Assessing Suitability for Conservation Action: Prioritizing Interpond Linkages for the California Tiger Salamander

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Abstract: *Conservation organizations and public agencies are interested in identifying and prioritizing areas for conservation action, often acquisition or easements. Typically, this requires the use of uncertain data and vaguely defined decision criteria. I developed a decision support system to address these uncertainty issues and assist in evaluating conservation opportunities for the endangered California tiger salamander (*Ambystoma californiense*) in Santa Barbara, California. Functionally defined planning units were used to aggregate data on land suitability, land cover change, salamander presence, and movement risk along potential linkages between breeding ponds. I used a fuzzy-logic-based inference engine to evaluate the planning units and rank the relative suitability of interpond linkages for conservation action. The sensitivity of the rankings was considered with respect to uncertainty in salamander occurrence data and the relationship between land-cover-change threats and site suitability. All linkages were substantially degraded, but five areas were consistently identified with high relative suitability for conservation action despite differences in assumptions and uncertainty in biological data. The combination of functionally defined planning units and a fuzzy-logic-based decision support system provides a general framework for considering the suitability of sites for conservation action.*

Key Words: *Ambystoma californiense*, connectivity, conservation easement, fuzzy logic, geographic information systems, planning units, systematic conservation planning

Evaluación de Aptitud para Acciones de Conservación: Priorización de Conexiones Intercharcas para *Ambystoma californiense*

Resumen: *Las organizaciones de conservación y las agencias públicas están interesadas en identificar y priorizar áreas para acciones de conservación, a menudo adquisiciones o convenios. Típicamente, esto requiere el uso de datos inciertos y criterios de decisión vagamente definidos. Desarrollé un sistema de apoyo de decisiones para abordar estos temas inciertos y ayudar en la evaluación de oportunidades de conservación de la salamandra* Ambystoma californiense *en Santa Bárbara, California. Se utilizaron unidades de planificación definidas funcionalmente para agregar datos sobre la aptitud del suelo, cambios en la cobertura de suelo, presencia de salamandras y riesgo de movimiento a lo largo de potenciales conexiones entre las charcas de reproducción. Utilicé un procesador de inferencia basado en lógica difusa para evaluar las unidades de planificación y clasificar la aptitud relativa de las conexiones intercharca para acciones de conservación. La sensibilidad de la clasificación fue considerada respecto a la incertidumbre en los datos de ocurrencia de salamandras y la relación entre cambio en la cobertura de suelo y aptitud del sitio. Todas las conexiones estaban sustancialmente degradadas, pero cinco áreas fueron consistentemente identificadas con alta aptitud relativa para acciones de conservación, no obstante diferencias en suposiciones e incertidumbre en los datos biológicos. La combinación de unidades de planificación definidas funcionalmente y un sistema de apoyo de*

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decisiones basado en lógica difusa proporciona un marco general para considerar la aptitud de sitios para acciones de conservación.

Palabras Clave: *Ambystoma californiense*, conectividad, convenio de conservación, lógica difusa, planificación de conservación sistemática, sistemas de información geográfica, unidades de planificación

Introduction

Identifying and prioritizing locations for conservation action is a multiscale interdisciplinary challenge. Systematic conservation planning efforts provide a variety of approaches for the development of regional portfolios (Pressey et al. 1993; Cowling & Pressey 2003) and the assessment of individual sites (Pressey et al. 1994; Noss et al. 2002). Conservation organizations and public agencies, however, need to identify locations with value for specific ecological functions, such as dispersal, that are also viable candidates for acquisition or easements. Issues of ecological function and implementation logistics are rarely considered explicitly in the conservation planning literature (but see Rouget et al. 2003). Moreover, local decisions are typically made in the context of substantial uncertainty about biological values, vague or poorly defined selection criteria, and an unpredictable set of conservation opportunities (Meir et al. 2004).

I developed a framework that (1) defines planning units with respect to a specific ecological process and (2) provides a decision support system that integrates biological, socioeconomic, and implementation concerns. I applied the framework to identify and prioritize specific areas for conservation action to benefit the endangered California tiger salamander (*Ambystoma californiense*) in Santa Barbara, California.

Case Study: Santa Barbara California Tiger Salamander

Importance of Connectivity for Amphibians

Connectivity between breeding ponds is important for the persistence of amphibians in spatially structured populations (Semlitsch 2000; Marsh & Trenham 2001; Skelly 2001), but these landscape linkages typically receive no formal regulatory protection (Semlitsch 2002). This contrasts with wetland breeding sites that are often subject to regulation by multiple state and federal agencies (USFWS [U.S. Fish and Wildlife Service] 2000). Field observations suggest that a substantial fraction of breeding sites within an amphibian metapopulation may have negative long-term population growth rates (Marsh & Trenham 2001). These populations must be sustained over time by periodic recolonization (Skelly 2001). The lack of protection for upland dispersal areas and the importance of connectivity for salamander persistence suggest that interpond linkages are a weak link in amphibian conservation efforts.

California Tiger Salamander

I focused on the Santa Barbara population of the California tiger salamander (SBCTS). The SBCTS is a large, pond-breeding amphibian endemic to California (Shaffer et al. 1991; Trenham et al. 2000). It typically occurs at low elevations and is associated with vernal pools and seasonal ponds in landscapes with grassland, oak-savannah, and coastal-scrub plant communities (Loredo et al. 1996). The SBCTS typically breeds in ephemeral wetlands, but it can also occur in a variety of human-made or modified wetland habitats, where fish are not present (USFWS 2000). The USFWS listed the Santa Barbara population as endangered because of substantial reduction and degradation of their natural habitats (USFWS 2000).

Interpond movement and upland utilization by California tiger salamanders is an active area of research, but details of their terrestrial life cycle remain poorly known (Trenham 2001; Trenham et al. 2001). California tiger salamanders spend the majority of their lives (>10 years) in upland burrows near their natal ponds (Loredo et al. 1996). Salamanders can move relatively long distances between breeding sites, and in oak-savannah settings, genetic evidence indicates that interpond movements up to 5 km occur at least once per generation (Trenham et al. 2001). Observations suggest that certain features, such as roads, are prominent sources of anthropogenic mortality (Trenham 2001), but the relationship of salamander movements to topography, vegetation, and human land uses remains poorly understood (P. Trenham, personal communication).

Uncertainty and Ambiguity

Conservation decisions for the SBCTS are made in a complex environment, where biological factors are considered in the context of prominent social, economic, and political concerns. All known or suspected populations of the SBCTS occur on private lands, and limited access for biological surveys creates uncertainty about its geographic distribution.

The other major source of uncertainty is the future pattern of agricultural intensification and urban growth. Santa Barbara has a long agricultural tradition and a county-level governmental mandate to promote agriculture. Traditional cattle ranching activities are relatively compatible with maintenance of SBCTS habitat, but more profitable, higher-intensity activities such as vineyards can substantially reduce available habitat (USFWS 2000). Although Clean Water Act regulations protect wetlands from these activities, upland areas essential to SBCTS are not protected and remain vulnerable to conversion.

The extent of agricultural activities is controlled by complex interactions between the availability of suitable local conditions and regional and global market demands (Lambin et al. 2000; Rounsevell et al. 2003). Modeling potential changes in agricultural markets is challenging, but it is easier to assess the relative suitability of lands for agricultural activity (Pontius et al. 2001; Sands & Leimbach 2003).

The most serious long-term threat to SBCTS is the expansion of urban areas and the permanent loss of habitat. Only a small percentage of the SBCTS' range is currently urbanized, but urban areas are projected to cover a substantial fraction of the region by 2100 (Landis & Zhang 1998*a,* 1998*b*).

Agricultural intensification and urban growth combine to create the risk that remaining SBCTS will ultimately be limited to isolated ponds and small fringes of upland habitat. Substantial evidence suggests that these isolated populations will be highly vulnerable to extinction (Gibbs 1993; Lehtinen et al. 1999). Once local extinctions occur and ponds are known to be unoccupied, they will become easier targets for development. This feeds a cycle of degradation and development that threatens to eventually eliminate the entire population.

Breaking this cycle requires strategic conservation efforts to maintain viable, connected populations of SBCTS, but there is no clear consensus among practitioners on the appropriate response to these threats. Some maintain that land-use threats should prioritize conservation actions, with areas of greater threat attracting more immediate attention. Others assert that conservation action is more efficient if it avoids threats (i.e., perceived as high-cost conflict zones) and focuses on areas with the highest biological value. There is limited empirical support for either point of view.

Identifying and Evaluating Conservation Opportunities

The complexity of factors involved in prioritizing sites for conservation action requires a decision support system that can explicitly integrate disparate concerns, including the reliability of survey data, future distributions of land cover, and philosophical approaches to threat. I developed such a system to (1) rank the relative suitability of interpond linkages for conservation action, (2) assess the sensitivity of linkage rankings to views of threat and uncertainty in SBCTS occurrence data, and (3) evaluate the implications of changes in spatial scale.

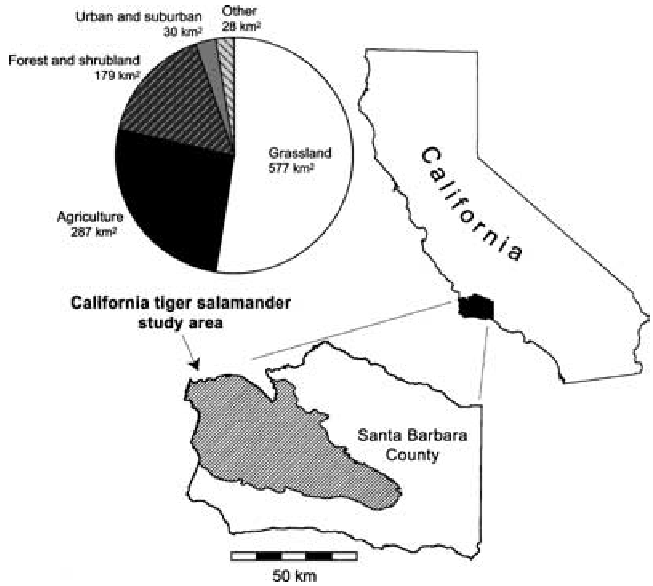

Figure 1. Study area in northern Santa Barbara County, California.

Methods

Study Area and Planning Units

My analysis covered the entire known range of the SBCTS (Fig. 1). The study area was bounded to the north by the Santa Maria River and to the south by the Santa Ynez River. The western border was bounded by the Pacific Ocean. The eastern border was delineated by the transition between coastal and montane geologic formations.

Most systematic conservation planning tools are designed to inform the representation of large sets of biodiversity elements, typically species, scattered across a regional collection of planning units (Pressey et al. 1993; Cowling & Pressey 2003). Planning units are usually areas such as watersheds and hexagons, or political subdivisions such as counties (Bassett & Edwards 2003). Data are aggregated to these units, and an analytical procedure selects a subset of planning units that satisfy a specified conservation objective (Underhill 1994; Church et al. 1996). This planning-unit approach creates problems when considering ecological functions such as connectivity because information on habitat configuration is lost when data are aggregated to large spatial units.

One way to alleviate this problem is to specifically define planning units with respect to functional characteristics of a given landscape. A number of recent studies have demonstrated that geographic networks or graphs can be used to analyze connectivity among a set of patches (Urban & Keitt 2001; Vuilleumier & Prelaz-Droux 2002). In these analyses, habitat patches become nodes connected by movement along network edges (Bunn et al. 2000). This representation is not meant to imply that organisms actually move exactly along linear edges; instead, the edges act as geographic place holders for analysis and data aggregation. Networks have the advantage of specifically incorporating the geographic structure and topology of a set of habitat patches (Theobald 2001). Recently researchers have used network models primarily to demonstrate the applications of graph-analysis tools (Bunn et al. 2000). I considered the benefits of using a network framework to create functionally defined planning units.

The components of this functional network included nodes (known or suspected breeding ponds) and edges (potential linkages between ponds). The resulting fully connected graph linked 122 wetlands identified by the USFWS Recovery Team with 14,280 potential linkages. I reduced the full graph to 3398 links by removing edges >8 km in length (Fig. 2a). The 8-km threshold is substantially more than any observed or inferred SBCTS movements (Trenham et al. 2001). I buffered the network to create three scales of assessment units with widths of 100, 250, and 500 m, respectively. The result was three sets of planning units with 3398 polygons each (Fig. 2b).

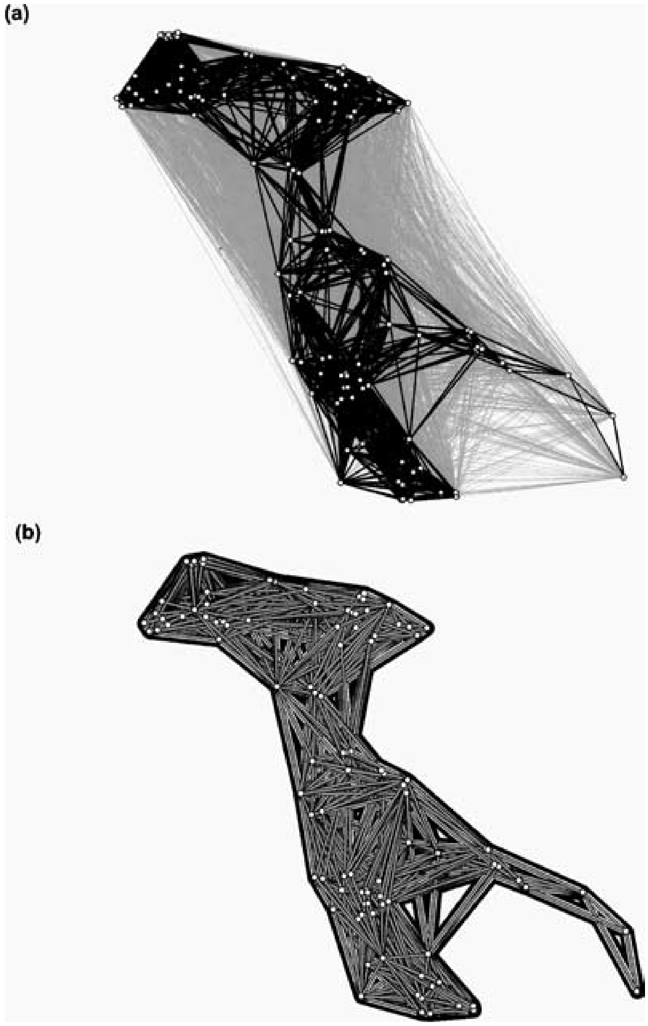

*Figure 2. (a) Geographic network linking known or suspected Santa Barbara population of the California tiger salamander (SBCTS) breeding ponds. There are 3398 black links, < 8 km in length, of the total set of 14,280 potential linkages. (b) Geographic links buffered to become 100-, 250-, and 500-m wide assessment units. Open circles indicate known or suspected SBCTS breeding ponds (*n *= 120).*

Suitability Criteria

Although land trusts and public agencies buy millions of dollars worth of land each year, decision criteria for their acquisitions are rarely described quantitatively, and the relationship between goals and actual outcomes is poorly known. It is possible, however, to devise hypotheses about the general characteristics of land cover, threat, SBCTS presence, and crossability that make a site suitable for acquisition or a conservation easement. The first set of criteria involves the characteristics of a given area of land itself. Although many more criteria are potentially relevant, I identified three simple components to land suitability: large parcels, low road density, and extensive natural land cover.

Threats from agricultural development and urban growth also contribute to the suitability of a given location. Linkages are threatened if they are highly suitable for agricultural development or within areas projected for urban growth over the next 20 to 100 years. But the relationship between threat and suitability is multifaceted, and at least two plausible hypotheses exist—threat increases suitability for action and threat does not change suitability for action.

Successful conservation efforts must include both populations of SBCTS and interpond linkages that allow successful movement between ponds. This requires the best linkages to have extensive records of breeding salamanders and low movement risk for dispersing SBCTS.

The goal of maximizing interpond connectivity (i.e., chances of successful migration), however, conflicts with the goal of identifying long linkages that promote regional connectivity. In other words, short linkages that are easy for salamanders to cross may yield relatively low benefits for the maintenance of regional connectivity. This can be offset by lengths short enough for SBCTS to cross but long enough to promote regional connectivity. The best linkages will have high scores for all of these factors across a range of spatial scales (i.e., potential linkages are suitable across a range of scales).

Although these criteria form a rational basis for identifying suitable places for conservation action, implementing them with respect to quantitative data requires the interpretation of vague, ambiguous, and context-dependent statements. Fuzzy logic systems provide a set of tools for interpreting these kinds of natural language rules in a quantitative framework (Zadeh 1965). Fuzzy logic allows for the consideration of gradations between values and the management of uncertainty or ambiguity in data. Fuzzy systems have been used for a wide variety of decision support systems (Zedah 1983), including applications in reserve selection (Stoms et al. 2002) and land management (Hall et al. 1992).

Logical Propositions

I created a fuzzy inference system in Matlab's Fuzzy Toolbox (MathWorks 2002). The fuzzy-inference system consisted of data, propositions, logical operators, and membership functions. Data for each planning unit were summarized in the ArcView Geographic Information System (ESRI 2002) and supplied to the inference system as a data table. Each decision criterion needed to be translated into a corresponding logical proposition. In each of the following propositions, variables (bold) are evaluated against a fuzzy membership function (underlined) and linked by fuzzy operators (AND) (notation adapted from MathWorks [2002] Fuzzy Tool Box).

All the individual criteria are ultimately integrated into one primary proposition (P0).

> If **land suitability** is highest) AND (**threats** are highest) AND (**crossability** is best) AND (**SBCTS records** are most extensive) AND (**link length** is best) AND (**multiple scales** are most suitable), then "linkage is the most suitable for conservation action." (P0)

Each of the six variables in bold type in P0 is determined by antecedent propositions that evaluate data on land suitability, threat, SBCTS presence, crossability by SBCTS, link length, and multiscale suitability. The antecedent propositions are described in the sections that follow, and the complete Matlab fuzzy inference system is available from the author on request.

LAND SUITABILITY

The first antecedent proposition, P1, evaluated the suitability of a linkage for conservation action by a land-acquisition or easement-oriented organization (e.g., a land trust).

> If (**parcels** are large) AND (**road density** is low) AND (**natural land cover** is dominant), then (**land suitability** is high). (P1)

When a linkage traversed large parcels with few roads and high levels of natural land cover, P1 was true. Natural land cover included the fraction of nonurban and nonagricultural areas based on a combination of the National Land Cover Database and detailed photointerpretation of active agriculture by the Santa Barbara County Department of Planning and Development.

THREATS

The second antecedent proposition, P2, balanced threats of future agricultural expansion and urban growth with potential protection from local zoning and regulation.

> If (**agricultural suitability** is high) AND (**urban growth** is imminent) AND (**protective zoning** is low), then (**threat** is high). (P2)

The proximal threat to the SBCTS linkages is the expansion and intensification of agricultural activities. It was not possible to develop a spatially explicit model for agricultural intensification in this study, but suitability for agricultural expansion was estimated based on a linear, three-component model combining land-clearance costs, slopes, and existing infrastructure. The result was an agricultural intensification suitability score ranging from 0.0 (completely unsuitable) to 1.0 (most suitable). Clearance costs were greatest for closed-canopy stands of woody trees and least for pasture and fallow agricultural lands. Steep slopes increase the cost and complexity of agricultural activities, so suitability decreased linearly with increasing slope. Proximity to existing infrastructure facilitates agricultural intensification and suitability declined linearly with distance from existing high-intensity agriculture. This model was not tested or empirically calibrated, but it codified common perceptions of factors that favor general patterns of agricultural expansion. The average agricultural suitability was calculated for each linkage.

Threats from urban development were evaluated with respect to land-use-change projections from the California Urban Futures growth model for 2020 and 2100. California Urban Futures is a logistic-regression-based model that predicts changes in urban growth based on a variety of factors, including transportation, demography, proximity to existing urban areas, and excluded areas (e.g., parks; Landis & Zhang 1998*a,* 1998*b*). The projected changes in the fraction of urban land cover between 2000 and 2020 and 2100 were calculated for each linkage.

These threat factors are mitigated to some degree by local regulations and zoning, which are not considered by the agricultural intensification model or California Urban Features. The geographic extent of two regulations administered by the Santa Barbara County Department of Planning and Development were mapped for each potential linkage: (1) 30-m rural riparian buffers and (2) agricultural grading permits on slopes $>13.5°$. Both regulations require some kind of environmental review and permitting before development can proceed, and they provide opportunities to avoid impacts to sensitive areas. Therefore, high fractions of either regulation offset threats from agricultural intensification or urban growth.

CROSSABILITY

The third antecedent proposition, P3, evaluated the potential crossability of linkages by the SBCTS.

If (**length** is short) AND (**average movement risk** is low) AND (**other wetlands** are present) AND (**barriers** are rare), then (**crossability** is best). (P3)

Because relatively little is known about the details of SBCTS terrestrial movements (P. Trenham, personal communication), P3 is based on several simple assumptions. Crossability is low when (1) linkages are long, (2) movement risk is high, (3) wetlands between the source and prospective destination are rare, and (4) movement barriers are widespread.

Linkage length was calculated as the simple geographic distance between the centers of ponds. Movement risk along a link was calculated by creating a movement-risk grid based on a subjective assessment of the relative risks associated with different National Land Cover Database cover types (Ray et al. 2002). The least risky land-cover types included annual grasslands and pastures (risk = 1); the most risky areas included urban areas and major roads (risk = 4). There are few data available to calibrate these values, and scores were based on expert biological judgment (P. Trenham & P. Collins, personal communication). Average movement risk was calculated by multiplying the length of the link by the average movement risk.

The presence of palustrine wetlands was considered favorable for crossability, and I calculated the fraction of each linkage covered by nonriparian wetlands in the local 1:24,000 National Wetlands Inventory database. Finally, the total number of potential barrier pixels was summed for each linkage. Barriers included limited-access highways and major streams. Road mortality is well known among SBCTS, and large, divided highways probably present serious obstacles (L. Hunt, personal communication). Although salamanders are capable swimmers, large streams with predatory fish and steep banks are also considered obstacles for dispersing SBCTS (P. Collins, personal communication).

SBCTS OCCURRENCE

The fourth antecedent proposition, P4, evaluated the fraction of a given linkage covered by mapped SBCTS observations either by the Santa Barbara SBCTS Recovery Team or in the California Natural Diversity Database.

If (**recovery team records** are extensive) OR (**National Diversity Database records** are extensive), then (SBCTS is present). (P4)

The rule used a fuzzy OR statement to combine these values so that a link could receive a full score even without National Diversity Database records but only partial truth in the absence of recovery team records. This reflects the relative confidence in data among local experts (L. Hunt and P. Collins, personal communication).

LINKAGE LENGTH

The fifth antecedent proposition, P5, balances conservation objectives with biological constraints.

If (**link length** is 1 km), then (**link length** is suitable). (P5)

A strict focus on crossability would favor only the shortest linkages, but conservationists are interested in identifying linkages that are both reasonably crossable and sufficiently long to enhance regional interpond connectivity. This proposition increases the suitability of relatively long linkages independent of their biological qualities.

MULTISCALE SUITABILITY

Finally, the sixth antecedent proposition, P6, combines results from P1–P5 for each of the three spatial scales, favoring potential linkages that are highly suitable across all three scales.

If (**100 m linkage** is best) AND (**250 m linkage** is best) AND (**500 m linkage** is best), then (**multiple scales** are most suitable). (P6)

Evaluating the Propositions

In fuzzy logic systems, the tests or queries (underlined terms) in the proposition are evaluated against membership functions. These describe the relationship between a score and a value. The end members of the membership functions (the best or the worst) are easy to interpret, but the strength of fuzzy logic lies in its ability to deal with the majority of planning units that lie somewhere in between. In the vocabulary of fuzzy logic, partial truth values from each antecedent proposition are combined to yield a composite truth value. The resulting truth value is not a probability; rather, it is a rule-based statement about the degree to which the data support a given logical proposition (Jensen et al. 2000; Reynolds et al. 2000).

I considered scores for each proposition relative to the set of all linkages in the study area rather than the best conceivable scores. This allowed scores to be normalized for the range of conditions actually available for each criterion. Links with the best available score for each component of the proposition received a score of 1.0, and the lowest available score was 0.0. The decision support system maintained this convention, so composite results for P0 are also presented on a scale ranging from 0.0 to 1.0.

Sensitivity Analysis

A complete sensitivity analysis for this decision support system would require considering at least 325 combinations of primary input variables across a reasonable range of variation and covariation. Although this kind of analysis was beyond the scope of this project, I assessed the sensitivity of two critical components: (1) agricultural intensification and urban growth threats and (2) SBCTS occurrence data. The first assessment involved the relationships between threat and conservation suitability. Analyzing this with the fuzzy inference system required conducting the analysis with and without P2. The second analysis addressed the importance of confirmed presence data by manipulating P4. Combinations of these two factors were considered in a simple two-by-two matrix of sensitivity scenarios: (1) threat increases suitability with data on presence, (2) threat increases suitability without SBCTS presence data, (3) threat does not change suitability with SBCTS presence data, and (4) threat does not change suitability without SBCTS presence data.

Linkage Suitability Mapping

Results were mapped across the study area in two formats: (1) as a continuous surface of land suitability and (2) as aggregated data on the suitability of individual land parcels. The first product was created by mapping high-suitability areas (top quartile) for each sensitivity analysis scenario and then adding up the number of times that areas (30-m pixels) were identified by each of the four scenarios. This converted the vector network into a continuous raster surface of suitability for which the value of each pixel was the number of times that it occurred in the top quartile (minimum = 0, maximum = 4). Isolated 30-m pixels, however, have limited conservation value, and I was more interested in areas with high concentrations of high-suitability areas. Consequently, I passed a moving window with an area equal to the average parcel size in the area (182 ha) over the composite raster map. The moving window replaced the value of each pixel with the sum or average of the pixels in the window, providing an estimate of the relative value of an average parcel centered on each pixel.

This continuous raster-suitability map yielded information on the suitability of any area on the ground. Conservation actions, though, are often constrained by fiat boundaries such as parcels. So the composite raster map was transformed into two complementary representations for individual parcels: (1) the sum of top quartile occurrences (range: 0–9390) and (2) the average number of top quartile occurrences (range: 0–4). The first measure provided a metric of the total value of a given parcel, and the second normalized the result by parcel area.

Results

Link Suitability

The overall suitability scores for linkages were relatively low and no links received perfect scores (best possible = 1.0; maximum = 0.43; average = 0.18; SD = 0.07). Most links are currently dominated by grassland or intensive agriculture; however, the California Urban Features model projects that urban and suburban land uses will become increasingly important in the coming decades. The effects of urban land-cover change are projected to be bimodal by 2100: 32% of linkages will have a >90% increase in urbanization, and 28% will have <10% increase in urban land uses.

The suitability of individual linkages varied across the sensitivity analysis scenarios. Scores were positively correlated between the sensitivity scenarios; however, scores for individual linkages varied considerably (Fig. 3). Despite changes in the scores of individual planning units, the actual areas identified between the scenarios showed considerable geographic fidelity (Fig. 4). The minimum overlap between scenarios was 50% (threat increases suitability without presence data + threat does not change suitability with presence data) and the maximum overlap exceeded 98% (threat increases suitability + no presence data *by* threat does not change suitability + no presence data; Table 1). This indicates that even the least-similar sensitivity analysis combinations still had half of their highest-ranking areas in common. Moreover, approximately 40% of linkage areas identified by any model are overlapped by all four. Only 18% of linkage areas were identified as high-ranking by only one model (Table 2).

Mapping areas identified as highly suitable under multiple sensitivity scenarios yielded two representations of areas with high conservation value. Summing the number of top-quartile occurrences within parcels emphasized the value of large parcels (Fig. 5a). Normalizing the aggregated scores by area suggests a more compact pattern with less emphasis on large parcels (Fig. 5b). Regardless of the aggregation method, five high-suitability areas were consistently identified across all four model combinations.

Scale Sensitivity

Scores for individual assessment factors (e.g., agricultural suitability and crossability) varied with assessment scale. The response of variables was dominated by differences between continuous and categorical types. Correlations between scales for categorically based data, such as the fraction of the linkage covered by known SBCTS occurrences or the presence of major roads, were more strongly scale dependent (e.g., area covered by major roads 100 × 500 m: $R^2 = 0.572$; Fig. 6a). Spatially continuous variables, such as agricultural suitability, elevation, and slope, tended to be relatively insensitive and highly correlated across the three analytical scales (e.g., agricultural suitability 100 × 500 m: $R^2 = 0.894$; Fig. 6b).

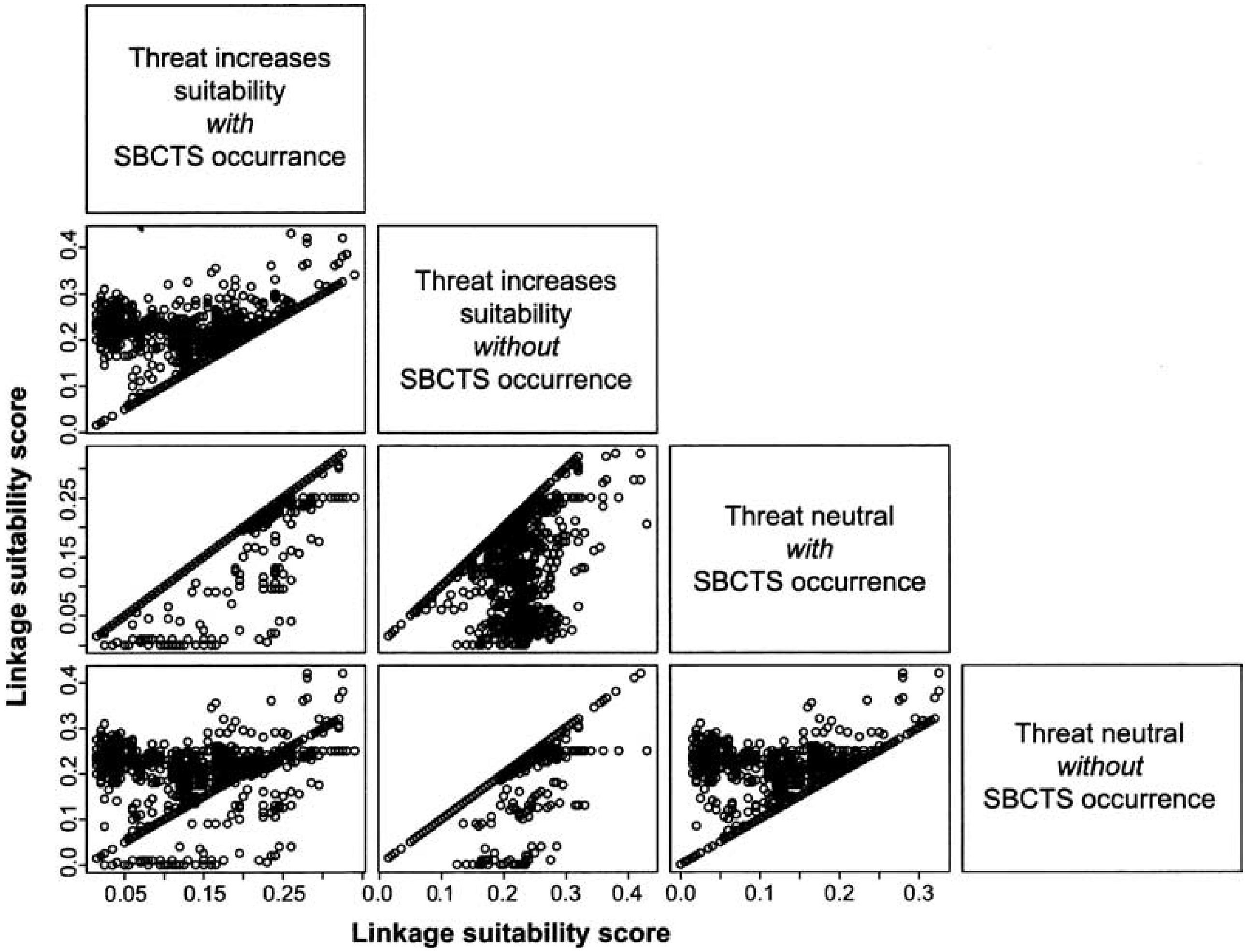

Figure 3. Cross-correlation comparison of multiscale suitability scores for the four combinations of urbanization and agricultural intensification threat and Santa Barbara tiger salamander (SBTS) presence data. All axes refer to normalized values between the best possible (1.0) and worst possible (0.0) linkages. Most axes do not approach these scores, indicating the low absolute quality of most linkages.

Discussion

Suitability for Conservation Action

My study demonstrates a method to combine logical, but poorly defined, criteria for the identification and prioritization of interpond linkages to benefit SBCTS. My analysis focused on a single species in a relatively small landscape, and, in some respects, it is quite limited, although these constraints were required to create information directly relevant to guiding conservation actions of local nongovernmental organizations and public agencies. Moreover, this work demonstrates that even this simple problem becomes dauntingly complex when data and decision criteria on biology, socioeconomics, and implementation factors are explicitly integrated. This problem is distinct from many reserve design approaches oriented toward the selection of reserve portfolios, and it complements other approaches for quantifying site value, such as irreplaceability (Pressey et al. 1994; Noss et al. 2002).

Consequently, one of the most obvious limitations of this research is the lack of consideration of site complementarity. The network framework used to create the planning units might lend itself to a sophisticated treatment of this problem, but recent research points to the challenges of selecting conservation portfolios when acquisition (or easements) will be implemented over a long period of time (Meir et al. 2004). When habitat loss is rapid or conservation opportunities are unpredictable, portfolio-based plans are likely to be inefficient (Peterson et al. 2003; Costello & Polasky 2004). This is exactly the situation in this region, with rapid development, a polarized political environment, and sparse conservation opportunities combining to limit the ability of conservation groups and public agencies to implement regional conservation plans.

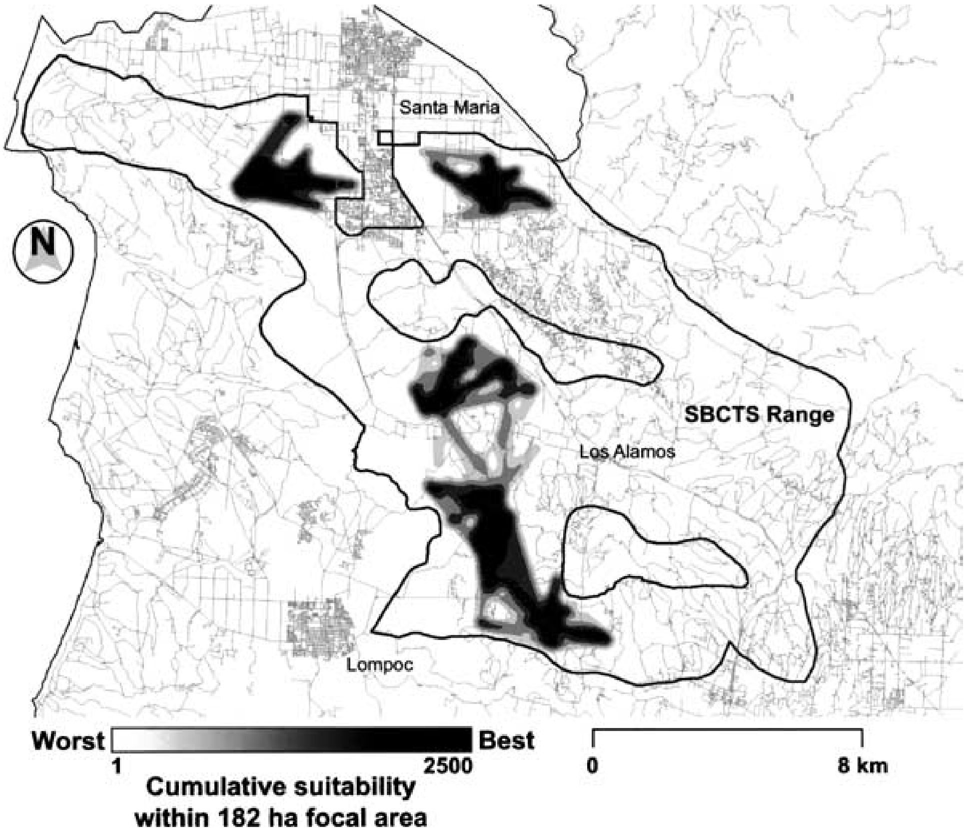

Figure 4. Composite view of four combinations of urbanization and agricultural intensification threat and Santa Barbara population of the California tiger salamander (SBCTS) presence data. Intensity was calculated by aggregating occurrences in one or more of the best quartiles for each of the combinations within a 182-ha moving window (equivalent to the average parcel size). The darkest areas have the highest suitability for conservation action across multiple models in the sensitivity analysis.

Planning Units

This project illustrated the utility of functionally defined, network-based planning units for site assessment and conservation planning. This approach is relatively easy to implement and results in a set of planning units defined explicitly with regard to ecological functions. Network-based planning units have potential for any system in which spatially structured populations are linked by flows of individuals, genes, energy, or material. My implementation is only a first step, however, and there are important opportunities for increasing analytical power and computational efficiency.

My work did not include any consideration of contingencies based on the value of multiple linkages, and making explicit use of network topology would be a logical extension (Theobald 2001). Network topology could add information about network structure and connectivity to planning units, but any such approach would add substantially to the complexity of the decision support system. It is also important to consider the capacity of conservation organizations or public agencies to implement such

Table 1. The extent of overlap areas for sensitivity scenarios with different combinations of threat rules and Santa Barbara California Tiger Salamander occurrence data.*

	Threat increases suitability		*Threat neutral*	
	with occurrence	*without occurrence*	*with occurrence*	*without occurrence*
Threat increases suitability				
with occurrence	**28,778**			
without occurrence	15,222	**17,852**		
Threat neutral				
+ with occurrence	27,827	15,460	**30,737**	
– without occurrence	20,923	17,621	21,844	**28,059**

**Intersections in the matrix indicate the number of hectares overlapping for the top quartile of linkages identified for each combination. The values in bold type on the diagonal indicate the total number of hectares in the top quartile for each scenario. For example, the scenario "threat increases suitability with occurrence data" had 28,778 ha in its top quartile. The alternative scenario "threat neutral without occurrence data" overlapped 20,923 ha (73%) of those areas.*

Table 2. Extent and percentage of areas overlapped by the four sensitivity analysis models (see Sensitivity Analysis for details).[a]

Overlap[b]	*Hectares*	*High-suitability areas (%)*	*Cumulative (%)*
1	7,514	18	18
2	10,833	26	44
3	7,110	17	60
4	16,658	40	100
Total	42,114	100	

[a] *High-suitability areas include any areas ranked in the top quartile for any model combination.*
[b] *Code: 1, area identified in only one model; 4, area identified in all four models.*

integrated strategies. The failure to implement all pieces of an integrated design can severely compromise the value of the selection or design process (Costello & Polasky 2004).

Scale Dependence

The suitability of linkages for conservation action was partially dependent on the spatial scale of analysis. This relationship can be understood with respect to the patterns of spatial autocorrelation demonstrated by the different data types. Continuous data are typically highly autocorrelated, with values grading from one location to

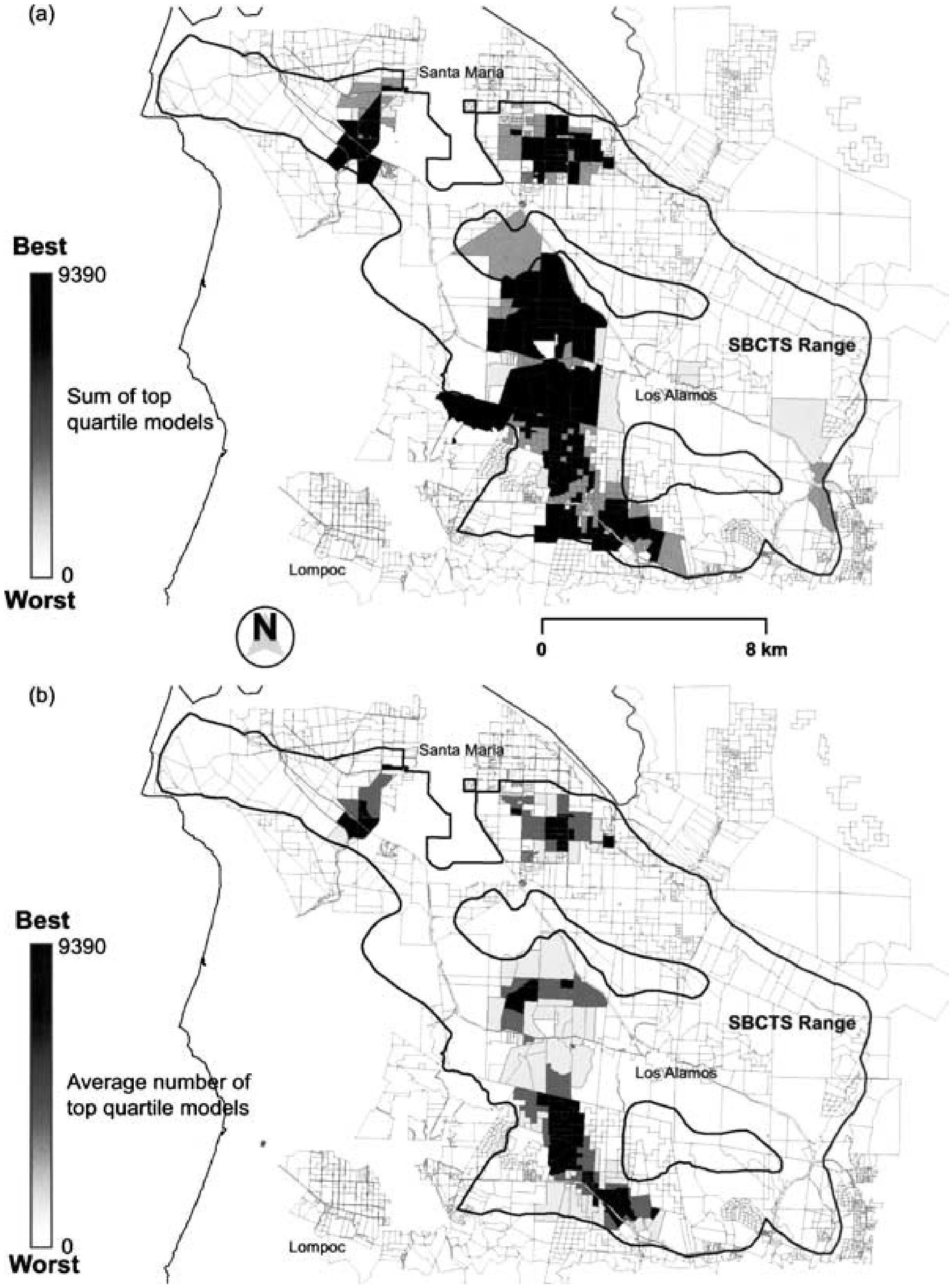

Figure 5. Linkage suitability for conservation action aggregated to individual parcels for the Santa Barbara population of the California tiger salamander (SBCTS): (a) summed value (tone indicates number of high-ranking [top quartile] 30-m pixels in each parcel) and (b) average value (tone indicates average values of 30-m pixels in each parcel). The darkest areas have the highest suitability for conservation action across multiple models in the sensitivity analysis.

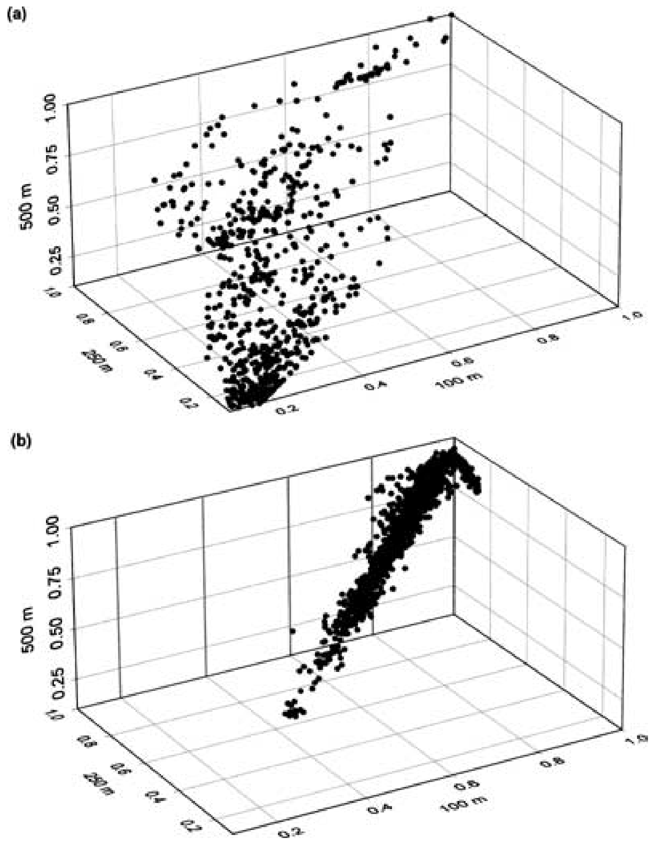

Figure 6. Correlation for variables evaluated at 100-, 250-, and 500-m buffer scales for (a) the categorically based variable "fraction of linkage with probable Santa Barbara California Tiger Salamander occurrences" and (b) the continuously based variable "agricultural suitability."

another (Goodchild 1986). Consequently, data aggregated at one analytical scale (e.g., a 100-m buffer) are highly correlated with values over a larger domain (e.g., a 500-m buffer). This is not the case for data based on categorical map representations of factors such as species occurrences, roads, or human settlements. Although these features have strong spatial characteristics (e.g., clustering or linear contiguity), at the scale of 100- to 500-m buffers they are relatively unpredictable. Increasing scale from 100 m to 500 m may dilute roads that dominate the 100-m buffer or add an entirely new area of urban development. This suggests that analyses based on continuous data will be less sensitive to changes in scale.

Sensitivity Analysis

I focused the sensitivity analysis on two issues particularly relevant to conservation decision makers: views of human threat and the availability of survey data. The role and importance of threat in guiding conservation is frequently a topic of debate (O'Connor et al. 2003). Some contend that conservation actions should be primarily guided by threat, with the most threatened areas receiving the highest priority (e.g., Maddock & Benn 2000). Others emphasize the protection of distinctive biological resources with neutral (e.g., Spector 2002) or even negative views toward threat. In this case, the sensitivity analysis suggested that this dichotomy has little bearing on the suitability of linkages for SBCTS conservation. In northern Santa Barbara County, areas retaining the most suitable linkages for conservation action occur in essentially the same places regardless of the view of threat. Two factors drive these results. First, threat and degradation are correlated. The best linkages provide lots of natural land cover and few roads, and have low movement risk. These conditions are rare in the most threatened areas, especially in this landscape, where land use typically progresses from grazing to intensive agriculture and finally low-density urban development. Highly threatened places may still be very important for conservation; unfortunately, they are rarely highly suitable for acquisition and easements.

A final pair of contrasting factors is tension between confirmed and suspected breeding ponds. This issue is grounded in the desire to give sites with confirmed presence data more importance than sites only suspected of occupation. This logic has problems on two levels. First, uncertainty associated with historic observations can complicate priority setting, and it is difficult to quantify (Burgman & Fox 2003). Second, this emphasis undermines the importance of open habitats for spatially structured populations (Hanski 1999). As with views of threat, however, this tension had little bearing on the identification and ranking of highly suitable areas for conservation action. This may reflect the fact that, despite poor access, pools with confirmed records of occupation are often close to other pools where SBCTS status is unknown. As a result, confirmed records appear sufficiently well distributed among unknown pools that they are essentially representative. Consequently, the patterns generated with data from confirmed versus suspected ponds are very similar. This finding supports the conclusion that the patterns of site suitability revealed in this study will be relatively insensitive to changes in occurrence data and views of threat in the setting of conservation priorities.

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