
Combining Strategies to Select Reserves in Fragmented Landscapes

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Abstract: *In the identification of reserve networks in fragmented landscapes with limited species-specific data at hand, one approach is to use selection criteria, such as patch size, to rank the habitat patches' conservation value and evaluate reserve-network alternatives. These criteria are assumed to be reasonable surrogates for the true network objectives. Caution is warranted, however, because the relationships between the selection criteria and the reserve-network objectives may be inconsistent. Conflicts are also likely to arise because no single reserve network will be optimal with respect to multiple objectives (or selection criteria) simultaneously. Instead, reserve planners must compromise between conflicting demands. We field tested the relationships between a variety of selection criteria and the objectives of a reserve network for the sandplain natural communities on Martha's Vineyard Island, Massachusetts (U.S.A.). Selection criteria that correlated with the reserve-network objectives were used in a multi-objective integer program to identify the 10-patch reserve networks that were optimal with each objective independently and those that offered optimal tradeoffs between the reserve-network objectives. From these 10-patch networks, one can select a final reserve network that provides the preferred compromise between the objectives.*

Combinación de Estrategias para Seleccionar Reservas en Paisajes Fragmentados

Resumen: *La utilización de criterios de selección, como el tamaño de parche, para clasificar el valor de conservación de los parches de hábitat y evaluar redes de reservas alternativas es un método para identificar redes de reservas en paisajes fragmentados con datos especie-específicos limitados. Se asume que estos criterios son sustitutos razonables de los verdaderos objetivos de la red. Sin embargo, se requiere cuidado porque las relaciones entre los criterios de selección y los objetivos de la red de reservas pueden ser inconsistentes. Es probable que surjan conflictos porque ninguna red de reservas será óptima con respecto a objetivos (o criterios de selección) múltiples simultáneamente. Más bien, los planificadores de reservas deben transigir entre demandas conflictivas. Probamos las relaciones entre una variedad de criterios de selección y los objetivos de una red de reservas para comunidades arenícolas naturales en la Isla Martha's Vineyard, Massachusetts (E.U.A.). Los criterios de selección que se correlacionaron con los objetivos de la red de reservas fueron utilizados en un programa multi-objetivo integral para identificar las 10 redes de reservas de fragmentos óptimas con cada objetivo independientemente y las que ofrecían compensaciones óptimas entre los objetivos de la red de reservas. De estas 10 redes de reservas de fragmentos, se puede seleccionar una red de reservas final que proporcione el compromiso preferido entre los objetivos.*

Introduction

The establishment of reserves and reserve networks in fragmented landscapes is a frequent occurrence because

some ecosystems and species now only occur as or in habitat fragments and because of the growing recognition of the conservation potential of these sites (Lombard et al. 1997; Shafer 1997; Williams-Linera et al. 1998; Schwartz

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1999; Tschardt et al. 2002a). Reserves in such landscapes are often constrained to relatively small, isolated habitat patches surrounded by a potentially inhospitable matrix. The general objectives for these reserve networks are to include representatives of target species or ecosystems, promote the persistence of these targets, support biodiversity, and sustain ecological and evolutionary processes (Noss et al. 1999b; Margules & Pressey 2000).

There are many challenges to creating reserve networks in any landscape, fragmented or otherwise, two of which we address directly. First, a complete description of the species and ecosystems of interest, including current distribution and dynamic behavior, is often unavailable (Gaston & Rodrigues 2003). Instead, it is necessary to make decisions based on existing data and data that can be efficiently collected. One approach is to use selection criteria to rank the habitat patches' conservation value and evaluate reserve-network alternatives. Selection criteria are variables that are assumed to be reasonable surrogates for the true network objectives and are relatively easy to measure. For example, size has been suggested as a practical criterion for ranking patches (Shafer 1990), although the effectiveness of this criterion may vary according to the habitat preferences and life history of species (Bender et al. 1998). The negative impacts of roads on natural communities (Peres & Terborgh 1995; Trombulak & Frisell 2000) may justify road density as a useful selection criterion. Given the uniqueness of each conservation scenario, it is unlikely that any single criterion could be considered best, and a variety of criteria have been applied (e.g., Soulé & Simberloff 1986; Vane-Wright et al. 1991; Witting & Loeschcke 1995; Howard et al. 2000; Rothley 2002).

A second challenge is that typically no single criterion can satisfy the multiple, potentially conflicting objectives (Vane-Wright et al. 1991; Stoms et al. 1998; Rothley 1999; Sarkar 1999) imposed on reserve networks (e.g., the largest patches may not contain the most rare species). Similarly, it is unlikely that any single reserve network could be optimal with respect to all selection criteria and still satisfy all constraints (e.g., funds for procuring land). Instead, reserve planners must compromise between competing demands. As the number of potential reserve sites and the number of selection criteria increase, ad hoc evaluation of candidate reserve alternatives becomes difficult. Instead, planners increasingly rely on quantitative techniques for the selection of reserve networks (Church et al. 1996; Cabeza & Moilanen 2001) that can be loosely grouped as either scoring approaches or iterative techniques (see Rothley 1999). More recently, multi-objective programming (Church et al. 1996; Rothley 1999; McDonnell et al. 2002) has been suggested for the assemblage of reserve networks.

A solution to these problems is to begin the reserve-selection process with field tests (with the extent of the tests guided by available time and resources) of the re-

lationships between the selection criteria and network objectives. Then, rather than settling on just one selection criterion, the next step is to unite multiple strategies (Noss et al. 1999a, 1999b) and consider a series of reserve alternatives representing various levels of compromise between the criteria. We tested the utility of nine selection criteria in the selection of a reserve network for the sandplain natural communities (SNC) on Martha's Vineyard Island, Massachusetts (U.S.A.). The objectives of the reserve network are to (1) protect occurrences of rare plant species, (2) protect nesting sites of the Northern Harrier (*Circus cyaneus*; a threatened species in Massachusetts), (3) promote plant species richness, (4) promote invertebrate family biodiversity, and (5) promote Northern Harrier nest fledging success. They were derived from the general conservation goals of the Nature Conservancy's Massachusetts Islands program for SNC. The selection criteria were chosen according to existing data, time available to supplement these data, and expert knowledge on the natural history of the SNC. The conservation significance of the remaining SNC fragments supported the inclusion in the reserve network of as many SNC patches as possible, but given the high cost of real estate on Martha's Vineyard it was assumed that a 10-patch network was the largest area feasible to preserve (based on the resources necessary to procure, monitor, and manage preserves). We used the selection criteria that correlated with the reserve-network objectives in a multi-objective integer program to identify 10-patch reserve networks that offered optimal trade-offs among the reserve-network objectives. A single reserve network that minimizes the losses from the trade-offs between the reserve-network objectives can then be selected from these 10-patch networks.

Methods

Study Area

The sandplain natural communities are a dynamic assemblage of open, scrub, and wooded communities on dry, sandy outwash soils derived from moraines. Once common in the northern United States, they have been in steady decline as the result of development and suppression of natural fires, surviving in <1% of their original global range. On Martha's Vineyard the remaining SNC exist as fragments (0.01–672 ha) on the southern half of the island (Fig. 1) within a matrix of agricultural and developed land. Our reserve-selection efforts were focused on two SNC communities: the maritime shrublands (MS) and the scrub oak barrens (SO). The rarity of these communities makes them a conservation priority, and both are used as nesting sites by the Northern Harrier. The MS are dense shrubby areas <2 m tall, typically dominated by *Rosa rugosa* Thunb. and *Myrica pensylvanica*

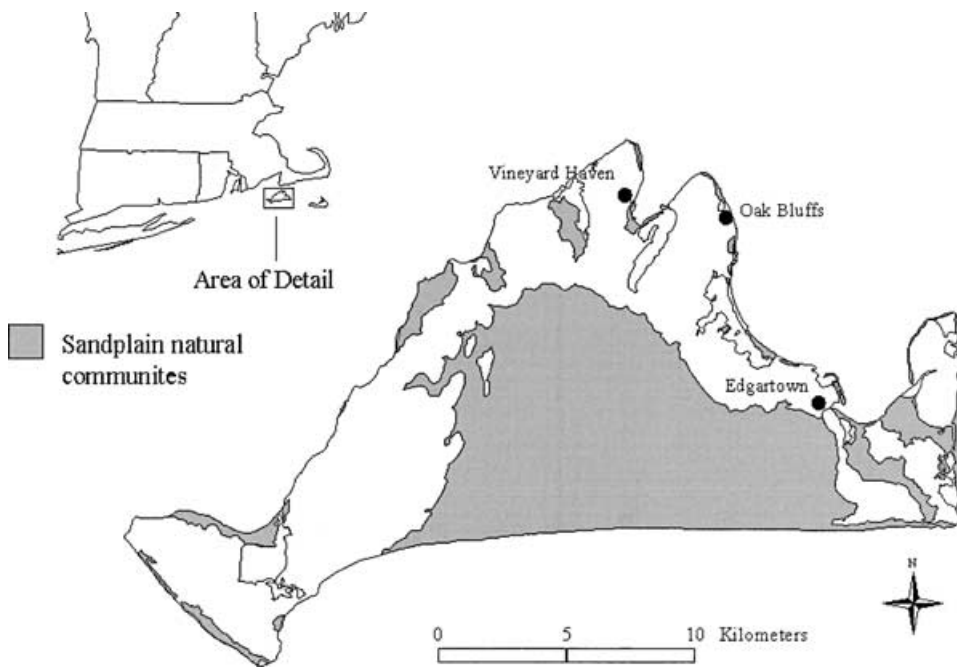


Figure 1. Island of Martha's Vineyard, Massachusetts (U.S.A.).

Loisel. ex Duhamel interlaced with an abundance of vines such as *Toxicodendron radicans* (L.) Kuntze and *Smilax* spp. (Lundgren et al. 1999). Maritime shrublands exist on the unconsolidated sand of coastal dunes from Maine to Delaware. Scrub oak barrens are comprised of 1- to 2-m-tall thickets dominated by *Quercus ilicifolia* Wang and occur on the sandy soils of glacial outwash, often in frost pockets or on landscapes exposed to coastal influences.

Selection Criteria

We chose the nine selection criteria in coordination with ecologists from the Nature Conservancy's Islands Program. Patch area is positively correlated with species richness in a variety of settings and for a variety of taxa (Shafer 1990), and larger patches may support higher densities of some species (Bender et al. 1998), which lessens their susceptibility to extinction associated with stochastic events (Hanski et al. 1995). In our system, the MS and SO patches are frequently adjacent to communities with noticeably taller vegetation so that area can be relatively easily and reliably calculated from aerial photographs (Lee et al. 2001). The patch shape (circularity) criteria, C2 and C4 (defined below), are scale-independent metrics of edge effects. Percent cover (relative abundance of each land-cover type in a 250-m buffer surrounding each patch) incorporates the effect that land cover outside patch boundaries might exert on ecological conditions within a patch (Fisher et al. 2002). The criterion of road density was included to represent the effect of road exposure on species (Trombulak & Frissell 2000). Height of tallest shrub stem is a surrogate for time since the last major patch disturbance, such as fire or mechanical removal of shrubs. We included vertical vegetative (structural) heterogeneity because of the

observed positive relationship between habitat structural diversity and species diversity in other systems (Davies et al. 1998; Lindenmayer et al. 2000).

We used the presence or absence of Northern Harrier nests as a means to set conservation priorities for several reasons. First, Northern Harriers nest (almost exclusively) and hunt (frequently) in the MS and SO patches on Martha's Vineyard and hence may serve as an umbrella species. Second, the birds are a well-known, charismatic species on Martha's Vineyard and may therefore serve as a flagship species (Caro & O'Doherty 1999). Third, Northern Harriers are a migratory visitor to Massachusetts islands and may reevaluate potential nesting sites each time they return at the beginning of the breeding season. It is therefore likely that their habitat usage patterns will serve as a biodindicator of degradation of the environment (T. Chase, personal communication). In our study, the presence or absence of Northern Harrier nests is both a selection criterion and a reserve-network objective. Finally, prey density (*Peromyscus* and *Microtus* spp. only; MacWhirter & Bildstein 1996) is a patch size-independent metric of prey abundance for Northern Harriers (small mammals comprise the majority of their diet in many sites; Dechant et al. 2001).

Data Collection

A digital polygon map of the vegetation on the Martha's Vineyard sandplains (with 24 land-cover categories) was previously interpreted by The Nature Conservancy from orthophotographs. Polygons representing MS and SO patches were redrawn based on a second photointerpretation of 1994 color orthographic images (the accuracy of these new polygons was qualitatively evaluated during

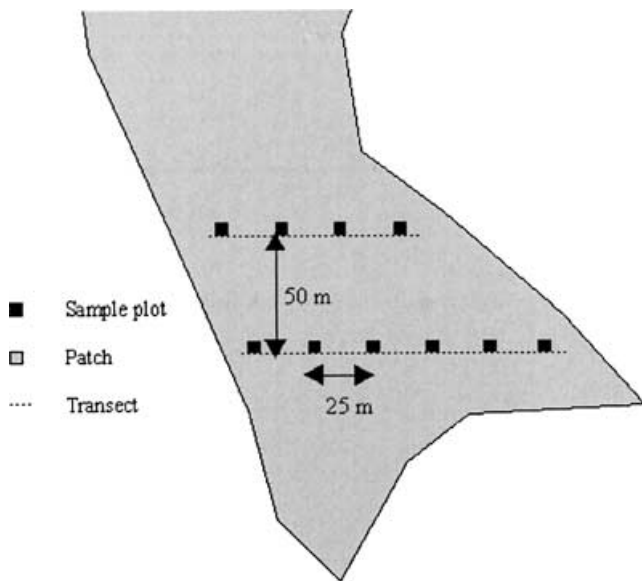


Figure 2. Example of vegetation sampling transect layout used in the summer of 2000.

the course of the fieldwork and judged acceptable). Patch area and percent cover (for each land-cover type) were measured according to these polygons, as were C_2 and C_4 , which were defined as

$$C_2 = 4A/P^2$$

$$C_4 = (A/A_C)^{0.5}$$

(Davis 2002), where A is the area of the patch, P is the perimeter of the patch, and A_C is the area of the smallest enclosing circle for the patch. The equation for C_4 is independent of P and therefore less sensitive to the digitizing habits of the photointerpreter. Road density (total road length within the patches plus a 250-m buffer surrounding the patches, divided by patch area) for the sampled MS and SO patches was calculated according to a digital road map (U.S. Census Bureau 1995).

We estimated plant species richness in 19 (from a total of 114) MS and SO patches (1.47–42.76 km²) during the summer of 2000 based on sample plots defined by 1-m² quadrats. Patches were chosen according to a stratified random design that considered patch size, road density, and proximity to similar patches (but they were limited to properties for which we were granted access). Sample plots were located every 25 m along transects spaced 50 m apart and perpendicular to the longest patch axis (Fig. 2). Because patch area varied, the number of sample plots in each patch was scaled according to patch size. On a daily basis we prepared graphs of the cumulative number of plant species identified as a function of the number of sample plots performed for each patch sampled. If the cumulative number of plant species for a given patch did not reach an asymptote for the current sampling intensity, we added more sample plots the following day. In each

plot, all plant stems, excluding trees, were counted. We recorded the species of each stem and the vertical stratum in which the top of the plant extended (tall shrub, 2–5 m; short shrub, 0.5–2 m; dwarf shrub, <0.5 m; herbaceous, epiphytes, or nonvascular). The height and the species of the tallest stem in each plot were also recorded. We categorized the rarity of each plant species according to its description in a local flora guide (Swanson & Knapp 1999).

Using pitfall-style traps, we estimated invertebrate family richness during the summer of 2000 in the same 19 MS and SO patches. We placed three 10.16-cm diameter, 2.54-cm deep plastic containers in holes dug just deep enough so that the rim of the container was flush with the surrounding earth and then filled the containers with antifreeze. We left the traps open for between 2 and 5 nights. We rinsed invertebrates caught in the traps in water, transferred them to glass vials containing ethyl alcohol, and later identified them according to the family level with the aid of a dissecting microscope.

We determined the presence or absence of Northern Harrier nests through field surveys conducted in the summers of 2000 and 2001. During the summer of 2000, the same 19 patches that were covered for the plant and invertebrate sampling plus two additional patches were monitored. Starting on June 1, we monitored each patch for a minimum of 16 hours (typically four nonconsecutive 4-hour blocks) before we considered it as containing no nest. We monitored patches that contained nests to determine the number of chicks fledging from the nests. In the summer of 2001, we expanded the number of patches sampled for Northern Harrier nests. During April and May of 2001, we monitored as many MS and SO patches as possible for evidence of impending Northern Harrier nesting (courtship behaviors of males and females, copulations). In this manner, we found 16 patches containing nests. Out of 98 MS and SO patches without nests, 30 were then randomly selected and monitored to establish with certainty that no nest was contained within. The 16 patches found to contain nests were subsequently monitored to determine the number of fledging chicks.

We conducted small-mammal trapping with 7.62 × 8.89 × 30.48 cm Sherman-style traps in the summers of 2000 and 2001 in the same 19 patches that were sampled for plants and invertebrates in the summer of 2000. Thirty-nine traps, baited with an apple slice, a piece of paper towel smeared with 1 teaspoon of peanut butter, and approximately 15 corn pieces and sunflower seeds, were placed in a 20 × 35 m, evenly spaced grid pattern after sunset. We checked the traps the following morning just after sunrise. We marked animals caught during the first night of trapping on their lightly colored ventral side with a permanent marker and recorded the species and the trap in which the animal was caught. We closed all traps subsequent to checking them so that no animals were caught during the heat of the day. We then reset

the traps after sunset for a second night (traps in which we caught animals on the first night were rebaited). We checked the ventral sides of all animals caught during the second night of trapping for a mark indicating that they had been caught on the previous night. Again, we recorded the species of each trapped animal and the trap in which it was caught.

Analysis

We transformed the mark-recapture data from the small-mammal trapping into estimates of prey density based on the Peterson method (Krebs 1989). We arc-sine transformed all raw values of percent cover before initiating the analysis (Snedecor & Cochran 1989). We used a jackknife estimate to adjust plant species richness estimates (Krebs 1989) to account for differences in sample sizes. Vertical heterogeneity for each vegetation sample plot was calculated according to the exponential form of the Shannon-Wiener index (Krebs 1989):

$$I = 2^{-\sum_{i=1}^c p_i \log_2 p_i},$$

where i is the plant height stratum, c is the number of height strata, and p_i is the proportion of the total number of stems extending into plant stratum i , averaged for each patch.

We tested all pairs of selection criteria for correlation. We tested SO and MS patches for differences with respect to the selection criteria and the reserve objectives (we used a one-tailed t test for normally distributed variables; otherwise, we applied the two-sided Kruskal-Wallis H test; Davis 2002). We tested the rank correlation between plant species richness, rare plant species richness, invertebrate family richness, fledging success, and each selection criterion. We compared patches with Northern Harrier nests to patches without nests according to the selection criteria and the reserve-network objectives. We assumed that values measured in the summer of 2000 for vertical heterogeneity and height of the tallest shrub stem were the same for the summer of 2001. Because the spatial context of the SO patches compared with that of the MS patches was drastically different (e.g., MS patches were frequently in close proximity to barrier-beach areas, whereas SO patches never were), we separated the SO and MS data before comparing percent cover for patches with nests to that of patches without nests. We tested the reserve-network objectives measured in the summer of 2000—plant species richness, occurrence of rare plants, invertebrate family richness, and fledging success of Northern Harrier nests—for correlations.

From all the selection criteria significantly correlated to the reserve-network objectives, we chose one “best” criterion for each objective. We excluded locally measured selection criteria from consideration because they could not be measured for all MS and SO patches on Martha’s Vineyard. We then ranked all patches according to these

criteria one at a time and recorded the 10 best patches according to each of these best predictors. Finally, we used the ranked lists as objectives in a multi-objective integer program (MOIP) to identify the reserve-network alternatives that are optimal with respect to each objective independently and those that provide an optimal compromise between the objectives. We considered reserve networks for the MS and SO reserve networks separately.

Results

Field Survey Data

We found 113 plant species during the course of the inventory (101 identified species and 12 unidentified mosses and lichens). Of these, 8 species were rare, endangered, or of special concern. A regression line between the raw species richness data and the adjusted jackknife estimates suggested a highly linear relationship ($R^2 = 0.97$) in which the intercept was not significantly different from zero ($t = 1.42$, $n = 19$, $p = 0.17$). We used the adjusted jackknife estimates of species richness throughout the remainder of the analyses (the results were identical when the raw species richness data were used instead). Only 20 species occurred in both the SO and MS patches. Plant species richness in SO patches was significantly lower than in MS patches (Table 1). No rare species occurred in SO patches, whereas the number of rare plant species in any MS patch ranged from 0 to 2.

Fifty-four invertebrate families were trapped. Over 58% (28 families) of the invertebrate families occurred in both the SO and MS patches. The number of invertebrate families in SO patches and in MS patches did not differ significantly (Table 1).

Of the 21 total patches surveyed for Harriers in the summer of 2000, 7 contained Northern Harrier nests. The average number of chicks fledged was 2.5 ($n = 6$, $\sigma = 1.4$, mode = 2). Despite a significant difference in prey density (Table 1), there was no statistical evidence that the Harriers preferred either MS or SO patches for nesting ($n = 21$, $\chi^2 = 0.000$, $p = 1.00$), and there was no significant difference in fledging success between MS and SO patches (Table 1). In the summer of 2001, 16 out of 46 patches contained nests (2 patches each contained 2 nests). For these nests, the average number of chicks fledged was 1.1 ($n = 18$, $\sigma = 1.4$). Again there was no significant difference in fledging success between MS and SO patches, and there was no statistical evidence that the Northern Harriers preferred either MS or SO patches for nesting ($n = 46$, $\chi^2 = 2.867$, $p = 0.09$). Prey density was significantly lower in the summer of 2001 than in the summer of 2000 (one-tailed paired t test; $n_{2000} = 19$, $n_{2001} = 19$, $t = 4.565$, $p < 0.01$). The average number of chicks that fledged from each nest was also significantly lower in the

Table 1. Comparison of maritime shrubland (MS) and scrub oak (SO) patches.^a

Design criterion or objective	Summer 2000					Summer 2001				
	n ^b	MS mean	SO mean	H or t	p	n ^b	MS mean	SO mean	H or t	p
Area	21	65535	95213	$H = 0.005$	ns	46	68104	102585	$H = 0.878$	ns
C2 ^c	21	0.14	0.10	$t = -1.869$	0.04	46	0.11	0.10	$H = 0.684$	ns
Road density	21	0.03	0.05	$t = 1.888$	0.04	46	0.06	0.01	$H = 0.368$	ns
Prey density	19	10.56	23.61	$t = 3.640$	<0.01	19	5.49	7.41	$t = 0.704$	ns
C4 ^d	21	0.65	0.59	$t = -1.208$	ns	46	0.59	0.59	$t = 0.178$	ns
Height of tallest shrub stem	19	78.09	100.65	$t = 1.973$	0.03	17	79.31	105.74	$t = 2.020$	0.03
Vertical heterogeneity	19	2.37	2.89	$t = 3.275$	<0.01	17	2.41	2.86	$t = 2.400$	0.02
Plant species richness	19	35.52	19.11	$H = 10.140$	<0.01	n/a				
Rare plants	19	1.3	0.0	n/a		n/a				
Invertebrate family richness	19	11.4	12.0	$t = 0.312$	ns	n/a				
Fledgelings	6	2.0	3.0	$t = 0.866$	ns	18	1.25	0.67	$H = 0.599$	ns

^aAbbreviations: ns, not significant; n/a, not applicable.

^bNumber of patches for all categories except fledgelings, for which it refers to number of nests.

^cOur first criterion of patch shape, defined as $(4 \times \text{area}/\text{perimeter}^2)$.

^dOur second criterion of patch shape, defined as $(\text{area}/\text{area of smallest enclosing circle})^{0.5}$.

Table 2. Best selection criteria for each objective of the reserve network.^a

Objective	Maritime shrublands (MS)	Scrub oak (SO)
Invertebrate family richness	(+) combination of % dune, % mixed oak, and % salt marsh	(+) % grassland/heathland
Northern Harrier nests	(+) area	(+) area
Fledging success	(-) % salt pond	(-) % shrub swamp
Plant species richness	(+) area	(-) % SO
Rare plant species	(-) % salt pond	n/a ^b

^aSymbols: +, positive correlation between the objective and the selection criterion; -, negative correlation between the objective and the selection criterion.

^bNot applicable.

summer of 2001 (one-tailed t test, $n_{2000} = 6$, $n_{2001} = 18$, $t = -2.156$, $p = 0.02$).

In the summer of 2000, there was a positive correlation between rare plant species richness and total plant species richness ($n = 19$, $r_s = 0.79$, $p < 0.01$) in MS and SO patches together. This result is somewhat spurious because there were no rare plants in the SO patches and no correlation when MS patches were considered alone. In the MS patches, plant species richness was significantly higher in patches with Northern Harrier nests (one-tailed t test; $n = 10$, $t = 2.142$, $p = 0.03$).

Identification of Optimal Reserve Networks

For the MS patches, area was the best predictor (Table 2) of nest-site selection by Northern Harriers (the area of patches with nests was consistently higher in both the summers of 2000 and 2001; Table 3). The positive association between percent barrier beach and nest-site selection was only observed in the summer of 2001 (Table 4), and C2 and road density (both lower in patches without nests) were significantly correlated with area in 2000 and 2001. Area was correlated with C2 ($r_s = -0.59$,

$n = 21$, $p = 0.01$), road density ($r_s = -0.69$, $n = 21$, $p = <0.01$), and height of tallest shrub stem ($r_s = -0.51$, $n = 19$, $p = 0.03$) in 2000, and with C2 ($r_s = -0.59$, $n = 46$, $p = <0.01$), road density ($r_s = -0.83$, $n = 46$, $p = <0.01$), and height of tallest shrub stem ($r_s = -0.57$, $n = 17$, $p = 0.02$) in 2001. Because plant species richness was significantly higher in patches containing Northern Harrier nests, area was also chosen as the best predictor of plant species richness. Percent salt pond was the only significant ($r_s = -0.79$, $n = 10$, $p = 0.02$) and therefore the best predictor of rare plant species richness. Percent salt pond was also the best predictor of the success of Northern Harrier fledging success (the correlations between percent grassland-heathland, percent salt marsh, and fledging success were based on only three observations). Three design criteria, percent dune, percent mixed oak, and percent salt marsh, were correlated positively with invertebrate family richness. Rather than choosing only one best predictor of invertebrate family richness, we ranked the MS patches according to each of these selection criteria, and the three best patches from each ranked list (plus the fourth best from the percent mixed-oak ranking list) were combined to create a single list of the 10 best patches for invertebrate family richness.

Table 3. Comparison of design criteria for patches with and without Northern Harrier nests.^a

Design criterion	Summer 2000					Summer 2001				
	n ^b	with	without	H or t	p	n ^b	with	without	H or t	p
Area	21	151242	41760	<i>H</i> = 6.341	0.01	46	139982	53906	<i>H</i> = 7.660	<0.01
C2 ^c	21	0.09	0.14	<i>t</i> = 2.198	0.04	46	0.08	0.12	<i>H</i> = 8.179	<0.01
Road density	21	0.03	0.04	<i>t</i> = 1.726	0.05	46	0.027	0.069	<i>H</i> = 5.977	0.01
Prey density	19	18.65	16.06	<i>t</i> = 0.479	ns	17	4.643	7.976	<i>t</i> = 0.516	ns
C4 ^d	21	0.59	0.65	<i>t</i> = 1.072	ns	46	0.566	0.602	<i>t</i> = 0.828	ns
Height of tallest shrub stem	19	81.59	91.34	<i>t</i> = 0.688	ns	17	67.574	107.368	<i>t</i> = 4.105	<0.01
Vertical heterogeneity	19	2.66	2.60	<i>t</i> = 0.283	ns	17	2.412	2.709	<i>t</i> = 1.500	ns

^aAbbreviation: ns, not significant.

^bNumber of patches.

^cOur first criterion of patch shape, defined as (4 × area/perimeter²).

^dOur second criterion of patch shape, defined as (area/area of smallest enclosing circle)^{0.5}.

For the SO patches, area was again the best predictor (Table 3) of nest-site selection by Northern Harriers (the negative association between percent shrub swamp and nest-site selection was only observed in the summer of 2001; Table 4). Percent grassland-heathland was the only significant predictor (*r_s* = 0.80, *n* = 9, *p* = 0.03) and therefore the best predictor of invertebrate family richness. Percent shrub swamp was the only significant and therefore the best predictor of success of Northern Harrier fledging (percent shrub swamp was also significantly associated with Northern Harrier nest-site selection; Table 4). Percent SO was the only significant (*r_s* = -0.91, *n* = 9, *p* = 0.02) and therefore the best predictor of plant species richness. Because 9 of the 10 best patches for minimizing percent shrub swamp and minimizing percent SO were identical, these two objectives were combined to form a single objective (and list of the 10 best patches; the tenth patch in this list was the tenth item on the percent shrub swamp 10-best list and was also on the 10-best lists for the other two objectives).

The best predictors for each network objective (Table 2) formed the objectives for the MOIP. The general formulation of the MOIP was as follows:

$$\text{maximize } Z_i = \sum_{j \in B_i} x_j, \quad i = 1, \dots, k,$$

subject to

$$\sum_{i=1}^k Z_i \leq 10,$$

$$x_i = \text{integer}(0 \text{ or } 1),$$

where *Z_i* is reserve-network objective *i* (the number of 10-best patches according to objective *i* included in the network); *x_j* is an integer variable that equals 1 if patch *j* is included in the network and 0 if it is not; *B_i* is the set of patches that are members of the 10-best list for objective *i*; and *k* is the total number of reserve network objectives. A constraint is included (the inequality) to limit the number of patches included in a reserve-network alternative to 10. Additional constraints were included to ensure that

patches entered the solution according to their rankings. For example, when the number of Northern Harrier nest sites is maximized, the third-largest patch would not be added as a member to the solution unless the second-largest patch was already a member. However, for percent salt pond and the combined percent shrub swamp and percent SO objectives, the score for all the 10 best patches was 0%, so patches satisfying these objectives could enter in any order.

For the MS patches,

$$32(\text{out of a potential } \binom{25}{10} = 3,268,760 \text{ combinations})$$

optimal reserve alternatives were identified (summary tables describing the patches included in each optimal alternative are available from the authors upon request). Three alternatives were optimal (scored 10) with respect to the objectives of Northern Harrier nest sites (and plant species richness), invertebrate family richness, and Northern Harrier fledging success (and occurrence of rare plants). One alternative was an intermediate optimal solution that included the 4 best patches for the Northern Harrier nest objective, the 6 best patches for the invertebrate family richness objective, and 2 of the 10 best patches for the Northern Harrier fledging success objective.

For the SO patches, 34 combinations (again, out of a potential 3,268,760 combinations) of 10 patches represented the optimal compromise solutions. Three alternatives were optimal with respect to Northern Harrier nest sites, invertebrate family richness, and Northern Harrier fledging success nests (and plant species richness) objectives.

Discussion

Our study was a mensurative rather than manipulative study (Hurlbert 1984), so it is inappropriate to make conclusions about the mechanisms responsible for observed patterns. However, the relationships between the

Table 4. Comparison of buffer composition of patches with and without Northern Harrier nests.^a

Land cover type	Summer 2000										Summer 2001									
	MS					SO					MS					SO				
	n ^b	with ^c	without ^c	H ^d	p	n ^b	with	without	H	p	n ^b	with ^c	without ^c	H	p	n ^b	with ^c	without ^c	H	p
Agriculture	12	0.2	0.19	0.153	ns ^d	n/a ^b					25	0.2	0.12	3.106	ns	n/a				
Beach	12	0.29	0.28	0.008	ns	n/a					25	0.27	0.27	0.028	ns	n/a				
Barrier beach	12	0.25	0.26	0.000	ns	n/a					25	0.30	0.16	6.646	0.01	n/a				
Dune	12	0.16	0.21	0.526	ns	n/a					25	0.17	0.13	2.551	ns	n/a				
Deep marsh	12	0.00	0.02	0.500	ns	n/a					25	0.10	0.10	1.273	ns	n/a				
Developed		n/a				9	0.23	0.02	0.500	ns	25	0.16	0.17	0.150	ns	21	0.22	0.13	0.723	ns
Grassland/heathland	12	0.49	0.54	0.000	ns	9	0.31	0.19	0.276	ns	25	0.50	0.41	0.147	ns	21	0.17	0.23	0.088	ns
Mixed oak	12	0.19	0.19	0.092	ns	9	0.49	0.95	1.667	ns	25	0.10	0.19	2.114	ns	21	0.71	0.88	0.682	ns
Oak-pine plantation		n/a				n/a					25	0.10	0.12	2.559	ns	21	0.11	0.11	.0313	ns
Pine plantation		n/a				9	0.17	0.29	2.880	ns	25	0.10	0.10	0.000	ns	21	0.34	0.21	0.837	ns
Pitch pine-oak	12	0.14	0.1	0.827	ns	9	0.26	0.28	0.320	ns	25	0.11	0.17	0.340	ns	21	0.18	0.47	0.009	ns
Freshwater pond	12	<0.01	<0.01	0.500	ns	n/a					25	0.09	0.09	0.595	ns	n/a				
Salt marsh	12	0	0.02	0.500	ns	9	0.12	0.17	2.000	ns	25	0.18	0.17	0.076	ns	21	0.09	0.11	3.2	ns
Sea cliff	12	0.00	0.01	0.500	ns	n/a					25	0.10	0.10	0.890	ns	n/a				
Sea	12	0.00	0.04	0.500	ns	n/a					25	0.14	0.11	2.215	ns	n/a				
Shrubland	12	0.35	0.27	0.468	ns	9	0.12	0.17	2.000	ns	25	0.31	0.22	0.946	ns	21	0.1	0.11	1.177	ns
Scrub oak	12	0.17	0.15	0.050	ns	9	0.39	0.34	0.720	ns	25	0.10	0.15	2.559	ns	21	0.28	0.32	0.155	ns
Salt pond	12	0.51	0.52	0.115	ns	9	0.17	0.168	0.000	ns	25	0.44	0.48	0.127	ns	n/a				
Shrub swamp	12	0.00	0.02	0.500	ns	9	<0.01	<0.01	2.000	ns	25	0.10	0.10	0.000	ns	21	0.08	0.11	6.720	0.01
Tree oak	12	0.18	0.24	1.120	ns	9	0.45	0.21	.0720	ns	25	0.20	0.26	0.001	ns	21	0.31	0.21	1.102	ns
Wooded swamp		n/a				n/a					25	0.10	0.11	0.790	ns	21	0.11	0.11	0.313	ns

^aAbbreviations: ns, not significant; n/a, not applicable; MS, maritime shrubland; SO, shrub oak.

^bNumber of patches.

^cValues in this column represent the (arc-sine transformed) percentage of the patch buffers composed of each land-cover type.

^dTwo-sided Kruskal-Wallis H.

selection criteria and the reserve-network objectives seem reasonable. The inverse relationship between plant species richness and height of the tallest shrub stem in the MS patches ($r = -0.66$, $n = 10$, $p = 0.04$) is consistent with an argument that plant species richness is lost as shorter herbaceous plants and grasses are succeeded by taller woody plants. In the plant species-poor SO patches, where plant species richness was inversely related to percent SO, plant species richness may be dominated by propagules from surrounding dissimilar habitats. Northern Harriers consistently nested in the largest patches, where food abundance was high. An observed (summer 2000) positive relationship between height of the tallest shrub stem and fledging success ($r = 0.89$, $n = 5$, $p = 0.04$) may reflect the protection from predators provided for Northern Harrier chicks by ground cover. Prey density and fledging success were significantly higher in the summer of 2000 than in the summer of 2001, suggesting a close association between prey abundance and nest productivity that has been observed in other sites (Dechant et al. 2001).

Considerable theoretical and empirical evidence demonstrates that caution is warranted in the use of selection criteria to stand as surrogates for reserve-network objectives (Shafer 1990). For example, species may be differentially affected by habitat fragmentation: some species may have higher densities in small habitat fragments (Tscharnke et al. 2002b). The geographical spread of reserve networks maximizes the isolation of habitat patches but may improve coverage of a larger number of species (Higgs & Usher 1980; Honnay et al. 1999; Tscharnke et al. 2002b). As patch size decreases, the importance of intrinsic characteristics of the patches (e.g., size and shape) decreases, whereas the influence of neighboring vegetation types increases (Shafer 1999; Fisher et al. 2002). Indeed, we discovered such inconsistencies between selection criteria and reserve objectives on Martha's Vineyard. Northern Harriers steadily nested in the largest MS and SO patches, but neither plant species richness nor the occurrence of rare plants was correlated with patch size. In MS we predicted that patches with higher a percentage of dune in the buffer would have higher invertebrate family richness ($r_s = 0.86$, $n = 10$, $p = 0.03$), but patches with a lower percentage of salt pond in the buffer would have higher fledging success ($r_s = -0.59$, $n = 12$, $p = 0.01$). The surrogate criteria used in our MOIP were chosen because of an observed statistical relationship between the criteria and the objectives that may not describe a true casual relationship. For example, although there was a statistical relationship between fledging success and the percentage of salt pond, salt pond abundance may be a surrogate for another factor such as food availability.

The inconsistent overlap (or conflict) between reserve-network objectives is also well documented. For example, the dissimilar habitat requirements of different taxa may require conservation of different habitat types. On Martha's Vineyard there was a significant negative corre-

lation ($r_s = -0.64$, $n = 10$, $p = 0.05$) between plant species richness and prey density (which is likely to support Northern Harrier persistence) in the MS patches. Of all the reserve-network objectives, only the occurrence of Northern Harrier nests (objective 2) and plant species richness (objective 3) showed potential synergy (this result is supported by only two seasons of field data). Maritime shrubland patches containing nests had higher plant species richness than patches without nests. Also, the height of shrubs in patches with nests was lower on average than no-nest patches, whereas plant species richness was negatively correlated with average shrub height.

With MOIP (or any other quantitative decision-support tool designed to explore trade-offs between competing objectives), the inconsistent performance—the identity of the best selection criterion was not consistent across all objectives—of our selection criteria and the conflicts between our reserve objectives were not an insurmountable problem. Instead, we identified the reserve-network alternatives that were optimal with respect to each objective independently and the reserve-network alternatives that provided optimal compromise between the objectives (independent of any subjective judgements on the relative merits of the objectives). Included with each alternative was the level of satisfaction for each. For example, the best alternative for the MS included the top 10 patches to promote Northern Harrier nesting and plant species richness and the best patch to promote fledging success and rare plant richness.

The final step is to choose a single best network. Formal quantitative methods are available to deduce relative weights for the objectives (Cohon & Rothley 1997). Fortunately, there was considerable overlap in the identities of the patches that comprised the reserve-network alternatives in the optimal lists, so selection of any one alternative was not an either/or situation. Nevertheless, because of hindrances such as complications associated with current land tenure, the full patch set for any alternative cannot be immediately or even, perhaps, quickly acquired. One solution is to rank the urgency of patch protection according to vulnerability or irreplaceability (Pressey & Taffs 2001). A complementary approach considers the frequency with which patches appear in the optimal alternatives (Stoms et al. 1998). For example, because three patches appear in over 30 out of 34 of the optimal reserve-network alternatives for the SO, the consideration of these patches is a priority. For the MS, 2 patches appeared in over 29 of the optimal reserve networks. These patches, predicted to have high conservation value, can now be targeted for survey work (if they were not included in the initial field surveys) to determine exactly which plant species and invertebrate families occur there (as a test of representativeness and complementarity) and whether they are being used by nesting Northern Harriers. The 10 patches most frequently included may not together form an optimal alternative. For the SO, an optimal alternative was composed of the 10 most frequently included patches,

and for the MS patches no optimal alternative matched the 10 most frequently included patches. Therefore, the ranking according to frequency of citation should only be used to prioritize patch acquisition that will ultimately form a set that matches the preferred optimal alternative. It is also important to remember that only remotely measured selection criteria were considered in the MOIP analysis. No conclusions have been reached about optimal reserve networks that incorporate locally measured selection criteria, such as the height of the woody stems in the patches. Considerable fieldwork would be necessary to supply the data necessary to do so, but inclusion of these additional selection criteria in the MOIP would be straightforward.

At every decision-making point in the design of this study, we were careful to ensure that errors were minimized, but its limitations may warrant cautious interpretation of results or further fieldwork. First, the invertebrate survey for this project was extremely limited and should be expanded before conclusions about patterns of invertebrate family diversity are reached. Second, a field-sampling technique more appropriate for locating occurrences of rare plant species (e.g., transect-based sampling) would bolster the conclusions about the distribution patterns of rare plants. Third, in the MS patches area was assumed to be the best selection criteria for plant species richness because patches with Northern Harrier nests had the highest plant species richness and because the Northern Harriers were nesting in the largest patches. But the relationship between area and plant species richness, although positive ($r = 0.42$, $n = 10$, $p = 0.23$), was not significant. More field sampling would support this assumption. Fourth, without a (more) complete biotic inventory, it is impossible to evaluate the actual plant species richness, invertebrate family richness, or occurrence of rare plants in the proposed optimal reserve networks or to consider complementarity (Vane-Wright et al. 1991; Pressey et al. 1993; Justus & Sarkar 2002) as a means of efficient species or family coverage. Finally, during the field season of the summer of 2000, the Northern Harrier nest survey did not begin until 1 June. Any nest failures prior to this date would not have been detected, resulting in an overestimation of fledging success.

Data limitations and conflicting objectives are the regrettable reality in many conservation scenarios. Our results provided specific information that supported reserve network design in the SNC on Martha's Vineyard. Our methods can, however, be adapted to support similar endeavors in other systems.

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