed information to be included in the logic networks. The third change

was that Stage 1 criteria were not carried over to Stage 2 if they no longer helped distinguish relative suitability. For instance, in Stage 2, all assessment units adequately filled gaps in the NRS, so the criterion was no longer useful.

The nature of the existing vernal pool density map (Holland 1998) necessitated the use of a different multi-criteria analysis function in EMDS. This map contained area polygons classified as having high, medium, or low densities of vernal pools. Any given assessment unit therefore might have some combination of these three, as well as land with no vernal pools. Because these class data could not be converted to continuous values, pool density was calculated as a weighted sum of the proportions of the assessment unit in each density class. This calculated value could then be translated into a truth value that "vernal pool density is high."

Scientific suitability in Stage 2 was characterized by the integrity of the ecosystem in terms of area affected by roads (Stoms 2000) and land use conversion from photo-interpreted maps of farmland use (Fig. 6). *Academic suitability* was defined solely by travel time from the proposed campus site as modeled over the road network using previously stated speed and distance assumptions. Because of the large size of the assessment subregion, data on individual parcels were not available. Instead, the potential ease of acquisition was based on the number of landowners and size of largest parcel in a unit. The assumption behind these criteria was that it would be less desirable to assemble a reserve from many small parcels with multiple owners rather than from a few larger parcels. 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 (see Stoms 2000 for details). 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 from the California Farmland Mapping and Monitoring Program (http://conservation.ca.gov/dlrp/fmmp/Pages/Index.aspx). Site importance was also based on data from the San Joaquin Endangered Species Recovery Plan (U. S. Fish and Wildlife Service 1998).

The Stage 2 assessment subregion encompassed over 12,628 km^2 (Fig. 7) or 20 % of the Stage 1 assessment region (Fig. 1). To allow finer resolution of the Stage 2 assessment, the assessment units were redefined so that they would 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. This process delineated 623 assessment units, ranging in size from 136 to 12,285 ha, with a mean size of 2,027 ha (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).

The overall suitability, therefore, gave the highest truth values (0.601–0.924) to a small set of contiguous assessment units surrounding, and including, the proposed campus site (Fig. 7). A few additional assessment units had moderately high scores just north or south of the most highly rated units. The areas with the highest density of vernal pools occurred along the grassy base of the Sierra Nevada, with a

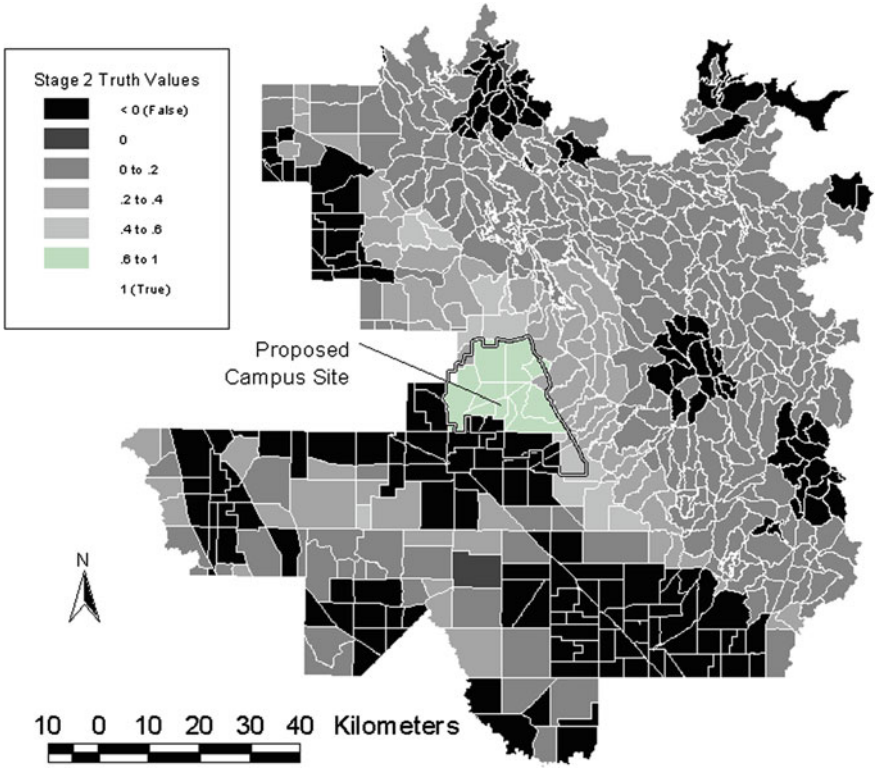


Fig. 7 Map of truth values for vernal pool site suitability for sites within the stage 2 assessment region. The *bold black outline* with *white inner line* shows the Stage 3 planning boundary. With kind permission from Springer Science+Business Media (Stoms et al. 2002, p 551, Figure 3)

secondary zone in the wetlands near the various wildlife refuges west of Merced. The large extent of dense vernal pool complexes in these assessment units would most likely contain a broader diversity in pool size, depth, duration of inundation, and number of species than sites with small or less dense complexes (Mead 1996). These same locations were also important 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, rated the ranchlands in the vernal pool zone among the highest suitability sites. Assessment units in the Sierra Nevada had high ecological integrity but rated very low to low positive values because they contained few or no vernal pools. Otherwise, assessment units tended to have negative truth values, and were unsuitable for a new NRS vernal pool habitat reserve.

The area containing and surrounding the proposed UC Merced campus contained a very dense complex of vernal pools, among the best remaining examples

in the Central Valley (Holland 2000). These assessment units also achieved a high level of concurrence with the UC-NRS guidelines for their *scientific*, *academic*, and *administrative suitability*, were relatively intact ecologically, contained few roads or converted lands, consisted of larger ranches rather than small farms or rural residential lots; and were within an easy commuting distance for class field trips. There were other vernal pool complexes within the Stage 2 assessment subregion that perhaps rivaled those near the campus in size and density; however, the sites containing them did not meet the university guidelines as well as those closer to the campus. Only the highly rated assessment units in the vicinity of the proposed campus (Fig. 7) were further evaluated in Stage 3. Other vernal pool sites were not evaluated further unless no available parcels could be found among the Stage 3 candidates.

2.4 Stage 3

In Stage 3, the NRS guidelines were coded into a logic network that was similar to Stages 1 and 2, starting with the same three primary criteria (*scientific, administrative, and academic suitability*); however, *academic suitability* based on travel time from campus was considered uniform across all parcels (after Stage 2 analysis) and dropped from the Stage 3 model). The scientific and administrative suitability of assessment units was then assessed only for vernal pool/grassland habitat in Stage 3 as it was in Stage 2. The logic was 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, suitability was based on 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, soil mapping units (Arkley 1954) were used to infer the pedological diversity and any associated biological diversity. Second, the smaller size of the assessment region permitted detailed parcel-level information to be included in the logic networks. For instance, information on actual and potential land use from assessor's records was used to estimate the existing capital investment and land value that influences the degree of difficulty in acquiring parcels for a new reserve. The full logic network and terminal data nodes are shown graphically in Fig. 8.

Stage 3 analysis narrowed the domain to 430 km^2 (Figs. 1, 9), or 3 % of the Stage 2 assessment area (Figs. 1, 5), and less than 1 % of Stage 1 area (Fig. 1). To allow finer resolution of the Stage 3 assessment, the assessment units were redefined as 298 assessor's parcels from Merced County. The parcel coverage, purchased from the county, contained attribute data about current use, zoning and general plan designation, and the owner. Several large ranches encompass multiple parcels so the number of landowners is smaller than the number of parcels.

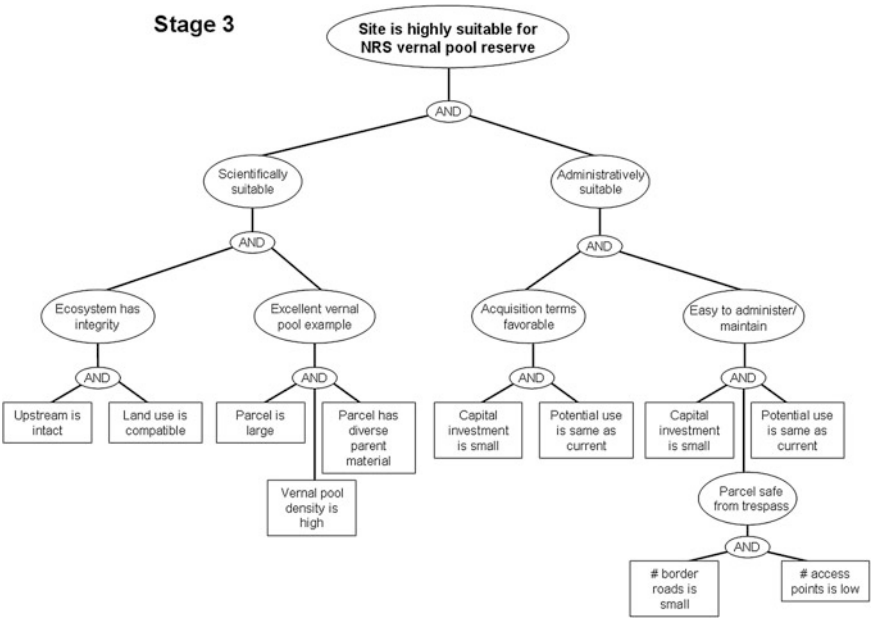


Fig. 8 The network for the Stage 3 proposition that the "site is highly suitable for an NRS vernal pool reserve." Networks are shown as *ovals* and data links as *rectangles*. With kind permission from Springer Science+Business Media (Stoms et al. 2002, p 552, Figure 4)

Three clusters of parcels labeled A, B, and C (Fig. 9) had the highest overall suitability (greater than 0.9). Most parcels had relatively high suitability for most factors, except for those on the edges of the Stage 3 area that are currently agricultural, or are zoned for development, and those that are influenced by irrigation 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 Stage 3 area had only a single soil parent material type in each parcel and therefore relatively low diversity. A few parcels at lower elevations 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. Generally, the parcels in the north of the Stage 3 region 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. The most highly rated parcels had truth values too close to confidently select one or more as the appropriate site for a reserve, given the nature of the 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.

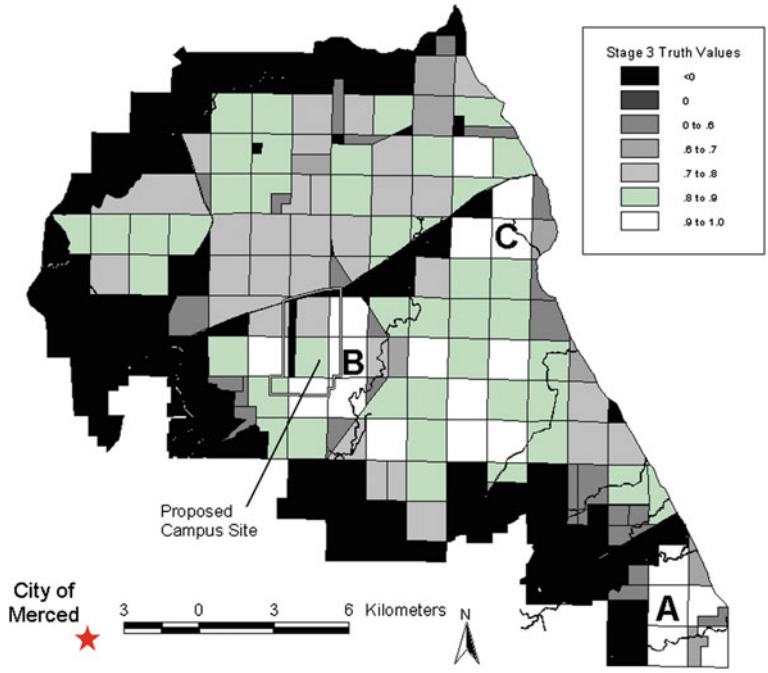


Fig. 9 Map of truth values for vernal pool site suitability for sites within the Stage 3 assessment region. The *bold line* indicates the boundary of the proposed UC Merced campus site. With kind permission from Springer Science+Business Media (Stoms et al. 2002, p 553, Figure 5)

3 Conclusions and Future Directions

Selection of ecological research reserves tends to be opportunistic, where one or more known sites are compared against formal or informal criteria. The UC-NRS guidelines, for example, define a general set of qualities UC reserves should possess, but provide little specific guidance for a quantitative, systematic, and repeatable process for selecting sites for the NRS network. This is not uncommon among organizations that designate lands for research reserves. The Forest Service, for instance, has similar guidelines for its network of research natural areas (Stoms et al. 1998). The informal process for assessing a single candidate site is analogous to how most people purchase a house. They may have a particular neighborhood in mind that constrains the search area. Then they look at a few houses. Once they find one that has the features they must have (e.g., close enough to work) and many they want (e.g., nice style), they make a decision to make an offer. But selecting a reserve is essentially a permanent commitment on behalf of the institution with important implications for the scientific validity of management recommendations, political controversy over land uses, and costs to the

institution, taxpayers, or donors. In high profile cases, the screening process must be explicit and transparent.

The original impetus for creating the UC-NRS was the actual loss of a wild, natural study site (Ford and Norris 1988), which explains the criterion favoring undisturbed condition. Although maintaining sites for monitoring baseline reference conditions is still valuable, there has also been a paradigm shift toward scientific study of coupled human and natural systems (Collins et al. 2007; Liu et al. 2007). Study sites for this type of integrated research span the land use spectrum (Liu et al. 2007). In principle, a hierarchical knowledgebase could be developed that considers both natural and human criteria for assessing potential research site suitability, but this remains a future research need.

EMDS provides a solid decision-support tool for organizing criteria, expert knowledge, and spatial data to structure the problem of screening sites for potential ecological research reserves. NetWeaver allows the analyst to structure objectives hierarchically from the most general down to the specific. This hierarchical structure superbly matched the UC-NRS guidelines. The fuzzy logic approach facilitates the interpretation of vague or imprecise criteria such as "close to campus" into measurable continuous values. Using the fuzzy membership function standardizes all criteria, both qualitative and quantitative, to a common measurement scale with a common interpretation of the truth of the proposition associated with the criterion. Fuzzy logic is based upon a rigorous mathematical foundation with formal operators, avoiding the ad hoc nature of many multicriteria analyses. On the other hand, NetWeaver also supports the use of many mathematical operations, for example, we used multiplication within NetWeaver to calculate the weighted sum of vernal pool density classes, as described above.

One particularly attractive feature of EMDS is how it tracks the truth value of all propositions at all levels of the knowledgebase hierarchy. This transparency allows a decision maker or stakeholder to explore precisely how assessment units were rated as they were. Not only does this increase understanding of the complex information and hopefully greater acceptance of the results, but it can also reveal errors in logic and where a criterion may be improperly specified. This wealth of information throughout the knowledgebase hierarchy can be rather daunting, however. We found it particularly useful to lay out the whole hierarchy in poster form to absorb the big picture. The poster contained the full logic network, with each proposition and data link portrayed with both a map of its values (Figs. 5, 7, and 9) and the fuzzy membership function (Fig. 4). Plotting this in poster format facilitated reviews of the knowledgebase and its implications for the suitability assessment. We note that other studies found utility in presenting the map hierarchy along with the logic representations (e.g., see Hessburg et al. 2007; Reynolds et al. 2009; Staus et al. 2010).

EMDS can be readily adapted to various geographic scales of assessment. In this case study, assessments for the UC-NRS guidelines were performed at three scales. The criteria at top levels remained the same, but they were modified at the lower levels (stages) in response to the availability and appropriate usage of higher resolution data. For example, in Stage 1, ecological condition was defined by a

measure of road density and area of native habitat from a low resolution (1:100,000) land cover map. In Stage 2, percent conversion was calculated from a higher resolution (1:24,000) land use map. In Stage 3, condition was based on the intactness of the catchment upstream of the parcel and the compatibility of the specific land use with management of a reserve. Thus the finest resolution data were only required for a relatively small area. While this does not guarantee that excellent parcels were not overlooked at the coarser scales, it expedited analysis and because of its explicitness can be subjected to review by regional experts.

The vernal pool reserve case study described in this chapter represents just one type of application related to siting and designing reserves that a fuzzy logic assessment of suitability could support. In this example, the decision maker's concern was principally with the suitability of each assessment unit to support the mission of the reserve system. Where setting aside land for scientific or conservation purposes potentially conflicts with other interests, the knowledgebase may be expanded to incorporate the objectives of other stakeholders. Wood and Dragicevic (2007) illustrate this type of expanded scope using fuzzy logic for assessing potential marine protected areas. They assessed two conflicting objectives—biodiversity conservation and fisheries profit-maximization—as separate primary topics of their knowledgebase. Interestingly, some criteria were (appropriately) applied to both objectives (e.g., species persistence).

The assessment units used to identify a candidate reserve do not necessarily make good boundaries for its final design. Once a general location has been selected for consideration as a reserve, multi-criteria analysis could also be used to design its final configuration. Bojorquez-Tapia et al. (2003, 2004) demonstrated the use of multi-criteria suitability analysis with optimization modeling to reach consensus on the location of boundaries for a park (2004) and a biosphere reserve (2003). The design for the park addressed maximizing conservation value within the boundary and minimizing conflicts at the boundaries. The biosphere reserve design balanced winter habitat for Monarch butterflies with timber production from the local forest. The use of a fuzzy logic knowledgebase to design reserve boundaries has not been reported in the scientific literature to date; however, in principle, the approach might be the reverse of that used in the present study. In the reserve boundary design case, the assessment units would be smaller than a reserve and the assessment would involve assembling a set of units that make a logical whole. With respect to the case study in this chapter, a final reserve might be assembled from a set of contiguous assessor's parcels similar to the clusters labeled in Fig. 9. In a related example, Staus et al. (2010) used EMDS to map high conservation value lands in western Oregon to identify contiguous blocks of land worth investigating further based on their value and condition for both terrestrial and aquatic biodiversity.

Designing networks or systems of conservation areas is frequently done by selecting a set of sites that optimally satisfies specific conservation targets (e.g., a percentage of the area of each habitat type, Margules and Pressey 2000). Optimization is used to minimize the cost (or total area) of the network. Economic cost is often difficult to estimate in these planning projects, so planners sometimes use

the size of the assessment or planning units as a surrogate for cost, i.e., meet conservation targets in the least total area. The quality or integrity of the unit can also be considered a type of cost. Davis et al. (1996, 1999) used a multi-criteria measure of "unsuitability" to standardize quality in cost terms, combined with area, to select units that minimized total area and unsuitability. Humphries et al. (2008) adapted this framework but used a knowledgebase approach to assess unsuitability for conservation. The biological significance criteria in conservation area network selection is detached from suitability and treated as a minimal constraint in the reserve system optimization problem. Similarly, cost is detached from the suitability proposition and becomes the objective function to be minimized by the network.

Stoms et al. (2005) proposed using a logic network to assess the suitability of terrestrial sites based on (1) the risk to coastal ecosystem features where the land was not in protected status, and (2) the importance of coastal resources at risk. This idea extended the traditional measure of site suitability based on intrinsic factors to include its geographic neighborhood. The land-sea linkage proposed by Stoms et al. (2005) would also incorporate ecological linkages between sites and ecosystems.

The theme of this chapter has been the application of fuzzy logic networks in planning for ecological research reserves. It should be noted that the basic framework is equally appropriate for screening for other types of protected areas, such as national wildlife refuges, nature preserves, regional parks, and urban open space. More generally, EMDS can support suitability assessment for any form of land use where the criteria are either precise or imprecise.

Acknowledgments The financial support for this study by the University of California, Office of the President is gratefully acknowledged. Frank Davis conceived of the idea of applying EMDS to this application and guided the development of the knowledgebase. Alex Glazer of the UC-NRS provided valuable comments. Keith Reynolds and Noah Goldstein gave technical advice on applying the EMDS software. Jennifer McDonald assisted with GIS analysis, and the Merced County Association of Governments and the Map and Imagery Laboratory at UCSB helped provide data.

A.1 4 University of California Natural Reserve System–NRS Acquisition Guidelines June 1984

A.1.1 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 human 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 humans 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 enamored 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 possesses special features, such as:

- Important variations of the common habitat types, such as different successional stages (including important human-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.

A.1.2 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 3-h laboratory period. Sites close to a campus will naturally receive more use and make a correspondingly high contribution to the NRS.

A.1.3 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.

References

Arkley RJ (1954) Soils of eastern Merced County, California. University of California, College of Agriculture. Agricultural Experiment Station, Berkeley

Belbin L (1995) A multivariate approach to the selection of biological reserves. Biodivers Conserv 4:951–963

Bojorquez-Tapia LA, Brower LP, Castilleja G, Sanchez-Colon S, Hernandez M, Calvert W, Diaz S, Gomez-Priego P, Alcantar G, Melgarejo ED, Solares MJ, Gutierrez L, Juarez MD (2003) Mapping expert knowledge: redesigning the monarch butterfly biosphere reserve. Conserv Biol 17:367–379

Bojorquez-Tapia LA, de la Cueva H, Diaz S, Melgarejo D, Alcantar G, Jose Solares M, Grobet G, Cruz-Bello G (2004) Environmental conflicts and nature reserves: redesigning Sierra San Pedro Martir National Park, Mexico. Biol Conserv 117:111–126

Burke I, Lauenroth WK (1993) What do LTER results mean? extrapolating from site to region and decade to century. Ecol Model 67:19–35

Collins SL, Swinton SM, Anderson CW, Benson BJ, Brunt J, Gragson T, Grimm NB, Grove M, Henshaw D, Knapp AK, Kofinas G, Magnuson JJ, McDowell W, Melack J, Moore JC, Ogden L, Porter JH, Reichman OJ, Robertson GP, Smith MD, Vande Castle J, Whitmer AC (2007) Integrative science for society and the environment: a strategic research initiative. Publication #23 of the US LTER Network. LTER Network Office, Albuquerque, NM

Davis FW, Stoms DM, Andelman S (1999) Systematic reserve selection in the USA: an example from the Columbia Plateau ecoregion. Parks 9:31–41

Davis FW, Stoms DM, Church R.L, Okin WJ, Johnson KN (1996) Selecting biodiversity management areas. In: Sierra Nevada Ecosystem Project: final report to Congress, vol. II. Assessments and scientific basis for management options. University of California, Centers for Water and Wildlands Resources, Davis, pp 1503–1528

Davis FW, Stoms DM, Hollander AD, Thomas KA, P. A. Stine, Odion D, Borchert MI, Thorne JH, Gray MV, Walker RE, Warner K, Graae J (1998) The California Gap Analysis Project-final report. University of California, Santa Barbara. Available at: http://www.biogeog.ucsb.edu/projects/gap/gap_rep.html

Engelking LD, Humphries HC, Reid MS, DeVelice RL, Muldavin EH, Bourgeron PS (1994) Regional conservation strategies: assessing the value of conservation areas at regional scales. In: Jensen ME, Bourgeron PS (eds) Eastside forest ecosystem health assessment. Forest service general technical report PNW, Portland, US, pp 208–223

Faith DP, Walker PA (1996) Environmental diversity: on the best-possible use of surrogate data for assessing the relative biodiversity of sets of areas. Biodivers Conserv 5:399–415

Ford LD, Norris KS (1988) The University of California natural reserve system. Bioscience 38:463–470

Franklin JF, Bledsoe CS, Callahan JT (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

Hargrove WW, Hoffman FM (2004) A flux atlas for representativeness and statistical extrapolation of the AmeriFlux Network. Oak Ridge National Laboratory Technical Memorandum ORNL/TM–2004/112. Available at http://www.geobabble.ornl.gov/flux-ecoregions

Hessburg PF, Reynolds KM, Keane RE, James KM, Salter RB (2007) Evaluating wildland fire danger and prioritizing vegetation and fuels treatments. For Ecol Manag 247:1–17

Hobbie JE, Carpenter SR, Grimm NB, Gosz JR, Seastedt TR (2003) The US Long Term Ecological Research program. Bioscience 53:21–32

Holland RF (1998) Great Valley vernal pool distribution, photorevised 1996. In: Witham CW, Bauder ET, Belk D, Ferren WR, Ornduff R (eds) Ecology, conservation, and management of vernal pool ecosystems. California Native Plant Society, Sacramento, pp 71–75

Holland RF (2000) The Flying M Ranch: soils, plants, and vernal pools in eastern Merced County. Fremontia 27(28):28–32

Hopkins L (1977) Methods for generating land suitability maps: a comparative evaluation. J Am Inst Plan 43:386–400

Humphries HC, Bourgeron PS, Reynolds KM (2008) Suitability for conservation as a criterion in regional conservation network selection. Biodivers Conserv 17:467–492

Jiang H, Eastman JR (2000) Application of fuzzy measures in multi-criteria evaluation in GIS. Int J Geogr Inf Sci 14:173–184

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

Keller M, Schimel DS, Hargrove WW, Hoffman FM (2008) A continental strategy for the National Ecological Observatory Network. Front Ecol Environ 6:282–284

Kirkpatrick JB, Brown MJ (1994) A comparison of direct and environmental domain approaches to planning reservation of forest higher plant communities and species in Tasmania. Conserv Biol 8:217–224

Liu J, Dietz T, Carpenter SR, Alberti M, Folke C, Moran E, Pell AN, Deadman P, Kratz T, Lubchenco J, Ostrom E, Ouyang Z, Provencher W, Redman CL, Schneider SH, Taylor WW (2007) Complexity of coupled human and natural systems. Science 317:1513–1516

Lugo AE, Swanson FJ, González OR, Adams MB, Palik B, Thill RE, Brockway DG, Kern C, Woodsmith R, Musselman R. (2006) Long-term research at the USDA Forest Service's experimental forests and ranges. Bioscience 56: 39–48

Mackey BG, Nix HA, Hutchinson MF, MacMahon JP, Fleming PM (1988) Assessing representativeness of places for conservation reservation and heritage listing. Environ Manag 12:501–514

Malczewski J (1999) GIS and multicriteria decision analysis. Wiley, New York, p 392

Malczewski J (2002) Fuzzy screening for land suitability analysis. Geogr Environ Model 6:27–39

Margules CR, Pressey RL (2000) Systematic conservation planning. Nature 405:243–253

Mead DL (1996) Determination of available credits and service areas for ESA vernal pool preservation banks. In: Witham CW, Bauder ET, Belk D, Ferren JWR, Ornduff R (eds.) Ecology, conservation, and management of vernal pool ecosystems. pp 274–281, California Native Plant Society, Sacramento, California

Menning KM, Erman DC, Johnson KN, Sessions J (1997) Modeling aquatic and riparian systems, assessing cumulative watershed effects, and limiting watershed disturbance. Sierra Nevada ecosystem project. Final report to Congress University of California, Centers for Water and Wildlands Resources, Davis, California, pp 33–51

Michener WK, Bildstein KL, McKee A, Parmenter RR, Hargrove WW, McClearn D, Stromberg M (2009) Biological field stations: research legacies and sites for serendipity. Bioscience 59:300–310

Norris KS (1968) California's Natural Land and Water Reserve System. Bioscience 18:415–417

Peters DP, Groffman PM, Nadelhoffer KJ, Grimm NB, Collins SL, Michener WK, Huston MA (2008) Living in an increasingly connected world: a framework for continental-scale environmental science. Front Ecol Environ 6:229–237

Pressey RL, Ferrier S, Hager TC, Woods CA, Tully SL, Weinman KM (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. For Ecol Manage 85:311–333

Reiner R, Swenson R (2000) Saving vernal pools in the Cosumnes River watershed. Fremontia 27(28):33–37

Reynolds KM, Hessburg PF, Keane RE, Menakis JP (2009) National fuel-treatment budgeting in US federal agencies: capturing opportunities for transparent decision-making. For Ecol Manag 258:2373–2381

Smith DW, Verrill WL (1996) Vernal pool-soil-landform relationships in the Central Valley, California. In: Witham CW, Bauder ET, Belk D, Ferren JWR, Ornduff R (eds) Ecology, conservation, and management of vernal pool ecosystems. pp 15–23, California Native Plant Society, Sacramento, California

Staus NL, Strittholt JR, DellaSala DA (2010) Evaluating areas of high conservation value in western Oregon with a decision-support model. Conserv Biol 24:711–720

Stoms DM (2000) GAP management status and regional indicators of threats to biodiversity. Landscape Ecol 15:21–33

Stoms DM, Borchert MI, Moritz MA, Davis FW, Church RL (1998) A systematic process for selecting representative Research Natural Areas. Nat Area J 18:338–349

Stoms DM, Davis FW, Andelman SJ, Carr MH, Gaines SD, Halpern BS, Hoenicke R, Leibowitz SG, Leydecker A, Madin EMP, Tallis H, Warner RR (2005) Integrated coastal reserve planning: making the land-sea connection. Front Ecol Environ 3:429–436

Stoms DM, Hargrove WW (2000) Potential NDVI as a baseline for monitoring ecosystem functioning. Int J Remote Sens 21:401–407

Stoms DM, McDonald JM, Davis FW (2000) Knowledge-based site suitability assessment for new NRS reserves for the proposed UC Merced campus. University of California, Santa Barbara. Online at http://www.biogeog.ucsb.edu/projects/snner/nrs_report.pdf

Stoms DM, McDonald JM, Davis FW (2002) Fuzzy assessment of land suitability for scientific research reserves. Environ Manag 29:545–558

University of California (1984) NRS acquisition guidelines. Oakland, California (Reprinted in the appendix of this chapter)

U. S. Fish and Wildlife Service (1998) Recovery plan for upland species of the San Joaquin Valley. California, Region 1, Portland, Oregon

Wood LJ, Dragicevic S (2007) GIS-based multicriteria evaluation and fuzzy sets to identify priority sites for marine protection. Biodivers Conserv 16:2539–2558

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