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ENVIRONMENTAL ASSESSMENT

Fuzzy Assessment of Land Suitability for Scientific Research Reserves

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ABSTRACT / Evaluating the characteristics of a set of sites as potential scientific research reserves is an example of land suitability assessment. Suitability in this case is based upon multiple criteria, many of which can be linguistically imprecise and often incompatible. Fuzzy logic is a useful method for characterizing imprecise suitability criteria and for combining criteria into an overall suitability rating. The Ecosystem Management Decision Support software combined a fuzzy logic knowledge base we developed to represent the assessment problem with a GIS database providing site-specific data for the assessment. Assessment of sites as a potential natural reserve for the new University of California campus at Merced demonstrates the benefits of fuzzy suitability assessment. The study was conducted in three stages of successively smaller assessment regions with increasingly fine spatial resolution and specificity of criteria. Several sites were identified that best satisfy the suitability criteria for a reserve to represent vernal pool habitat.

Many programs establish nature reserves for a variety of purposes. The IUCN Commission on National Parks and Protected Areas classifies reserves designated primarily for scientific research, education, and environmental monitoring as "scientific reserves" (Category Ia). Preservation of ecosystems and maintenance of ecological processes must be overriding goals for scientific reserves (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 and others 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 and others 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 and others 1977, Ford and Norris 1988) is the world's most extensive example of the latter, with 33 natural reserves affiliated with its nine campuses.

KEY WORDS: GIS; Fuzzy logic; Knowledge base; University of California Natural Reserve System; Ecosystem Management Decision Support software; Vernal pools; Land suitability analysis

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While these programs have developed qualitative criteria for evaluating the suitability of individual sites as research reserves, they generally lack an explicit, operational procedure for comparing candidate sites (Stoms and others 1998). In practice, site selection inevitably involves a trade-off between conflicting goals. For example, one goal may be easy access for research and management, while another requires minimal disruption of natural ecological processes. Roads tend to support the first goal but often run counter to the second goal.

All land use decisions are political, and setting aside potentially productive land for research purposes can be especially controversial. Furthermore, ecological findings from research reserves may be incorporated into management policy for other lands in similar landscapes (Burke and Lauenroth 1993). Use of a formal, explicit, and repeatable approach to selection is especially important where the decision is critically scrutinized and site selection has serious implications.

Approaches used for selecting new reserve 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

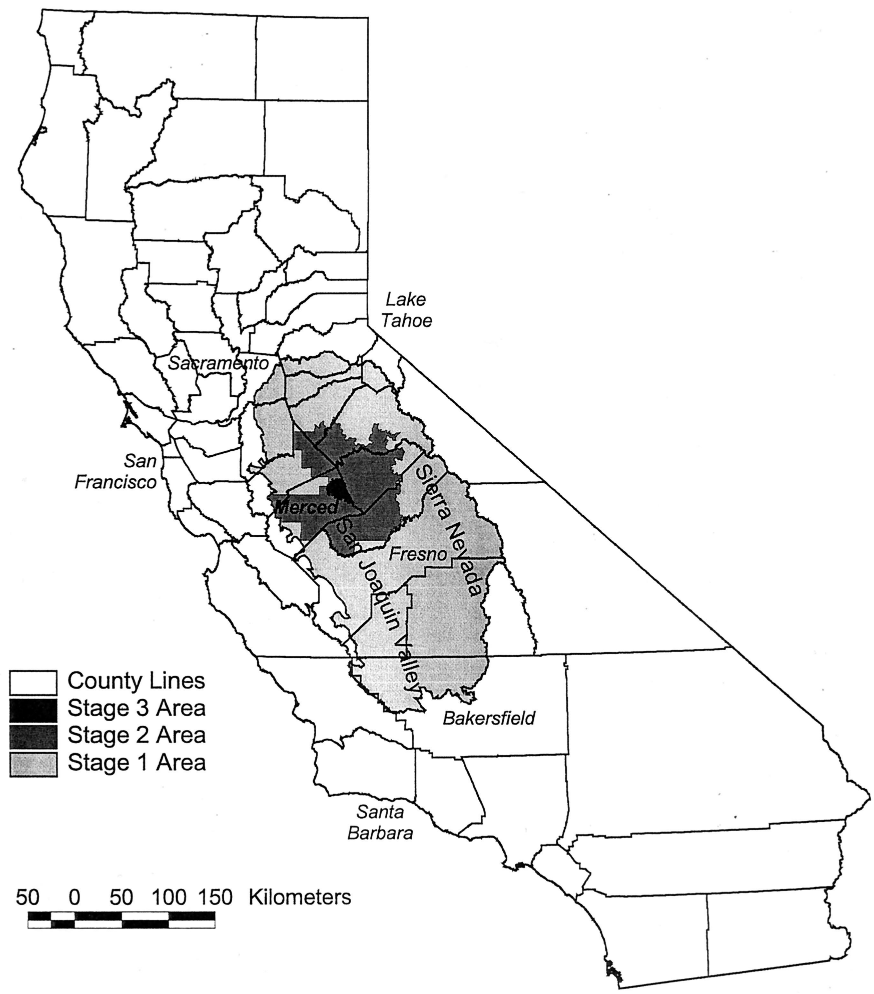

Figure 1. Location map of the study area and the assessment regions of the three stages.

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 identifies 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 and 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 used 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. Stage 1 confirmed that the vicinity of Merced was not well represented in the existing NRS network and that sites could be found there that matched the suitability of sites already selected for the NRS (Stoms and others

2000). Here we only describe the methods and results of the second and third stages.

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 adapt the generic knowledge-base network for assessing 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.
3. To 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

Land suitability is a context-dependent concept defined by a set of desired attributes of an ideal site for the intended purpose. Suitability assessment is the process of comparing desired attributes with actual conditions at a set of sites and then comparing suitability across sites. Since McHarg (1969) popularized the application of suitability assessment in land use planning, it has become standard practice in both selecting the best site for a particular use and choosing the use for which a site is most suitable. For some forms of suitability assessment, such as suitability for production of a particular crop, experts may use inductive reasoning with observations of yields from training sites to determine the best predictive environmental factors. In cases such as siting research reserves, there is no independent measure of suitability that can be observed directly, and thus no ground truth for validating or calibrating spatial models. Instead, suitability is a multicriteria evaluation in which experts define the most desirable attributes in terms of measurable factors, the optimum values of those factors, and their relative importance weights (Jiang and Eastman 2000). The assessment then follows a deductive process from these general rules applied to specific sites to "discover" the spatial pattern of suitability (Hopkins 1977).

Sites seldom score at the highest level for all factors. Thus some means must be developed by which the scores of the individual factors are combined into an overall ranking. The means of determining overall suitability have traditionally involved ordinal combination (McHarg 1969), weighted linear combination (Banai-Kashani 1989, Pereira and Duckstein 1993) or Boolean algebra, in which sites are screened through a series of logical filters (Hall and others 1992). Researchers have even investigated neural networks for suitability assessment in cases where training data are appropriate (Wang 1992). Geographic information systems (GIS) serve the multicriteria evaluation function of suitability assessment well, providing the attribute values for each location and both the arithmetic and logical operators for combining attributes (Jiang and Eastman 2000).

These approaches can be problematic (see reviews in Hopkins 1977, 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 beyond 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 and others 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 and others 1992, Davidson and others 1994, Van Ranst and others 1996, Charnpratheep and others 1997, Ray and others 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 multicriteria evaluation (Reynolds and others 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 and others (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 rule set grows 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 and others 1994, Van Ranst and others 1996, Kollias and Kalivas 1998, Ray and others 1998), or facility siting (Charnpratheep and others 1997).

Bourgeron and others (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 here with academic and administrative goals that are associated with scientific research reserves.

Methods and Results

Knowledge Base of Suitability Assessment Criteria

The University of California's Natural Reserve System 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. 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 from 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. No guidance is provided for the choices of measurement scales and how to combine factors (Hopkins 1977) nor how to weight the relative importance of criteria (Banai-Kashani 1989). 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 (i.e., the scientific, academic, and administrative criteria). Each of these criteria is similarly predicated on more specific antecedents. 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 unreasonable to consider sites 24.9 km from campus as suitable but those 25.0 km 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 and others 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 US Forest Service (Reynolds and others 2000). EMDS consists of three components: a knowledge base development tool (Netweaver), a GIS application framework (ArcView), 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, similar to spatial influence diagrams (Zhu and others 1998). 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. EMDS also allows analysts to assess individual portions of the logic network, for instance to determine which subordinate or antecedent conditions most influenced a site's overall suitability score.

The NRS guidelines were interpreted into a logic network, 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 parcel-level information on all criteria could not be practically compiled over the entire assessment region (Figure 1), the network was adapted at three different levels of spatial resolution and applied in stages. For stage 1 we assessed general suitability of small watersheds over much of the southern Sierra Nevada range and the San Joaquin Valley (Figure 1) (Stoms and others 2000). Rather than evaluating vernal pool suitability, this stage dealt with suitability for reserves more generally. The stage 1 assessment identified sites in a smaller region surrounding the proposed Merced campus site that best met the general criteria

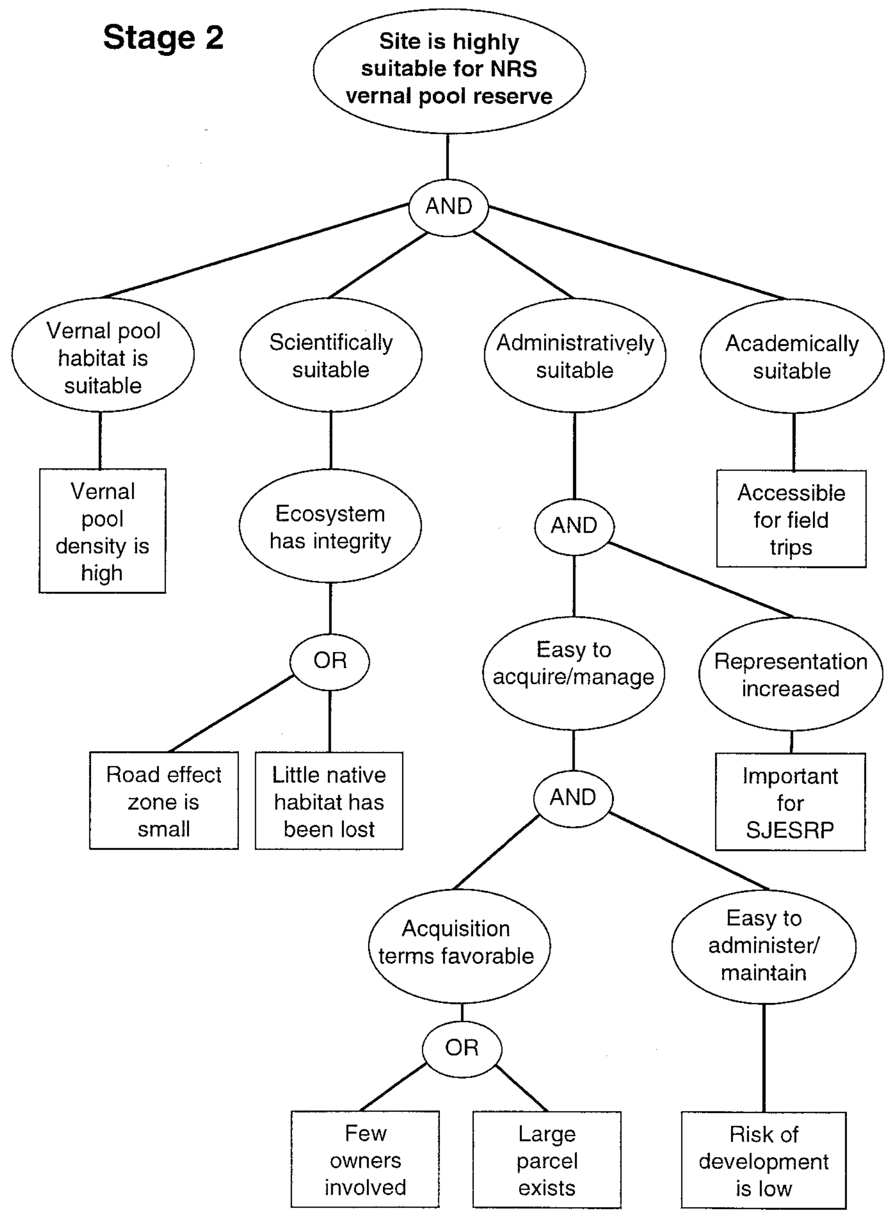

Figure 2. The network for the stage 2 proposition that the "site is highly suitable for an NRS vernal pool reserve." Networks are shown as ovals and data links are rectangles.

(Figure 1). This area was advanced to a more detailed assessment in stage 2, where we adapted the general knowledge-base network specifically to assess site suitability for vernal pool/grassland ecosystems as well as to take advantage of higher resolution spatial data for this smaller region (Figure 2). 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. A similar approach could be mounted for other nearby habitat types that are also not well represented in the NRS system, such as Sierran mixed conifer forest (Stoms and others 2000). The best sites from stage 2 were further assessed in even greater detail in stage 3.

The hierarchical logic network uses many of the features of Netweaver. Some nodes use OR logic, which takes its value as the maximum of the antecedent propositions or data links. This fuzzy operator is appropriate when the presence of any criterion makes the proposition true. Others use AND, which in Netweaver is similar to a minimum operator but adjusts for the other truth values being assessed. The AND operator requires that all antecedent data links or networks be true for the proposition to be true, such as that the site be easy to acquire and manage AND increase representation. The terminal nodes in the logic network are data links, which access the GIS database for data values that are then mapped into values of the truth of the dependent proposition. Netweaver also allows a calculated data link that computes a weighted linear combination of input data sets and then maps the truth of the calculated value. Netweaver uses a range of truth values from −1.0 to +1.0, deviating from traditional fuzzy set theory, which sets "completely false" at 0.

Stage 2 Suitability Assessment for a Vernal Pool/ Grassland Reserve

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 and Verrill 1996, Holland 2000, Reiner and Swenson 2000). Hummocky Pleistocene alluvial terraces with extensive hardpan, supporting a Northern hardpan vernal pool community underlies the vicinity of the Merced campus (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 (US Fish and Wildlife Service 1998).

The stage 2 assessment region encompassed 12,628 km^2 in portions of six counties (Figure 1). Most of the region occurs within a 75-km radius of the proposed UC Merced campus, because of the importance of travel time to potential sites in the UC guidelines in the stage 1 assessment. Although not explicitly stated in the UC guidelines, we assumed that major roads should not bisect potential reserves. 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 boundaries. This process delineated 623 assessment units, ranging in size from 136 to 12,285 ha, with a mean size of 2,027 ha. These assessment units are larger than many UC NRS sites, but they are compatible with the spatial resolution of the regional data on scientific, academic, and administrative factors (Stoms and others 1998).

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 for each assessment unit that "vernal pool/grassland habitat is suitable" (Figure 2), based on vernal pool quality and density (Holland 1998). Other habitat-specific networks could be substituted here. 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. 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 (US Fish and Wildlife Service 1998). The full logic network and terminal data nodes for stage 2 are depicted in Figure 2. A GIS database was compiled for the data links in the knowledge-base for each of the 623 assessment units.

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 3). The best areas for Northern hardpan vernal pools occur along the grassy base of the Sierra Nevada in hummocky, alluvial terraces. A secondary zone of smaller

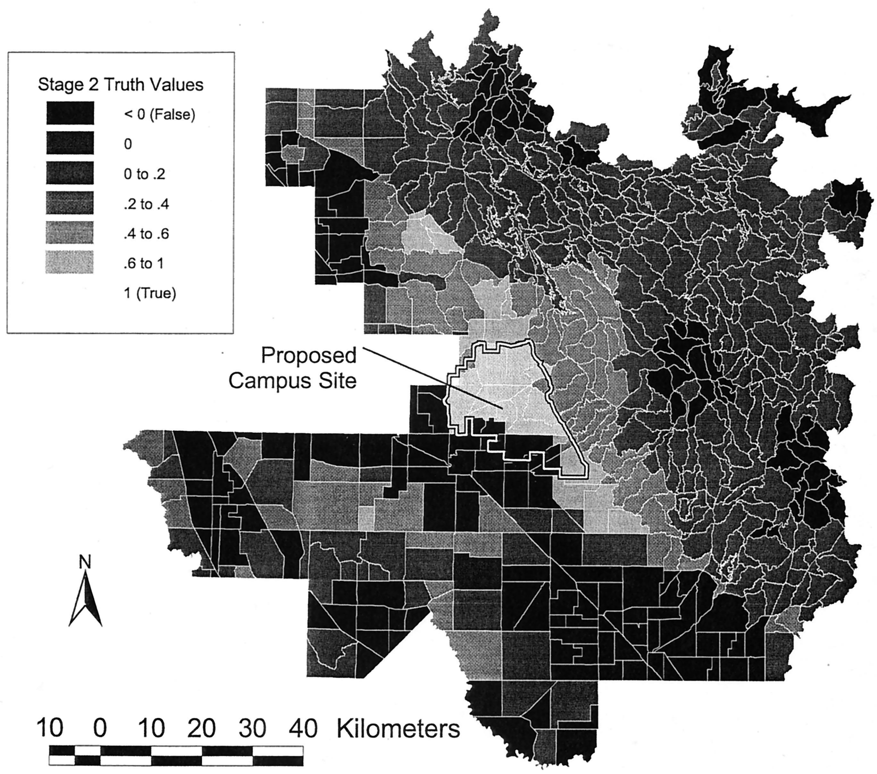

Figure 3. Map of truth values for vernal pool site suitability for the stage 2 assessment region. The bold black outline with white inner line shows the stage 3 planning boundary.

and less dense Northern claypan vernal pool complexes occurs on lower alluvial terraces west of Merced. These same locations also tend to be of importance for the San Joaquin Endangered Species Recovery Plan (US Fish and Wildlife Service 1998). The "accessible for field trips" criterion favors assessment units closer to the proposed campus site, which also contain some of the highest suitability vernal pool sites. In fact, running the assessment without the travel time criterion makes little difference in the resulting suitability truth values. That is, the highest scoring vernal pool sites also happen to be close to the proposed campus location. 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 most suitable sites.

The overall suitability assessment assigned 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. In addition, some units west of Merced with low to medium suitability tended to be rated lower because of relatively high densities of agricultural land uses and roads 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. Otherwise, assessment units tended to have negative truth values, i.e., were very unsuitable for a new NRS vernal pool reserve. A contiguous group of the highest ranked units (covering 430 km^2, or 3% of stage 2 and less than 1% of stage 1) were selected for additional assessment in greater detail in stage 3 (Figure 3).

None of the planning units absolutely met the suitability proposition (i.e., truth value = 1.0). The highest scoring assessment unit scored high in all four 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 site had a very high rating under the vernal pool suitability criterion but was assigned a negative overall suitability value solely because it was within the potential urban growth area (Stoms 2000). This is perhaps the most uncertain criterion, and so this assessment unit was retained for the stage 3 assessment.

Stage 3 Suitability Assessment for a Vernal Pool/ Grassland Reserve

In stage 3 the NRS guidelines were interpreted into a logic network that was similar to stages 1 and 2

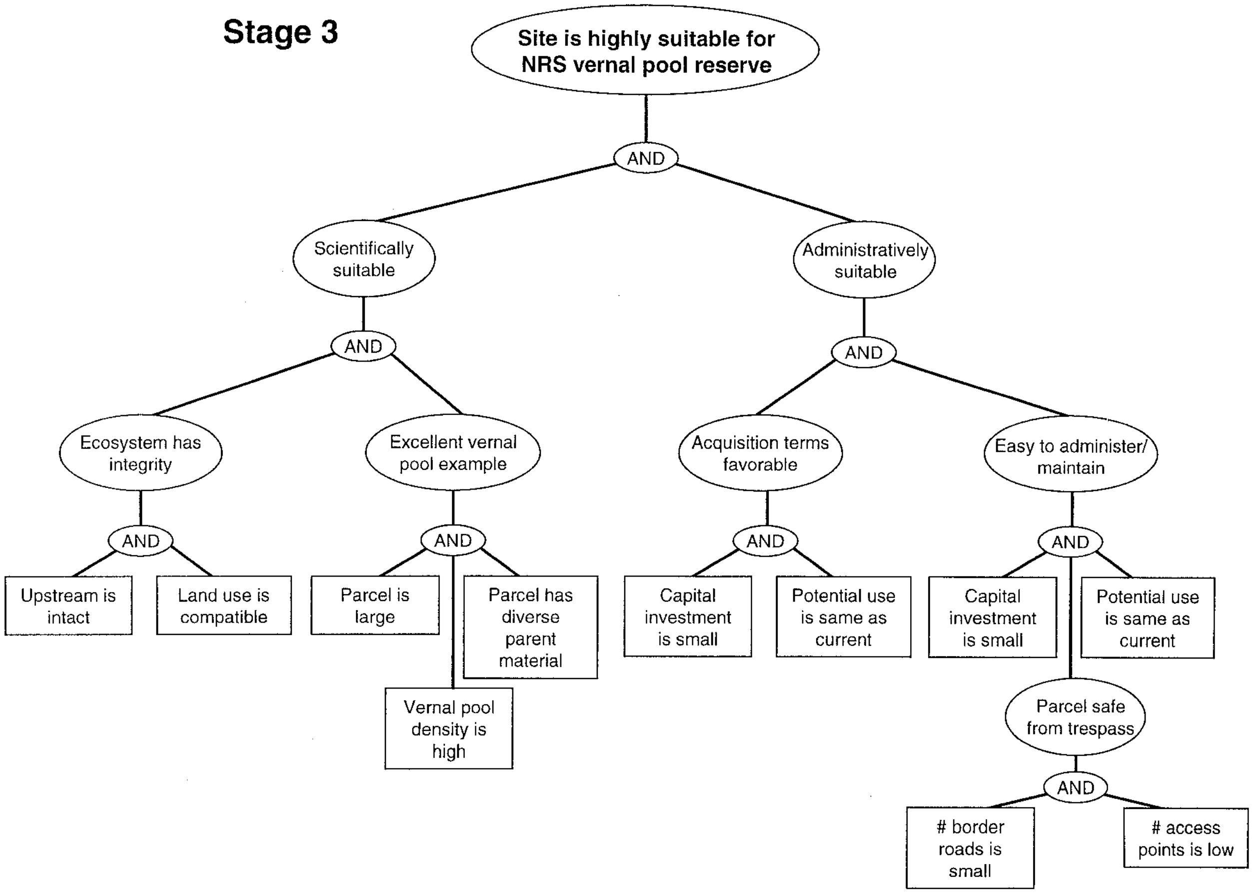

Figure 4. The network for the stage 3 proposition that the "site is highly suitable for an NRS vernal pool reserve." Networks are shown as ovals and data links are rectangles.

(Figure 4). The entire stage 3 assessment region, however, was considered accessible for field trips, and therefore academic suitability was not included. The generic 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). Moreover, the smaller size of the assessment region permitted more detailed information to be included in the logic network at the level of individual land parcels. 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. In the first two stages, we were more conservative in the logic network to minimize errors of omission. By stage 3, we believed all parcels had relatively high suitability, so the logic could be more discriminating. Therefore, we exclusively used fuzzy ANDs similar to a "most-limiting-characteristic" method (Wang 1992), such that parcels must have high truth values in all criteria to rate as top contenders.

To allow finer resolution in stage 3, assessment units were redefined as individual assessor's parcels, obtained as GIS data from the Merced County Association of Governments. These parcels largely represent units of the original public land survey, either full sections (approximately 640 acres or 259 ha) or some smaller division of sections. Roads or canals divided some sections in the assessment area. There were 298 separate parcels for assessment, although the number of unique landowners is much less because some individuals own multiple parcels in large ranches.

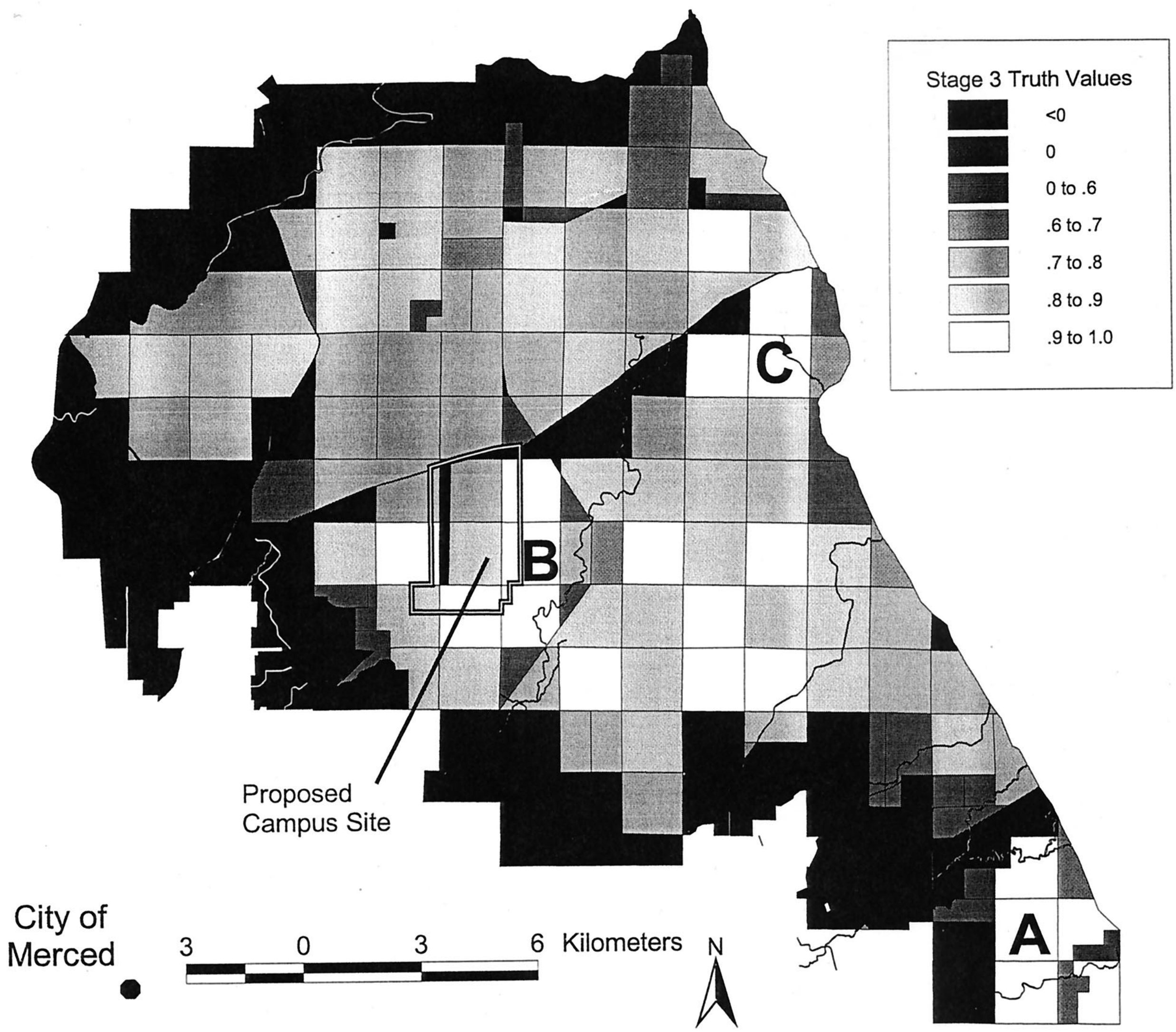

Figure 5. Map of truth values for vernal pool site suitability for the stage 3 assessment region. The bold line indicates the boundary of the proposed UC Merced campus site.

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 assigned by visual interpretation of USGS topographical maps in digital raster graphic format (watershed, encumbrances, and road access). In the absence of biological inventory data, we relied instead on analog maps of soils (Arkley 1954) to infer biophysical environmental heterogeneity and associated biological diversity. We used land use information to create an index of existing capital investment and compatibility of neighborhood uses and zoning information to classify acquisition costs.

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. Three clusters of parcels had the highest overall suitability (labeled A–C in Figure 5). Most parcels had relatively high suitability for most factors, except for some parcels on the edges of the assessment area that are currently agricultural, are zoned for development, or are influenced by canals or paved roads. The two criteria that had the most influence on the ratings were vernal pool quality and trespass factors. The majority of the study area had only a single soil type in each parcel and therefore relatively low diversity. A few parcels at lower elevations in the southeast portion (cluster A) tended to have two or three soil types and presumably greater biological diversity. Furthermore, the density of pools is greatest across the south half of the assessment area. Generally the parcels in the north half tended not to be prime examples of vernal pool complexes because of lower pool density and soil diversity than in the south. The areas that rated highest for ease of administration and maintenance were those with fewer roads in the northeast part of the study area, the southeast (cluster A), and lands immediately surrounding the proposed campus site (cluster B). The latter are being considered for development of the supporting facilities for the campus such as housing, private-sector research parks, and commercial services. Because of the AND operators in the logic network, some parcels that were unsuitable for a single lower level criterion were assessed as completely unsuitable.

The three highest-ranking parcels are found in the southeastern corner of the assessment region (cluster A). 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. All three parcels have high-density pool complexes on diverse parent soil materials, are not degraded by roads or canals, are zoned for low intensity use, and have minimal trespass issues. Ironically, the complete absence of roads in these parcels, while a positive for ecological integrity and security, could be viewed as a negative from the perspective of reserve management and access. With sites this small there also is a real trade-off between the diversity of soils and the area in each soil type.

The proposed campus site (near cluster B) scored moderately high as a potential reserve and the parcels surrounding it generally scored in the top 10 percentile (truth values 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 was the presence of only one type of soil parent material—high terrace/mixed alluvium. Another highly rated area just east of the proposed campus site is considered an outstanding vernal pool site (Holland 2000) and is already partially included in a conservation easement purchased by The Nature Conservancy.

Several highly rated parcels northeast of the proposed campus (cluster C) 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 parcels adjacent to the proposed campus, this area would probably be the easiest to access because of its proximity to a paved county road. The road actually bisects the cluster of highly ranked parcels, which thus could not be managed as a contiguous reserve.

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 California's 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 UC 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 range of truth values of the most highly rated parcels was too narrow 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 highly suitable parcels that could be made available to the University of California by acquisition or management agreement.

Without more detailed site information and NRS-specific design criteria, we could not assess the suitability of aggregations of parcels (stage 3 planning units) that could 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 its 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, perhaps because of the quality of their vernal pool ecosystems. These sites scored relatively lower 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 US Fish and Wildlife Service for determining credits for vernal pool preservation banks (Mead 1996). Having completed a systematic assessment, we can explain why a site scored as it did and which criteria most influenced the score.

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 they 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 US Forest Service, for instance, has similar guidelines for its network of research natural areas (Stoms and others 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. To overcome this limitation, we have developed a GIS-based process that interprets the guidelines for systematically evaluating the suitability of all lands in the assessment region.

The 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 too imprecise for operational suitability assessment. Fuzzy logic was designed specifically to cope with such linguistically imprecise criteria. In addition, it automatically casts all factors into a common range of truth (or membership) values. This assignment of membership has great flexibility, accommodating nonlinear 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 when the access criterion was removed from the logic network.

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 them. 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.

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 and others 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. In the hotly contested political arena of land use decisions, the entire process is objective, explicit, and transparent to critics.

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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 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 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.

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