A Method for Setting the Size of Plant Conservation Target Areas

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Abstract: *Realistic time frames in which management decisions are made often preclude the completion of the detailed analyses necessary for conservation planning. Under these circumstances, efficient alternatives may assist in approximating the results of more thorough studies that require extensive resources and time. We outline a set of concepts and formulas that may be used in lieu of detailed population viability analyses and habitat modeling exercises to estimate the protected areas required to provide desirable conservation outcomes for a suite of threatened plant species. We used expert judgment of parameters and assessment of a population size that results in a specified quasiextinction risk based on simple dynamic models. The area required to support a population of this size is adjusted to take into account deterministic and stochastic human influences, including small-scale disturbance, deterministic trends such as habitat loss, and changes in population density through processes such as predation and competition. We set targets for different disturbance regimes and geographic regions. We applied our methods to* Banksia cuneata, Boronia keysii, *and* Parsonsia dorrigoensis, *resulting in target areas for conservation of 1102, 733, and 1084 ha, respectively. These results provide guidance on target areas and priorities for conservation strategies.*

Método para Determinar el Tamaño de las Áreas de Interés para la Conservación de Plantas

Resumen: *Los tiempos en los cuales se llevan a cabo decisiones de manejo frecuentemente excluyen la culminación de análisis detallados necesarios para la planeación de la conservación. En estas circunstancias, medidas alternativas eficientes deben ayudar en la aproximación de resultados de estudios minuciosos factibles bajo un esquema de recursos y tiempo extensivos. Nuestro estudio resalta un conjunto de conceptos y fórmulas que pueden ser utilizados en lugar de análisis detallados de viabilidad poblacional y ejercicios de modelado del hábitat para estimar las áreas protegidas requeridas para proveer resultados de conservación deseables para un grupo de especies de plantas amenazadas. Utilizamos un juicio experto de parámetros basado en la evaluación de un tamaño poblacional que resulte en riesgos de casi-extinción específicos basados en modelos dinámicos. El área requerida para sostener una población de este tamaño es ajustable para que tome en consideración influencias humanas determinísticas y estocásticas incluyendo perturbaciones de pequeña escala, tendencias determinísticas como la pérdida del hábitat y los cambios en la densidad pobla-*

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cional mediante procesos como la depredación y la competencia. Establecimos áreas de interés basados en diferentes regímenes de perturbación y regiones geográficas. Aplicamos nuestros métodos a Banksia cuneata, Boronia keysii *y* Parsonia dorrigoensis *resultando en áreas de interés para la conservación de 1103, 733, y 1084 ha, respectivamente. Los resultados proveen dirección para áreas de interés y prioridades para las estrategias de conservación.*

Introduction

Governments throughout the world are formally committed to comprehensive, representative, and adequate reserve systems. Although the issues of comprehensiveness and representation can be addressed through reserve-design algorithms and gap analysis (Margules et al. 1988; Pressey 1994, 1995; Pressey et al. 1996, 1997), the issue of adequacy is best explored with population viability analysis (Boyce 1992; Burgman et al. 1993; Possingham et al. 1993). The Australian government has committed itself to adequate reserve systems that conserve "viable" populations of all species throughout their natural range (e.g., JANIS 1997). A species may be considered viable if it faces a "small" risk of decline or extinction or a negligible contraction in range within the next few decades. The notion of a viable population often is not clearly defined, but is essential if the issue of an adequate reserve system is to be addressed.

Vascular plants frequently are the focus of conservation efforts because their taxonomy is relatively complete, knowledge of species distributions is relatively good, and vegetation maps are used as surrogates for other elements of biodiversity in conservation planning (Elith 2000). For vascular plants in many Australian environments, processes that affect viability include both stochastic disturbance and deterministic pressures. Planning for individual species requires formal assessment of the risks posed by different effects, and population viability analysis provides one avenue for synthesizing available knowledge.

There are many computer-based simulation tools for estimating viable population sizes and minimum viable habitat areas (reviewed by Lindenmayer et al. 1995). Population modeling has been used to develop conservation strategies for many animals and plants. The number of published plant models allows some generalization about model structures, levels of variability, and related issues (Klemow & Raynal 1983; Burgman & Gerard 1988; van Groenendael & Slim 1988; Menges 1990; Oostermeijer et al. 1996). In many decision-making processes, however, there is insufficient time or data to develop models for more than a handful of species. In most cases, expert judgment determines the outcome.

The need for an efficient decision-support tool that uses available information is driven by the short time frames and the social and political imperatives of land-use decisions. In Australia, the state, territory, and federal governments have agreed that an extensive and permanent native forest estate will be maintained and managed in an ecologically sustainable manner with parallel development of internationally competitive and ecologically sustainable forest-based industries (Commonwealth of Australia 1992). A vital element of the National Forest Policy Statement is that joint Commonwealth–State Comprehensive Regional Assessments (CRAs) of the environmental, heritage, social, and economic values of the forests be undertaken to develop a reserve system. One of the challenges in the planning process is to prescribe adequate conservation strategies for a large number of threatened plant taxa (>5000 in Australia; Briggs & Leigh 1996). Although community-level preservation may accommodate common and widespread species, rare and threatened species tend to occur in localized or specialized habitats, and their conservation needs must be addressed specifically (Keith 1990; Lynch 1994).

We have devised a method for setting a preservation target for any plant species which may be particularly useful when there are insufficient data or time to conduct a formal population viability analysis. The approach is not intended to be an alternative to other ways of setting priorities, and it has many limitations. It is intended to provide a framework within which knowledge of each species can be ordered and considered, facilitating discussion about how best to set conservation targets to protect a suite of species in a context that is relatively transparent. The method is designed to be efficient: in a few weeks, a group of experts should be able to set area conservation targets for many of the threatened taxa (≥100) in a region. To emphasize the uncertainty inherent in the method, we have included calculations of bounds on estimates of target areas.

Methods

Any method for setting conservation goals should account for processes that lead to deterministic decline and those that result in extinction from stochastic events (Caughley 1994). We describe several mechanisms by which the consequences of both kinds of processes may be evaluated. Our method depends on the following general principles of extinction: (1) All populations face some risk of decline and extinction because they are exposed to the vagaries of natural temporal and spatial variation, even in habitat unaffected by humans. These background risks can be approximated by simple population models that include environmental and demographic variation. The guidelines we outline are based on simple models and the results of detailed population models for plants. (2) To minimize the number of plant extinctions in the medium term, priorities for conservation should reflect the risks faced by different taxa. The allocation of protection measures should be guided by an understanding of the kinds of threats that can be mitigated by creating reserves or active management. (3) Disturbance regimes can be modeled as processes resulting in an expected proportion of habitat remaining available throughout the period over which risks are evaluated. (4) Catastrophes can be implicated in the local extinction of many plant taxa, and conservation strategies are developed to minimize the risk of global loss.

The target-setting method is divided into a series of steps. Each step accounts for an assessment of habitat or for one kind of deterministic or stochastic process that affects the area necessary to achieve a conservation goal. The data required for implementation of the method are relatively modest (Table 1) compared with those required for a detailed population viability analysis (Boyce 1992; Beissinger & Westphal 1998). In many cases, direct, reliable estimates of these parameters are not available, but quantitative information based on subjective (expert) judgment may be adequate (Seiler & Alvarez 1996). The nature of conservation planning is such that decisions are often made without full scientific knowledge. Our method provides a transparent means of incorporating expert knowledge into a process for setting conservation priorities.

Table 1. Definitions of parameters used in the equations that make up the method for setting target areas for plant conservation.

Parameter	*Definition*
H_i	area of potential habitat in disturbance region *i* searched (surveyed) for the species (ha)
N	number of adult plants within the surveyed potential habitat, H
F	population size that faces a 0.1% chance of falling below 50 adults at least once in the next 50 years, assuming no detrimental human effects (a benchmark for evaluating risks across different taxa)
p_i	annual probability of disturbance (or the proportion of habitat disturbed annually) by small-scale disturbance, *i*
n_d	time taken for the species to recover from a disturbance
n_u	number of years after a disturbance until habitat is no longer suitable for the species (assuming no further disturbance)
L_i	proportion of remaining habitat lost to a deterministic process, *i*
r_i	proportional reduction in local density due to effect, *i*, that reduces populations within their habitat, such as predation and competition

Incorporating Uncertainty

Uncertainties should be propagated through the calculations and reported. The first step is to provide a best estimate and plausible upper and lower bounds for each of the parameters in Table 1. In most instances, confidence intervals or other formal statistics of dispersion are unavailable, in which case bounds may be estimated subjectively (Seiler & Alvarez 1996). Uncertainties in the parameters can be incorporated by applying the rules of interval arithmetic (Alefeld & Herzberger 1983) to the intervals formed by the upper and lower bounds of each of the parameters to calculate bounds for estimates of target areas providing adequate levels of protection.

Stepwise Identification of Protected-Area Targets

Step 1: Estimate the population size (F) likely to persist under the influences of demographic and environmental uncertainty, assuming an environment free of disturbances characteristic of recent human land-use practices. We used a risk of quasiextinction, a 0.1% probability of falling below 50 adults at least once in 50 years, to provide a background risk against which to measure the utility of conservation actions. The benchmark of 50 years reflects the fact that concerns are with risks on a scale over which current management prescriptions may be effective. Risks measured over relatively short time frames sometimes suggest management actions at odds with those measured over longer periods (Menges 1998). We envisaged that reserve decisions made at this point would have the most importance over the next 50 years. Over longer periods, other priorities and conservation strategies are likely to take precedence.

The benchmark of 50 adults acts as a common reference point for a variety of different taxa and represents the lower bound for the size of the population we find unacceptably small for any species. Our method could have used extinction as the benchmark, but populations of <50 adults are sufficiently small that processes other than those found in most population models play a role. We elected to concentrate on adult plants, defined as reproductively mature individuals, to provide a means of dealing with species with different life forms and life histories and to remain consistent with the conventions of the World Conservation Union (1994). For example, many plants have soil-stored seeds that provide a buffer against adverse environmental events, whereas others persist by means of underground perenniating organs or dormancy. These factors are accounted for in the estimation of the parameters for the equations used to calculate sufficient population sizes experiencing background disturbance regimes. Overall, the criteria represent a modest target for the conservation of species within a realistic management time frame. Values for *F* or the benchmarks of 50 adults and 50 years can be varied to suit long-lived species or ephemeral species with long-lived seed banks.

The quasiextinction risk criterion is expressed in terms of current population size by estimating an initial population size for each taxon such that there is <0.1% chance of the population declining to 50 individuals at least once over the next 50 years. This implies that it is acceptable for about 25 of 25,000 Australian vascular plants to become critically endangered within the next 50 years. We assumed that biologists can estimate this population size for each taxon, but we outline some guidelines.

The estimate of the parameter *F* is based on the background risk of extinction of the taxon, a benchmark likely to approximate the risks faced by many natural populations free of additional (recent) disturbances (in Australia this implies disturbance since 1750). It provides a standard against which to compare the relative risks faced by different taxa.

Ideally, the values for *F* should be based on the best available population model, taking into account factors such as seed bank dynamics, disturbance response mechanisms, life history, demographics, outbreeding and selfing characteristics, and genetic homogeneity. In the absence of a species-specific model, *F* can be calculated based on a simple birth and death model. In the absence of any model, expert judgement is sufficient. We constructed a simple birth and death model for a single population, with a growth rate approximately equal to its death rate (Table 2), and we calculated values of *F* for several taxa based on detailed population viability analyses for individual species and on more generic models reflecting broad life-history traits. These species represent several of the functional groups identified by Noble and Slatyer (1981), including obligate seeders and resprouters, species with short- and long-lived seed banks, and species in which adults are susceptible to disturbance (Table 2 is only a guide).

Values for survival and variation and hence for *F* may be adjusted to reflect the characteristics of biology and life history that are likely to affect background risks of decline. For example, persistent soil-stored seed reduces the probability of extinction of a local population and reduces the value of *F*. Species with poor dispersal abilities may require larger *F* values (Table 3). Any such modifica-

Table 2. Examples of values of the initial population size, *F*, necessary to achieve a probability of < 0.1% of falling below 50 mature individuals at least once in the next 50 years.[a]

			Initial population sizes giving p(quasiextinction) ≤ 0.1%					
			CV[d]					
Taxon	*Survivorship or life expectancy*[b]	*Regeneration response*[c]	*variable*	*0.05*	*0.1*	*0.15*	*0.2*	*0.25*
Hypothetical[e]	0	continuous		520	1000	7500	23000	60000
	0.2	continuous		480	800	2500	17000	50000
	0.5	continuous		390	650	1800	12500	44000
	0.9	continuous		280	550	1650	9800	40000
	0.98	continuous		180	500	1600	6000	38000
Banksia goodii[f]	300	continuous	300					
Banksia cuneata[g]	50	disturbance	6400					
Alnus incana[h]	20	continuous	750					
Arisaema triphyllum[i]		continuous	11100					
Pentaclethra macroloba[j]	100	continuous	2300					

[a] *In all the models, the average birth and death rates in the population were such that, under deterministic conditions, the population persists indefinitely without increasing (i.e., the growth rate* $\lambda = 1$*).*

[b] *First five values are survivorships,* s, *and remaining four are longevity in years.*

[c] *A variety of life-history strategies for plants may provide some guidance toward establishing the size of a population that is likely to persist for 50 years, given a habitat free of recent additional anthropogenic disturbances.*

[d] *For the hypothetical example, initial population sizes are provided for a range of levels of variation in vital rates expressed as a coefficient of variation (CV).*

[e] *The hypothetical taxon is based on a generic model that assumes a single, unstructured population in which survival and reproduction are sampled from a binomial distribution, and the vital rates are sampled independently from a log-normal distribution (Burgman et al. 1993). The CV represents the level of environmental variation in* λ *from year to year without autocorrelation or density dependence (Menges 1998).*

[f] *After Drechsler et al. (1999). The model uses pessimistic assumptions about survival following fire, based on limited field data. Different assumptions produce an* F *value of around 100.*

[g] *After Burgman and Lamont (1992).*

[h] *After Huenneke and Marks (1987).*

[i] *After Bierzychudek (1982). The model used the pooled data for two populations, with transition probabilities reduced uniformly by 10% to reduce* λ *to 1.01 so the model represents a population persisting at or close to its natural carrying capacity.*

[j] *After Hartshorn (1975). The model is for a large-canopy species dominating the tropical wet forests in the Atlantic lowlands of Costa Rica. There is limited seed dormancy and no asexual reproduction. The latter two models are based on implementations by Ferson (1991).*

tions can be guided by a simple model that accounts for demographic variation and moderate levels of environmental variation in an unstructured or stage-structured, single population model without density dependence (Table 2). The number *F* may be smaller than the current population size, especially for abundant species. If *F* is less than the current number, this implies that if there are no additional detrimental processes or catastrophes, there may be the loss of some individuals but the species may still have an acceptably low risk of quasiextinction.

Step 2: Identify populations or groups of populations that currently experience similar disturbance regimes, known as *disturbance regions*. Perform all subsequent analyses on each disturbance region.

Disturbance regions represent areas of the landscape subject to similar sources and intensities of disturbance. It is necessary to characterize differences between regions in terms of their frequency and extent and to estimate the time to recovery of the species following disturbance within each region. In this context, a disturbance is any process resulting from recent (post 1750) human activities that affects the abundance and distribution of plant taxa. Because only human disturbances are counted, in many cases land tenure may be a reasonable guide for defining disturbance regimes.

Step 3: Identify and map the area of potential habitat. Our method assumes that a map of the potential habitat for each species is available for each disturbance region. Potential habitat may be defined by several methods. For example, it may include all areas considered by an expert to be capable of supporting viable populations of the species in question. Alternatively, it may be defined by a set of spatial climate and/or environmental data layers and a bioclimatic model, or by a multiple regression model of existing locations together with data layers for each of the explanatory variables (Austin et al. 1990; Wiser et al. 1998; Elith 2000).

Other measures of the area inhabited by a species include the area of occupancy and the extent of occurrence (Fig. 1). Neither of these is ideal for the purposes of our method. In the majority of circumstances, potential habitat will be larger than the area of occupancy and smaller than the extent of occurrence because it includes unoccupied suitable habitat and excludes unoccupied unsuitable habitat. Caution must be exercised in estimating the area of potential habitat to account for competition, predation, and disturbance, which might exclude a species from otherwise suitable locations.

Step 4: Outline the area of potential habitat surveyed (H). In some circumstances, all potential habitat will have been surveyed systematically and occurrences of

Table 3. Ecological factors that affect the initial population size, *F*, required to provide adequate chances of species persistence, assuming no additional sources of disturbance.*

Positive circumstances (resilience)	*Negative circumstances (vulnerability)*
Many large populations	few small, isolated populations
Widespread distribution	restricted distribution
Habitat generalist	habitat specialist
Not restricted to a temporal niche	restricted to a temporal niche
Not subject to extreme habitat fluctuations	subject to extreme habitat fluctuations
No particular genetic vulnerability	genetic vulnerability
Vigorous post-disturbance regeneration	weak post-disturbance regeneration
Rapid, vigorous growth	slow, weak growth
Quickly achieves site dominance	a poor competitor
All life stages resilient	particular life stages vulnerable
Short time to set first seed or propagules	long time to set first seed or propagules
Long reproductive lifespan	short reproductive lifespan
Robust breeding system	dysfunctional breeding system
Readily pollinated	not readily pollinated
Reliable seed production	extremely variable seed production
High seed production and viability	low seed production and viability
Long seed or propagule viability	short seed or propagule viability
Seed or propagules not exhausted by disturbance	seed or propagules exhausted by disturbance
Good dispersal	poor dispersal
Generally survives fire and other damage	generally killed by fire and other damage
Not adversely affected by pre-1750 disturbance	adversely affected by pre-1750 disturbance
Adapted to existing grazing, drought, fire regime	not adapted to grazing, drought, fire regime
Able to coppice or resprout	not able to coppice or resprout
Not vulnerable to pathogens, disease, insects, etc.	vulnerable to pathogens, disease, insects, etc.
Not dependent on vulnerable mutualist	dependent on a vulnerable mutualist

**Table 2 provides estimates of adequate population sizes for a range of hypothetical and real taxa. Positive circumstances indicate deviations from the assumptions of a simple birth-and-death model that result in reduced chances of quasiextinction. Negative circumstances are ecological characteristics that predispose a species to increased chances of quasiextinction.*

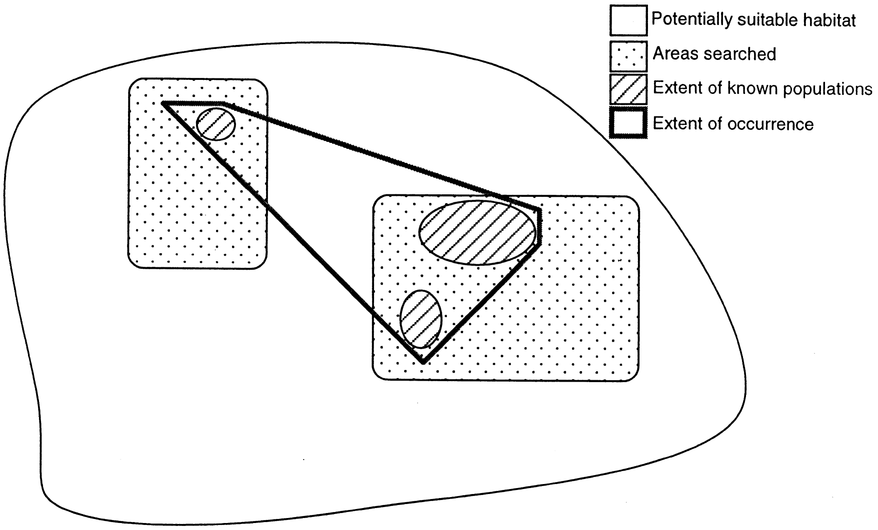

Figure 1. Representation of the area of potentially suitable habitat of a plant taxon based on a spatially explicit habitat model. To calculate the density of the taxon (ha/plant), the total area searched is divided by the number of adult plants found within the area searched. The area of occupancy defined by the World Conservation Union (1994) would include only the hatched areas representing the extent of the known populations. The extent of occurrence defined by the World Conservation Union (1994) would include a minimum convex polygon drawn around the known populations, shown by the heavy line.

the species mapped reliably. Parts of a species' potential range may have been surveyed in some repeatable fashion by standard sampling techniques. Surveys may have been intended to record the presence or absence of the species or to estimate abundance. Most often, maps of potential habitat are based on opportunistic records and expert judgment. Distribution information based on herbarium records (opportunistic presence-only information) may be supplemented by expert judgment of absences. Irrespective of how the information is acquired, the portion of the potential habitat searched should be outlined. The area of potential habitat searched within disturbance region i is H_i (Table 1).

Step 5: Estimate the size and density of the adult population (N_i) within the surveyed potential habitat. Estimates may be derived from quantitative survey information, if it is available or from expert knowledge. We used expert knowledge, together with the surveyed area, to calculate the number of adult plants per hectare (D),

$$D = N_i/H_i. \tag{1}$$

The average population density, D, should represent the average density of reproductively mature plants within potential habitat, accounting for the fact that the plants persist under the perturbations of a natural disturbance regime. It should not include any additional (anthropogenic) sources of disturbance considered explicitly in later steps.

Plant density may be calculated or estimated per disturbance region, although it may be difficult and time-consuming to have the experts arrive at density figures for each disturbance region and to quantify "areas searched" without considerable uncertainty. It may be preferable to use the density figure based on a single habitat model for all calculations. In most cases, the long-term average density will be best reflected in the disturbance region that has been least subjected to anthropogenic disturbance. For any particular species, it may be preferable to use the density figure for a disturbance region that represents the most undisturbed habitat.

Step 6: Estimate a target area for protection based on background disturbance processes. The raw target area for creation of reserves, A_0, is the area of potential habitat required to support a taxon, given particular life-history characteristics, such that it has a $<0.1\%$ chance of falling below 50 individuals once in the next 50 years, assuming pre-1750 conditions:

$$A_0 = F/D. \tag{2}$$

Step 7: Identify relatively small-scale disturbances affecting the species' potential habitat from which the species recovers within the management time frame of 50 years. Use estimates of the characteristics of these disturbances to calculate the proportion, S, of potential habitat, available to the species at any time.

We identified the different kinds of stochastic events that may cause an area to become unsuitable. This could be a single event such as a prescribed fire at a particular time of year or a logging event. More typically it will be a combination of events such as two or more fires within a short time. These are termed adverse regimes 1, 2, 3. . . .

The average annual area of these effects should generally be less than the total potential habitat. We assumed that these events are randomly and independently distributed across the landscape with respect to the distribution of the taxon. This is a plausible model for a surprisingly broad class of disturbance processes (Gardner et al. 1987; Johnson & Gutsell 1994; Pacala et al. 1996; McCarthy & Gill 1997).

Habitat requires n years before it is again suitable for the taxon—known as *recovery time*—representing the time between disturbance and the appearance of reproductively mature adults. This parameter is required to calculate the average proportion, S, of potential habitat available to a species each year. If a disturbance has a characteristic annual probability independently distributed across the landscape, the expected proportion of areas that are n years old is equal to the probability that an area was disturbed n years ago (p), multiplied by the probability that the area was not disturbed subsequently, $(1 - p)^{n-1}$ (McCarthy & Burgman 1995). The proportion of the landscape expected to be disturbed each year is equal to the probability that a point in the landscape will be disturbed. For example, if 10% of the landscape burns each year, then there is an annual probability of 0.1 that a random point in the landscape will burn.

The parameter n_d is the time between disturbance and the point at which a plant has developed sufficiently to reproduce. It includes the time to reach reproductive maturity for plants eliminated by recurrent disturbance, such as obligate seeders. We also define n_u, the time between disturbance and the point at which the habitat has developed so that it is unsuitable for the species. This time period is relevant for species that inhabit early successional stages within a landscape and that rely on periodic disturbances of particular kinds for germination or regeneration. For these species, the absence of a disturbance may result in unfavorable habitat beyond n_u years.

Given p_x, the proportion of the potential habitat disturbed on average each year by process x within the disturbance region in question, the proportion of the landscape, q_u, that is undisturbed each year by a total of z disturbance processes is

$$q_u = (1-p_1)(1-p_2)\ldots(1-p_z), \tag{3}$$

where p_1, p_2 are the probabilities of disturbance from processes 1, 2, and so on for z independent processes. Relatively small-scale disturbances are modeled as processes that have similar consequences for the ecology of the species in question.

The parameters p may be estimated if any of the following characteristics are known or can be estimated: proportion of the landscape (or population) that is, on average, more than n years old; proportion of the landscape (or population) that is, on average, less than n years old; average size of disturbance events (annual total area disturbed within the potential habitat); or return time between events (average time between disturbances at a point in the landscape).

This information may be based on expert knowledge of disturbance processes or on recorded information such as fire perimeter records and spatial and temporal analysis of disturbance regimes. It may be that the disturbance regimes are too complex to allow a reliable estimate of the parameters p and n. In such circumstances, it may be easier to estimate S directly.

Given n_d and n_u, the average proportion S of the potential habitat that will be suitable for the species at any time within the management time horizon of 50 years, accounting for disturbances that are either too frequent or too infrequent, is

$$S = q_u^{n_d} - q_u^{n_u}. \tag{4}$$

The parameters n_d and n_u encapsulate the window of opportunity for the species. Before n_d the area is too young for a seed-producing individual to have developed, and after n_u the area is too old to support the species. We assumed that the recovery time following disturbance was the same, irrespective of the kind of disturbance.

For example, assume a taxon is adversely affected by unseasonal fire, and this disturbance regime is imposed on the background of a natural fire regime. The taxon recovers naturally after fire because its soil-stored seed bank is stimulated to regenerate by fire. Suppose, however, that a 10-year lag occurs between the fire event and the development of adults that will replenish the seed bank ($n_d = 10$). If the additional fire events burn about 1/80 of the potential habitat annually, then the probability of disturbance for a site, p, is 1/80. We assumed that there is no upper bound, n_u, in this example. The proportion of the potential habitat that will be suitable for the taxon, given this additional source of disturbance, is

$$S = \left(1 - \frac{1}{80}\right)^{10} = 88\%.$$

That is, about 12% of the potential habitat, on average, will support populations that are too young to withstand other disturbances such as unplanned wildfires, because they will not have produced seed to replenish the seed bank that was depleted following the most recent disturbance. Fire-management activities effectively reduce available habitat by 12%.

The last element of this step is to adjust the target area to take into account habitat that is temporarily unsuitable due to small-scale stochastic disturbances. The target area should be adjusted so that an area equivalent to A_0 will be available for a taxon in any 1 year:

$$A_1 = A_0/S\,. \tag{5}$$

Step 8: Adjust the target area to account for deterministic trends that irreversibly affect the species' potential habitat. Such adverse trends cause permanent loss of habitat (at least within the management time frame) and consequently permanent loss of the species at a site. Examples include land clearance for agriculture, roads, and urban development, or salinization processes. The parameter L is the rate of loss of potential habitat (the proportion of remaining habitat lost to this process) per year due to irreversible attrition. The proportion of the target area, A_1, remaining at the end of 50 years is $A_1 (1 - L)^{50}$, and the area of potential habitat required at present such that A_0 could be expected to be available 50 years hence, given i such processes, is

$$A_2 = \frac{A_1}{c_1(1-L_1)^{50} + c_2(1-L_2)^{50} + \ldots + (1 - \sum c_i)}, \tag{6}$$

where c_1, c_2 represent the proportion of the potential habitat threatened by processes 1 and 2 during the next 50 years. For example, if $L_1 = 0.25$, then one-fourth of the remaining habitat (starting with c_1 in year 1) is lost per year, so in 2 years $c_1 \times 9/16$ remains. The values of c_i should sum to ≤ 1. The formula assumes that a proportion c_1 of the habitat is threatened by process 1. A proportion c_2 is threatened by process 2, and so on. If processes 1 and 2 are coincident in space (such as land clearance and salinization), then they should be treated as a single process. This equation can be used to distinguish between reserved and unreserved components of the target area if there is a differential susceptibility to irreversible effects according to tenure. For example, land clearance may be a threat to a taxon on one tenure but not on another.

Step 9: Adjust the target area to account for processes that permanently reduce the density of populations within their area of occupancy. Some human actions result in more or less permanent reductions in local population density without an ongoing decline in abundance or range. Such processes may not eliminate the taxon from any location, but they could reduce the viability of a taxon at a site. Examples include grazing of livestock or increased disease rates, which result in reduced local population density. Then, estimate values for r_i, the proportional reduction in local density due to each of the i effects. The area of potential habitat required to ensure the level of persistence specified at the outset is

$$A_3 = A_2/(\Pi r_i)\,, \tag{7}$$

where Π represents the product of i numbers. For example, if grazing reduces by 10% the average density of a population within its extent of occurrence and a disease reduces population density by 20%, then r for grazing is 0.9 and r for disease effects is 0.8. The area A_3 will equal $A_2/(0.9 \times 0.8)$.

This is the final step in estimating the total area required for a particular taxon within each disturbance region so that it has a <0.1% chance of falling below 50 individuals once in the next 50 years. Subsequent steps may be used to guide the allocation of this area among different potential locations.

Step 10: Identify catastrophes likely to affect the species' potential habitat, its number of discrete populations, and its dispersal capabilities. We define catastrophes as events that completely eliminate a population. This is not standard use of the term but serves to discriminate extreme events from other random disturbances. Catastrophes include larger-scale, infrequent disturbances such as floods, intense wildfires, or disease outbreaks. The definition of catastrophes implies that the average annual area affected by these events is much greater than the total potential habitat area of each population of the species. For these purposes, a population may be thought of as any group of individuals affected by a common catastrophe.

Then, determine the annual probability of each catastrophe. In virtually all cases this will involve a certain amount of guesswork. In case of events such as extreme fires, the data may be the product of an explicit model. The number of populations a species needs to persist depends on the frequency of these catastrophes and whether the catastrophe results in local extirpation. The greater the frequency of catastrophes and the more intense their effects, the greater the number of populations.

Strategies for spreading risk among several populations assume that populations may be selected far enough apart to ensure that catastrophes occur more or less independently, requiring a minimum level of separation that exceeds the maximum area affected by each catastrophe. They also assume that the dispersal mechanisms of the species are sufficient to allow propagules or dispersing individuals to recolonize populations eliminated by a catastrophe.

Consideration of the appropriate number of populations must also take into account the magnitude of autocorrelation between environmental fluctuations (of a noncatastrophic nature) in different patches and the ability of the species to disperse among patches. If dispersal ability is poor and environmental correlations are strong, then fewer patches result in a lower overall risk of extinction. If dispersal abilities are good and environmental correlations are relatively weak, then more patches result in a lower overall risk of extinction.

Step 11: Combine targets across disturbance regions. Add regional targets together to achieve a species target. Select areas such that the total area protected is sufficient to meet the condition that the taxon is <0.1% likely to fall below 50 mature individuals within the next 50 years.

An area A_3, calculated for each disturbance region, would be required if the target area for the taxon were to be selected from that region alone. The A_3 areas differ because potential habitat subjected to different disturbances has different conservation value. Different types of "reserves" afford different levels of protection. Not all will be equally effective at offsetting extinction risks. The different values of A_3 reflect the different disturbance regimes. Land from each disturbance region is selected in step 11 according to its ability to maintain viable populations. Thus, the value of A_3 from a large national park may be half that of A_3 calculated for a zone subjected to a different disturbance regime. Targets for conservation may be met in a number of ways, and the formula in step 11 ensures that the target is met irrespective of the way in which land is allocated for a species among different disturbance regions.

The calculations between steps 1 and 10 result in a value of A_3 for each of k disturbance regions, denoted as $A_3{}^k$. Areas from the k disturbance regions should be selected so that

$$\frac{X^1}{A_3^1} + \frac{X^2}{A_3^2} + \frac{X^3}{A_3^3} + \ldots + \frac{X^k}{A_3^k} \geq 1, \tag{8}$$

where X^k areas are selected from n disturbance regions, and the values for A^k are the required areas, A_3, calculated for each of the n disturbance regions. That is, the Xs are the areas (in hectares) reserved in each disturbance region.

Strict application of this criterion will allow $k - 1$ sites to become extinct if one site is larger than the target area. This does not mean that such a strategy is recommended. Rather, the conservation of a species throughout its range and in representative parts of its habitat may be equally important considerations.

Step 12: Evaluate habitat maps and evaluate the adequacy of strategies; set objectives accounting for spatial and species-specific constraints. Any combination of patches may be selected to achieve the target area. A strategy that conserves many small, isolated patches, none of which is likely to survive for long, might appear to satisfy the criteria described here. Taken to its extreme, a target may be satisfied by circumscribing small areas around individual plants. Our method, however, is intended to support other decision-making tools, not to supplant common sense. For example, any decision process should be underpinned by an objective to conserve patches that have some minimum probability of persistence before they are counted toward species-wide management objectives. It may be possible, for instance, to specify that the minimum patch size should be one that supports at least 10% of the total target. The calculations we made assume that plants can disperse easily between patches and that existence of anything that inhibits dispersal—either by the species itself or its dispersal agents—influences decisions about the best spatial strategy for conservation of the species.

When decisions are made about plant conservation, not all targets will be met. In some cases, the required habitat will not be available. In other cases, it may not be possible to be protect or manage the habitat even if it is available. Given that an area X^i will be set aside in reserves in each on the i disturbance regions, the statistic A_3 may be used to provide information in addition to a simple area statement. The proportion of the required area that has been preserved,

$$I_M = \frac{X^1}{A_3^1} + \frac{X^2}{A_3^2} + \frac{X^3}{A_3^3} + \ldots + \frac{X^n}{A_3^n}, \tag{9}$$

gives an indication of how well the target has been met. When it equals 1, the target has been met; when it is >1, the target has been exceeded; when it is <1, the target has not been achieved. The ratio may also be used to provide guidance and support for the ranking of priorities for negotiations regarding land use and tenure. Satisfying this equation may create incentives to select as much area as possible from regions under the least threat, tempered by the requirement to conserve a minimum number of locations and the relative costs of reserving land in the different regions.

Similarly, A_3 may be compared with available habitat H. This provides an index of the proportion of the area required for preservation that currently exists,

$$I_H = \frac{H^1}{A_3^1} + \frac{H^2}{A_3^2} + \frac{H^3}{A_3^3} + \ldots + \frac{H^n}{A_3^n}. \tag{10}$$

If available habitat H is substantially less than the area required A_3, then I_H will be small. This implies that even the protection of all existing potential habitat would be unlikely to sustain the species. The larger the discrepancy, the greater the threat to the species' continued existence. The smaller the number, the greater the imperative to do more than just conserve land.

Application of the Model to Three Threatened Plant Species

The following three examples illustrate the utility of our method. The first set of calculations includes interval estimates for some of the most uncertain parameters. These intervals are carried through the calculations and are used to compare the results of the equations with the results of the detailed model.

Banksia cuneata

A detailed population viability analysis has been done for *Banksia cuneata*, (Burgman & Lamont 1992). We used it to illustrate the relationship between our equations and a more detailed viability analysis. *B. cuneata* is an endangered shrub that grows to 5 m tall in six localized stands in the undulating sand plains of southwestern Western Australia. Interactions among soil preferences, drought stress, and interspecific competition limit its geographic distribution (Lamont et al. 1991). Burgman and Lamont's (1992) population viability model uses 13 stages (five juvenile, seven subadult, and one adult stage), and we assumed that the parameters used in our method were those specified by them. To estimate F, we constructed a simple birth and death model, assuming coefficients of variation in demographic parameters of 10%, uncorrelated variation between fecundity and survivorship, perfect correlation between survivorship terms, demographic uncertainty, and exponential population growth. For the other parameters in our method, we assumed that adults are killed by fire and that regeneration is stimulated by random fire events. In our model, fires occur naturally with a probability of 0.1 per year and kill an average of half the mature plants in a stand.

Step 1: Under these conditions, an initial population size of 6400 mature plants (plants >5 years old) has a probability of close to 0.1% of falling below 50 individuals at least once in the next 50 years (F = 6400 [5400, 7400], where the values in brackets represent bounds for F). Step 2: All potential habitat is within a single disturbance region. Step 3: There are six remaining populations of fewer than 400 mature plants; they have a total range of <60 km. Steps 4 and 5: The total area of potential habitat has been surveyed. In places where they grow, stands of *B. cuneata* are dense but occur only sporadically. Average density (D) within remaining habitat is about 10 with a range of 5–15 plants/ha. The range results from uncertainty about what constitutes the limits of potential habitat. Step 6: The target area needed to support 6400 mature plants is 640 ha ($A_0 = F/D$ = 6400/10 = 640 [360, 1480] ha). Steps 7–9: For the sake of illustration, we assumed that fires originating in surrounding developed land increase the risk of fire in *B. cuneata* stands from 0.1 to 0.2. There is a 5-year time lag between germination and reproductive maturity (n_d = 5), and plants lose reproductive potential at about age 45 (n_u = 45). Thus,

$$S = p_u^{n_d} - p_u^{n_u} = (1-0.1)^5 - (1-0.1)^{45} = 0.58.$$

The adjusted habitat area is A_1 = 640/0.58 = 1103 [630, 2552] ha. There are no additional deterministic processes that reduce habitat area or local population density, so $A_1 = A_2 = A_3$. Step 10: There are no potentially catastrophic processes. The possibility of loss by land clearance is not entirely discounted, but the populations are legally protected, and clearance would lead to substantial penalties. We assume that these measures will be effective. Steps 11 & 12: The population size required for "adequate" protection, even in the absence of additional fire risk, is more than 10 times the existing population size. The ratio

$$I_H = \frac{H}{A_3} = 35/1103 = 0.03[0.01, 0.05]$$

shows that all available habitat should be protected and that active management strategies to reduce risk are warranted.

We compared this example to the population viability model by increasing the fire risk in the model from 0.1 to 0.2 and adjusting the initial population size so that it again gave a risk of close to 0.1% to falling below 50 individuals. The initial population size needed to achieve the equivalent extinction risk was 13,100, implying a population reduction to about 0.49 of the undisturbed population (compared to 0.58 based on the equations above) and an area target of 1310 [873, 2620] ha. When the same levels of uncertainty in density estimates are applied to both results, there is considerable overlap between the two interval estimates of the area required for adequate conservation. The equations give a reasonable approximation of the more detailed population model, given the levels of uncertainty in the calculations.

Boronia keysii

B. keysii is listed as vulnerable in Queensland and nationally, and it is endemic to Queensland. There has been no detailed population viability analysis for this species. It is a sprawling shrub that grows up to 2 m high, with a lifespan of 15–30 years. It is an obligate seeder, with a long-lived seed bank that is exhausted by frequent disturbance. A mildly explosive pod provides short-distance dispersal. There are about 10,000 known adult plants in 15 populations occurring from mixed eucalypt and brushbox woodland to open forest. The juvenile period is about 3 years, and the period from reproductive maturity to senescence is about 15 years. If there were an absence of disturbance in a population for more than 50 years, the seed bank would be exhausted. This species is included because it experiences deterministic declines in addition to stochastic pressures.

Step 1: The population target required for adequate protection in the absence of additional disturbance (F) is 4000. The value for F was estimated subjectively by placing the species in Table 2 based on its ecology and disturbance dynamics. Step 2: There is a single disturbance regime. Steps 3 & 4: The area of potential habitat (H) is 150 ha (same as occupied habitat). Step 5: The average density (D) of the species within its habitat is 67 plants/ha. Step 6: The target area (A_0) in the absence of additional sources of disturbance is 4000/67 = 60 ha. Step 7: Additional small-scale disturbances from which the species recovers include two fires in 4 years, which exhausts the seed bank. The probability of two fires, p_1, is 0.3. The proportion of suitable habitat is

$$S = p_u^{n_d} - p_u^{n_u} = (1-0.3)^3 - (1-0.3)^{18} = 0.341.$$

The target area accounting for additional disturbance is $A_1 = A_0/S = 60/0.341 = 176$ ha. Step 8: Trends that irreversibly affect the species' potential habitat include agricultural clearing and continual treatment (50% of habitat susceptible at 10% per year), changed hydrological conditions (20% of habitat susceptible at 5% per year), and weed invasion (6% of habitat susceptible at 5% per year):

$$A_2 = 110/[0.5(1-0.1)^{50} + 0.2(1-0.05)^{50} + 0.06(1-0.05)^{50} + (1-0.76)] = 733 \text{ ha}.$$

Step 9: The density of populations is not affected within their area of occupancy, so $A_3 = A_2$. Step 10: There are no obvious catastrophes that may affect the populations. Steps 11 & 12: The ratio of available habitat (H) to required habitat, (A_3), is 150/733 = 0.205.

Because the ratio is <1, under current disturbance conditions, the area of habitat available is not sufficient to ensure the species a better than 99.9% chance of surviving for the next 50 years. If all of the threats to which the species is subject and from which there is no recovery could be eliminated (land clearance, changed hydrological conditions and weed invasion; step 9), then the target could be achieved by protecting all remaining habitat. Another alternative may be to manage the fire regime to reduce the incidence of too-frequent fires.

Parsonsia dorrigoensis

Parsonsia dorrigoensis is a sparsely distributed vine of forests on the north coast of New South Wales. It recruits continuously but infrequently, and is killed by fire. There is no persistent seed bank, and age to maturity is about 4 years. Plants produce <1 pod per plant per year. A search prior to this study found 1500 plants within 375 ha of potential habitat. There is no detailed PVA for the species. We used it as an example because it persists within different disturbance regions. As in the previous example, interval calculations were omitted for clarity.

Step 1: The population target required for adequate protection in the absence of additional disturbance (F) is 4000. The value for F was estimated subjectively by placing the species in Table 2 based on its ecology and disturbance dynamics. Step 2: There are three disturbance regions. Step 3: The areas of potential habitat within each disturbance region were region 1, Ballinger River, New England, Ballinger River, Horseshoe Road (2000 ha); region 2, Dorrigo Tops (500 ha); region 3, Conglomerate - Orara (1000 ha).

For region 1 steps 4 and 5: Average density within potential habitat, D, is 4 plants/ha. Step 6: The target area (A_0) in the absence of additional disturbance is 4000/4 = 1000 ha. Step 7: The probability of fire is $p = 0.02$. The proportion of suitable habitat is $S = (1\text{-}0.02)^4 = 0.922$. The target area accounting for additional disturbance is $A_1 = A_0/S = 1000/0.922 = 1084$ ha. Step 8: There are no trends that irreversibly affect the species' potential habitat, so $A_2 = A_1$. Step 9: The density of populations is not affected within their area of occupancy, so $A_3 = A_2$.

For region 2 steps 4 and 5: Average density within potential habitat (D) is 4 plants/ha. Step 6: The target area (A_0) in the absence of additional disturbance is 4000/4 = 1000 ha. Step 7: The probability of fire is $p = 0.04$. The proportion of suitable habitat is $S = (1\text{-}0.04)^4 = 0.781$. The target area accounting for additional disturbance is $A_1 = A_0/S = 1000/0.781 = 1177$ ha. Step 8: There are no trends that irreversibly affect the species' potential habitat, so $A_2 = A_1$. Step 9: The density of populations is not affected within their area of occupancy, so $A_3 = A_2$.

For region 3 steps 4 and 5: Average density within potential habitat (D) is 4 plants/ha. Step 6: The target area (A_0) in the absence of additional disturbance is 4000/4 = 1000 ha. Step 7: The probability of fire is $p = 0.05$. The proportion of suitable habitat is $S = (1\text{-}0.05)^4 = 0.774$. The target area accounting for additional disturbance: $A_1 = A_0/S = 1000/0.774 = 1292$ ha. Step 8: There are no trends that irreversibly affect the species' potential habitat, so $A_2 = A_1$. Step 9: The density of populations is not affected within their area of occupancy, so $A_3 = A_2$.

The preservation strategy for the species may be informed by steps 10–12. Step 10: There are no obvious catastrophes that may affect the populations. Steps 11 and 12: There are three disturbance regions, so numerous solutions will satisfy the required target area. For example, option 1 may be to select all of the required land from disturbance region 1, yielding

$$I_M = \frac{1084}{1084} + \frac{0}{1177} + \frac{0}{1292} = 1.$$

Alternatively, the strategy may be to select equally valuable parcels of land from each of the three disturbance regions:

$$I_M = \frac{361}{1084} + \frac{392}{1177} + \frac{431}{1227} = 1.$$

More land is required from disturbance region 3 because it experiences more frequent fires and a larger proportion of its habitat is unsuitable on average. In all cases, the amount of available habitat (H) exceeds the required habitat, (A_3), and both of the above solutions provide a solution in which $I_M = 1$. This set of calculations assumes that the species is able to recolonize a burnt area immediately following fire. It is unlikely that this assumption is correct. It may be worth it to recalculate the above equations, assuming there is a lag between a fire and the reappearance of mature adults which includes both developmental time from seed and the average time taken to recolonize. If the delay is, say, 20 years, then this could be introduced by changing the power in step 7 from 4 to 24. The requirements for protection would increase to 1624, 2664, and 3425 ha, respectively, for each of the three regions in isolation, resulting in achievable targets given the amount of available habitat.

Discussion

Our examples show that application of a common set of rules does more than produce a number. Our method serves to focus attention on the causes of threat that affect habitat area and population density, and it may lead to recommendations that directly affect the most important processes. It requires that each threatening process be typified in terms of its effect on the disturbance and recovery dynamics of the species in question. Thus, the method may be used to evaluate the effects of land clearance, changed fire frequency, cattle grazing, competition from exotic species, harvesting, or changed hydrology, if the consequences of these processes can be characterized appropriately. The equations work equally well in circumstances in which species depend on ancient land-use practices, so long as changes in these practices are characterized appropriately.

In addition, the method puts the threats faced by different species in perspective with the threats faced by others. There may be many species on a list of endangered taxa, but the prospects for *B. cuneata*, for example are such that conservation resources should perhaps be directed toward it before the other two species evaluated here. A further advantage is that the assumptions made in reaching conclusions are explicit and the equations provide a means by which these assumptions may be relaxed. For example, we assumed immediate recolonization of disturbed sites by *Parsonsia dorrigoensis.* The assumption is in plain view, and we may re-evaluate our priorities after relaxing this assumption and recalculating the quantities.

In general, calculations of target areas and rank priorities for species should include a range of values from best guesses to lower bounds. If ranges are collected for all variables, then area targets may be estimated with appropriate minimum and maximum ranges. Apart from representing the reliability of target-area estimates, this makes it clear that estimates from the equations are only approximations and that they should be used to support decisions, rather than as the sole basis for decisions. Our results are only to be used as guides for reserve and management targets. In the end, all decisions should be tempered by expert judgment and constrained by information and priorities that are not part of these few equations.

Target areas may change as management practices change or as distributional and ecological knowledge improves. For example, the planning process may take into account the conservation status of species derived from independent rule sets, or the taxonomic uniqueness of a species. Resource constraints and political and public priorities contribute to conservation outcomes. The process of identifying land to satisfy individual species targets may also be constrained by the need for efficiency and comprehensiveness in achieving other conservation goals. The equations above are intended to provide a framework within which the relative susceptibility of plant taxa to explicitly defined disturbance regimes may be included in the conservation planning process.

In the absence of detailed population models, or at least some experience in building these models, estimating F may prove problematic. Absolute values are important because absolute land areas will be protected. But so long as the values for F make sense relative to one another, the relative status of the different species may be correctly interpreted. If the range of species is sufficiently broad, our examples can provide some guidance on setting absolute levels for the relative values of F (Table 2).

To achieve adequate conservation, it is necessary to evaluate population viability. Shaffer (1981) suggested that a viable population is one that has a <1% chance of extinction in 1000 years. Other authors set different target extinction probabilities over different time frames. In general, assessing viability without a detailed population viability analysis is difficult, and some authors suggest that all predictions of extinction probability should be treated with caution (Possingham et al. 1993; Taylor 1995; Beissinger & Westphal 1998; Ludwig 1999). The notion of adequacy is bound up with acceptable risk. If we assume that an adequate number of populations and an adequate area are those in which the chance of the total adult population falling below 50 individuals within 50 years is <0.1%, then we would accept that 0.1% of the biota could fall to population sizes below 50 adults. There are 25,000 species of vascular plants in Australia, meaning that we would find it acceptable for 25 species to become critically endangered at some time over the next 50 years. If this level of risk is too high, we might settle on, say, a 0.01% chance of the total adult population falling below 50 individuals within 50 years.

Our method pools populations within disturbance regions without taking dispersal into account. If populations are fragmented and dispersal is so low that recolonization of empty patches is rare over the time scales considered, then it may be necessary to further subdivide disturbance regions. Alternatively, this issue could be incorporated by increasing the value of F (Tables 2 & 3). The threshold of 50 mature individuals used in this study is arbitrary. The consequences of adopting a different benchmark and its effect on estimates of F and on subsequent calculations could be explored in a sensitivity analysis of the results.

It is important to be aware of the assumptions and limitations of our methods. We assumed that potential habitat can be mapped reliably and that there is information about each species' density, life history, and response to disturbance. The methods do not account explicitly for the spatial arrangement and adjacency of habitat, dependency on other species, and future disturbance regimes. They may be applied to species, subspecies, or taxa within regions. Although target areas reflect short-term (50-year) dynamics, conservation planners should also account for evolutionary potential and accommodate long-lived species by examining outcomes on the basis of several generations. The best way to make assumptions transparent is to supply a sensitivity analysis in which each of the assumptions is relaxed in turn and each of the parameters is varied within plausible bounds. This communicates the extent to which target areas depend on the assumptions.

Our methods attempt to address, in part, a need identified by Schemske et al. (1994:595): "The combination of escalating threats to species and severe fiscal and political constraints have created a need for conservation biologists and land managers to develop realistic and efficient guidelines for the management of rare and endangered species." Perhaps the most difficult part of developing tools to assist pragmatic decision making is to find the right balance between what is possible given time and knowledge constraints and what is necessary given the values at risk if the process results in bad decisions. The tools we present are not intended to replace existing methods for setting conservation targets. They provide a relatively rapid, transparent, and explicit means of assessing the conservation requirements of plants that may support decision-making processes in circumstances in which time and resource constraints preclude thorough habitat and population viability modeling.

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