Annu. Rev. Environ. Resour. 2006. 31:123–59
doi: 10.1146/annurev.energy.31.042606.085844
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BIODIVERSITY CONSERVATION PLANNING TOOLS: Present Status and Challenges for the Future

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Key Words biodiversity surrogates, conservation area networks, multicriteria analysis, reserve selection, software packages

■ **Abstract** Species extinctions and the deterioration of other biodiversity features worldwide have led to the adoption of systematic conservation planning in many regions of the world. As a consequence, various software tools for conservation planning have been developed over the past twenty years. These tools implement algorithms designed to identify conservation area networks for the representation and persistence of biodiversity features. Budgetary, ethical, and other sociopolitical constraints dictate that the prioritized sites represent biodiversity with minimum impact on human interests. Planning tools are typically also used to satisfy these criteria. This chapter reviews both the concepts and technical choices that underlie the development of these tools. Conservation planning problems can be formulated as optimization problems, and we evaluate the suitability of different algorithms for their solution. Finally, we also review some key issues associated with the use of these tools, such as computational efficiency, the effectiveness of taxa and abiotic parameters at choosing surrogates for biodiversity, the process of setting explicit targets of representation for biodiversity surrogates, and dealing with multiple criteria. The review concludes by identifying areas for future research, including the scheduling of conservation action over extensive time periods and incorporating data about site vulnerability.

CONTENTS

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1. INTRODUCTION

The accelerated pace of habitat change and natural resource utilization since the 1960s (1, 2), especially in the tropics (3), and the resultant threats to biodiversity have led to increased concern for protecting remaining natural areas since the 1970s (4). Sociopolitical considerations, including the legitimate desire for economic development in tropical countries, dictated that not all areas of biological interest could be protected. The design of adequate networks of conservation areas, protecting the most important sites in each region, became a central problem of the new interdisciplinary field of conservation biology, which emerged in the 1980s with the explicit task of halting the decline of biodiversity (5). Establishing representative conservation area networks in which biodiversity can persist has also become a policy goal for major governmental, intergovernmental, and nongovernmental organizations (reviewed in Reference 6). Early efforts at the design of conservation area networks were typically based on the theory of island biogeography (7): Nature reserves were supposed to be similar to islands in oceans of anthropogenically transformed habitats. Species-area curves were often invoked to estimate optimal sizes for conservation areas (8). These early efforts were guided by abstract ecological principles rather than attention to localized socioeconomic or biological data (5).

In the 1980s, these attempts were replaced by efforts to use detailed biogeographic distributional information for the design of conservation area networks and by an explicit attempt to achieve spatial economy within them (that is, achieve the biodiversity goals in as little area as possible) (9, 10). By the 1990s, efforts were also under way to include socioeconomic criteria in these designs (11). These new approaches were algorithmic and relied heavily on computers because they needed to process large quantities of data rapidly (11). The field of systematic conservation planning emerged from these efforts (12). Several protocols exist for systematic conservation planning (11–16). These involve a number of stages including the determination of stakeholders in the planning region, collection and treatment of biological and socioeconomic data, selection of features to represent biodiversity quantitatively, selection of individual conservation areas (the problem studied since the 1980s), assessing vulnerability and the prognosis for components of biodiversity, and multicriteria analysis to satisfy divergent socioeconomic and biological goals of the stakeholders. Each of these stages is aided by the use of planning tools consisting of software packages implementing a variety of algorithms for these purposes. Besides researchers, these tools are typically used by intergovernmental groups, governmental planning departments, nongovernmental conservation organizations, and, on occasion, by groups of landowners who want to manage relatively large areas for conservation and other uses.

The past 20 years have seen the emergence of a wide variety of such software packages. The rapid growth in the application of these tools has not been accompanied by reviews to identify their differences and similarities or their relative strengths and weaknesses. Here, we review the concepts and techniques on which conservation planning tools are based and identify issues that future developers must confront (for histories, see References 5, 16–19). A forthcoming review (R.L. Pressey, S. Andelman, M. Bakarr, P. Comer, R. Cowling, P. Crist, F. Davis, D. Faith, C. Groves, R. Machado, S. Polasky, H. Possingham, A. Rodrigues, S. Sarkar, D. Stoms, P. Williams, and K. Wilson, in preparation) describes the use of these tools by planners.

A conservation planning tool is defined as software with the following two characteristics:

- It can be used to guide decisions about conservation action for biodiversity, although it may also be used to plan for other natural values such as scenery or ecosystem services.
- At the very minimum, it can identify either (*a*) sets of complementary sites needed to achieve quantitative targets for biodiversity features or (*b*) the

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> complementary contribution that individual sites make to biodiversity conservation within a region.

This definition is intended to bound the scope of this review to software tools designed to help planners decide on the location and configuration of conservation areas. Thus, it does not consider geographical information systems (GIS), software for population or habitat-based viability analysis, or niche-modeling software, which are routinely used in conjunction with conservation planning tools. Biodiversity is construed here to include the variety of living features and processes at all levels of structural, taxonomic, and functional organization but not ecosystem services or culture-based categories.

The central goals of a conservation plan are *representation* and *persistence* (12). Representation requires that all relevant features of biodiversity are adequately accounted for in a plan. However, representation must be achieved with *economy*; that is, adequate coverage must be achieved at a minimum cost. Economy is also called efficiency in the literature (9), but here it is used to denote computational efficiency (21). Economy typically refers to spatial economy because the most relevant cost is usually that of designating land for conservation. Spatial economy is critical because conservation competes with other potential uses of the land; a conservation plan that ignores these demands has a reduced chance of implementation. In practice, owing to such constraints, entire conservation area networks have rarely been implemented. One exception is the set of areas recommended by Kirkpatrick in Tasmania (19). However, planning tools increasingly influence both policy and implementation (22–26a).

The second central goal of conservation planning, persistence, refers to the need for planning to go beyond the representation of biodiversity patterns. If biodiversity is to persist in conservation area networks for centuries or millennia, then a variety of ecological and evolutionary processes must be accommodated. These processes include dispersal, local extinctions and recolonizations, species interactions, migration, patch dynamics, adjustment of species' distributions to climate change, and diversification of lineages. Approaches to promote persistence using planning tools are discussed in detail below (see also Reference 27).

The aim of conservation planning tools is to help users make decisions, not to exclude them from decision making. Planning tools are decision support systems not sensu stricto decision-making systems. The use of planning tools has been criticized on the grounds that they do not incorporate local expertise (28), require inordinate amounts of data not normally available (28–30), and are expensive to apply, diverting resources that are better spent acquiring land (29). These unjustified criticisms are based on misconceptions about how tools should be used and what they have achieved (5, 31, 32). Conservation planning is a dynamic process in which these tools are supposed to aid decision makers in identifying good policy options. This process is ideally carried out iteratively during a planning exercise, with results from tools guiding the delineation and refinement of policy alternatives. The rapid recent growth of biological and environmental databases has ensured that there is now no terrestrial region for which there is not enough data for planning tools to improve policy formulation. Several studies have shown that ad hoc policy formulation is remarkably cost ineffective in prioritizing conservation areas (31–33).

In this review, the term "conservation area" is used instead of the more traditional "reserve" to indicate that reservation is one extreme of a continuum of policy options for management that can range from reservation to the restoration of degraded areas (34). The appropriate management regime depends on both the needs of the biota and sociopolitical constraints and opportunities. We also emphasize the prioritization of sites rather than their selection to indicate that not all sites deserving conservation management will be protected at any given time.

Three key concepts have guided the design of planning tools: *complementarity*, *irreplaceability*, and *vulnerability*. Complementarity goes back to the origin of planning tools in the work of Kirkpatrick and coworkers (35, 36). Their crucial insight was that, if the goal is to represent biodiversity maximally in a given land area, then sites should be selected to maximize the differences in their biotic content. This principle, later called complementarity, was independently discovered at least three other times in the 1980s (37–39). The term "complementarity" was introduced by Vane-Wright et al. (40). The complementarity value of a site, relative to an existing set of prioritized sites, is its quantitative contribution to the representation of biodiversity features that are not adequately represented in the existing set; here adequate representation consists of meeting predefined targets. Differences between sites are critical to representing biodiversity adequately; complementarity is thus related to β-diversity (41). However, complementarity is an essentially asymmetrical relationship between biotas (42). The use of complementarity requires information on the specific content of sites, namely, lists of surrogates present in them; summary statistics such as richness do not suffice. The complementarity value of a site must be updated whenever the set of prioritized sites changes.

A second key concept is irreplaceability. A site prioritization problem typically has multiple solutions—some closer to optimal than others. In this context, although finding a single solution can provide an indicative answer about the size and configuration of the required set of sites, single sets are of limited value in practical planning for two reasons. First, some of the unselected sites might be useful replacements for a selected one that cannot be included in a conservation area network. Second, it is unclear whether any particular selected site is essential for achieving targets or whether it could be replaced by others and is therefore negotiable. These limitations may be addressed by determining the irreplaceability of each site across the planning region (43). This indicates the probability of a site being needed to achieve targets. Complementarity is implicit in irreplaceability. Irreplaceability can be measured exactly for very small data sets by exhaustive analysis of all possible site combinations and then determining the proportion of representative combinations achieving all targets that contain each site (43).

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A variety of techniques have been developed to estimate irreplaceability in more complicated contexts (43–48).

Because the persistence of biodiversity is a crucial goal of conservation planning, a third critical concept guiding the design of planning tools is vulnerability. It may be inappropriate to include a site in a conservation area network if its use becomes incompatible with management for biodiversity or if its biotic components have low abundance or probability of persistence. Vulnerability refers to both. In the planning tools that exist today, concern for vulnerability is incorporated mainly through the specification of conservation targets, preferences between sites when developing plans, and scheduling of conservation action on the ground during the implementation phase (49).

Design and application of conservation planning tools occur in a dynamic context in which plans must be continually updated on the basis of new information. Additional or improved biological or other data might become available after initial plans have been formulated. The preferences of planners might change as a response to either the new data or sociopolitical developments. Initial plans may become partly unachievable because of the loss or degradation of some selected areas. With these goals in mind, we use six criteria to judge the performance of planning tools: economy, efficiency, flexibility, transparency, genericity, and modularity (see Table 1 and Reference 21).

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TABLE 1 Criteria for the evaluation of conservation planning tools

Spatial economy: planning tools designed to select sites should either minimize the cost (e.g., number, total extent, economic, or opportunity cost) of sites or maximize the representation of features within cost constraints (9).
Computational efficiency: planning tools should resolve data sets rapidly, particularly if multiple scenarios must be evaluated and stakeholders are involved in real-time negotiations (50).
Flexibility: planning tools should allow the incorporation of a wide variety of criteria that are relevant to conservation planning, in addition to the minimal ones that form part of the definition of planning tools (51, 52).
Transparency: it should be clear why each site is selected. If a site is subsequently excluded from conservation management, planners should know the implications for biodiversity and other goals, its effects on implementation prospects, and the potential to replace it with other sites (21).
Genericity: planning tools should solve a variety of problems encountered in practice, using data on any set of biodiversity surrogates, from any type of ecosystem and geographical location (21).
Modularity: this has two aspects. Flexibility and genericity require that a planning tool as a whole be a module that can interface easily with other tools, such as GIS, viability analysis, and niche-modeling software. Flexibility and transparency require internal modular organization: it should be possible to select individual functions or criteria within a planning tool (21).

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Section 2 provides a conceptual background to conservation planning: It discusses levels of planning, the use of biodiversity surrogates and representation targets, planning for persistence, and the incorporation of sociopolitical criteria. Section 3 sketches how planning problems are formalized so that they can be computationally solved. It discusses optimization, conservation area network selection, scheduling conservation action, multicriteria analysis, and the use of probabilistic data. Section 4 deals with algorithm and software design, discussing computational complexity and heuristic, metaheuristic, and optimal algorithms. Section 5 turns to the frontiers of research, including solving complex problems, the choice of biodiversity surrogates, planning without targets, planning for biodiversity processes, and the incorporation of vulnerability.

2. BACKGROUND

Users of conservation planning tools should be aware that they embody two sets of assumptions: (*a*) those about the structure of the problems being solved and (*b*) operational assumptions incorporated into software design for pragmatic reasons. Planning tools should not be used blindly without verifying whether these assumptions are satisfied. In this section, we discuss the most salient of these assumptions concerning the levels of planning (§ 2.1), existence of surrogate measures of biodiversity (§ 2.2), targets of representation (§ 2.3), and biodiversity persistence (§ 2.4).

2.1. Levels of Planning

Planning must take place, sometimes simultaneously, at a wide range of spatial scales from local plans (for areas of $\sim$100 km^2) to those for entire continents. Typically, planning tools are not restricted to particular spatial scales. However, data availability varies between scales, biological processes differ from level to level, and conservation priorities and decision-making scenarios may also vary with scale for the same region (53, 54). Methods and tools appropriate at one scale may not be appropriate at others. The advent of GIS technology has made the hierarchical representation of spatial features at different scales easier; nevertheless, this only partly mitigates this problem.

Equally importantly, conservation plans attempt to deal with biodiversity at every level of organization from subspecies to phyla. Moreover, even if priority sites are identified for all taxa, biological processes such as ecological and evolutionary processes as well as endangered biological phenomena are not automatically included (55–57). We review below the extent to which we know how to incorporate processes in planning (see § 2.4) and return to the question of how tools must be developed to do better in the future (§ 5.4).

2.2. Biodiversity Surrogates

Adequate representation requires that a conservation area network must include examples of all biodiversity features of a region. Biodiversity, as such, is impossible

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to define precisely; it refers to diversity at every level of the taxonomic, structural, and functional organization of life (58, 59). Moreover, it is presently impossible to measure all components of biodiversity in a given region. Even for well-known taxa such as birds and mammals, georeferenced information on distributions is typically incomplete. For planning purposes, features of biodiversity must be individuated and measured in some way (56, 57, 60). Consequently, partial measures, known as biodiversity surrogates, must be used. These surrogates must adequately represent biodiversity features in protocols using conservation planning tools. Although the tools themselves typically do not restrict what surrogates are used, care must be taken to ensure that adequate surrogates have been chosen in each planning context.

Surrogates that are supposed to represent total or general biodiversity are sometimes called "true" surrogates (56, 57). Usually, species or other taxa are used as true surrogates. However, because general biodiversity is too diffuse a term to be precisely defined, the choice of a true surrogate set appeals at least implicitly to some convention or consensus about what constitutes the relevant features of biodiversity in a given context. Thus, choosing a true surrogate set amounts to accepting an operational definition of biodiversity. Because complete distributional and other data on true surrogate sets are virtually impossible to obtain, estimator surrogates are used in their stead (46, 61). Many types of estimator surrogates have been proposed including well-known taxonomic groups, species assemblages, spatial classifications of land and water, and environmental classes (62, 63).

True surrogate set performance relative to overall biodiversity cannot be tested because there is no precise definition of overall biodiversity. However, we can test whether an estimator surrogate set adequately represents a nominated true surrogate set (64). Techniques proposed for such tests include predicting complementarity (65–67), use of species accumulation curves (68), surrogacy graphs (69, 70), marginal representation plots (71), spatial congruence analysis (71), and regression analyses (72). These test whether the results of planning using estimator surrogate sets are the same as those that would have been obtained using true surrogate sets.

The level of support in the literature for various estimator surrogate sets has been variable (27, 62, 71–75). For taxonomic surrogate sets, some studies report encouraging results (76–81), but in general, there remains much skepticism about their adequacy (82–84). There has also been controversy over whether environmental features form adequate estimator surrogate sets for a variety of taxonomic true surrogate groups, though recent results are generally optimistic (71, 75, 85–90). The simultaneous use of both species and environmental parameters as estimator surrogates may reduce these problems (63, 91–93).

Conservation planners must make the best use of all available environmental and biological data in order to inform decisions. Consequently, they have no option other than to use estimator surrogate sets or, at best, true surrogate sets. All planning tools we review assume the existence of adequate estimator surrogate sets; some, such as Surrogacy (94), provide explicit protocols for their evaluation against true surrogate sets.

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2.3. Representation and Targets

For each surrogate that must be represented in a conservation area network, planning tools typically require a targeted level of representation, for instance, the number of times a surrogate must be present or the fraction of its total area of occurrence that must be included. Additionally, in many cases, there is a targeted maximum area that can or must be set aside for conservation across the planning region. A maximum area requirement typically arises because of socially driven constraints (budgets) on set-aside land.

The existence of representation targets simplifies the design of algorithms (21). However, the use of targets has generated justified controversy. Targets are supposed to incorporate biological principles. At a rudimentary level, they often do; for instance, in many analyses, higher targets are set for species at risk than for those that are not (24, 95–97). However, many common targets, e.g., 10% of the original habitat of each species, are rules of thumb adopted with no biological justification (96, 98). For the total area that should be set aside for conservation in a region, a typical target is again 10% (99), which also has no biological basis (100, 101). Pointing out the lack of biological justification, Soulé & Sanjayan (102) have argued that the use of targets and success in meeting them may engender unjustified confidence that adequate conservation measures are in place. Nonetheless, recent conservation plans (103, 104) have used comprehensive data sets and carefully formulated targets intended to reflect the relative conservation requirements of land types and species. Targets have been based on threat, rarity of species, and spatial turnover or heterogeneity of species within land types. The conservation areas designed to achieve these targets and to promote the persistence of biodiversity processes often cover very large percentages of regions (50% to 70%) and present substantial challenges for implementation.

Though traditional population viability analysis can potentially be used to set targets, there is no consensus about the appropriate framework for such analysis (105). Moreover, population viability analysis can only be performed on a single or very few species at a time, requires large quantities of usually inaccessible data, and yields models with a high level of structural uncertainty (5). There have been some attempts to formulate methods for setting targets for a large number of species (95, 106). Appropriate targets for land types or environmental classes remain problematic, although some agreement can be reached on the relative sizes of targets for individual types (96).

In section 5.3, we assess whether planning without targets is feasible. We note here that existing tools that require targets should be used only with an explicit analysis of what targets are appropriate and why and with a clear understanding of the limitations of each target.

2.4. Persistence

To be successful, conservation plans must go beyond the mere representation of biodiversity patterns to ensure the persistence of biodiversity through

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TABLE 2 Ecological principles relevant to biodiversity persistence

Biogeographical theory: a conservation area network should consist of large circular reserves that are close together and linked by corridors (107, 108). However, caution must be exercised in applying equilibrium island biogeography theory to terrestrial conservation areas; there is little evidence supporting the analogy between oceanic islands and terrestrial reserves (109).
Metapopulation dynamics: many species are distributed across landscapes as metapopulations (110–113). Prioritization should include sites that establish connectivity between local populations to facilitate migration and minimize local extinctions (114).
Successional pathways: a conservation area network should represent different successional stages corresponding to surrogates' habitat requirements (115, 116). Large conservation areas are better at meeting this objective because they are less likely to be entirely reset to the early seral stages by a single event such as a fire.
Spatial autoecological requirements: a conservation area network should represent at least a minimum viable population for each species, but methods do not exist to estimate these values for large numbers of species (105). Many species have particular requirements for the configuration of conservation areas that must be accommodated. These include altitudinal migrants (117) and those requiring several habitat types in each conservation area (118).
Source-sink population structures: when species have a source-sink population structure in which a small percentage of habitat provides the most recruits for other habitat sites (119), the source/core habitats must be assigned high priority for conservation (120).
Effects of habitat modification: conservation areas in fragmented landscapes require special management to safeguard surrogate persistence, such as habitat restoration and the addition of new habitat between and along the perimeters of fragments (121–124).
Species as evolutionary units: higher priority should be given to sites with physical properties thought to encourage speciation (such as interfaces between soil types) or sites containing taxonomically distinct species or species with radiating phylogenies (96, 125, 126).

accommodating ecological, evolutionary, and sociopolitical processes. These processes might include dispersal, local extinctions and recolonizations, species interactions, migration, patch dynamics, adjustment of species' distributions to climate change, and diversification of lineages. Contemporary conservation planning draws on seven sets of ideas intended to safeguard the persistence of biodiversity in a conservation area network (see Table 2 and Reference 12). Planning for persistence requires, at the very least, incorporation of rules of spatial configuration that take these ideas into account. We return to the issues of planning for biological processes in section 5 (§§ 5.4–5.5).

2.5. Sociopolitical Contexts

Biodiversity conservation does not occur in a sociopolitical vacuum (5, 16, 25). Rather, designating land for conservation must compete with other social claims on land. In North America, early efforts at conservation planning often implicitly assumed that sociopolitical considerations were peripheral to biodiversity conservation for a variety of reasons, including normative claims about the equal importance of other species and humans (128, 129). These discussions were subsequently criticized on both philosophical and prudential grounds (5, 130, 131). Philosophically, attempts to found ethical bases for conservation on nonanthropocentric grounds have largely been rejected, though the issue remains controversial (5, 132). Prudentially, ignoring rather than addressing alternative claims on land is a recipe for political problems and likely failure of conservation plans (25, 131). Most international protocols for biodiversity conservation now legitimize sociopolitical interests (133–135).

To incorporate sociopolitical criteria into conservation planning, the process must be viewed as solving a multicriteria decision problem involving criteria other than the representation and persistence of biodiversity. Techniques of multicriteria analysis are used for this purpose (136). Part of this broad view of conservation planning includes stakeholders—people who are affected by or who can influence decisions and those who are responsible for their implementation. Communication with a variety of stakeholders throughout the planning process has been emphasized and given prominence in some planning protocols (15, 25, 26).

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3. FORMALIZATION OF CONSERVATION PROBLEMS

The design and implementation of software planning tools require the precise specification of both the problems to be solved and the algorithms to solve them. Many of the formal problems encountered in this context have long been studied within computer science and operations research. Although conservation biologists were aware of these connections from the beginning (10), recent years have seen increasing involvement of operations researchers (18, 137). There is scope for fruitful collaboration provided that the problems addressed remain relevant to planning in the field. This section and the next are oriented both to conservation planners as well as to algorithm and software developers to promote such collaboration.

3.1. Optimization Problems

Most of the problems solved by conservation planning tools are formalized as constrained optimization (minimization or maximization) problems. A basic problem is to look for the minimal set of sites in which all representation targets are met. What is being optimized (minimized) is the number of sites; the constraint is that all targets must be satisfied. Formalizing problems as ones of constrained optimization is useful because a wide variety of algorithms with known performance are available for their solution. Section 3.2 discusses the family of optimization problems associated with the selection of conservation area networks; section 3.3 discusses problems encountered when selection must be scheduled stage by stage because of budget constraints in the context of potential attrition of unselected sites.

Representing the various conservation planning problems as optimization problems involves one choice among many available options for their formalization. For instance, if the adequate representation of biodiversity surrogates and the minimization of the number of selected sites are viewed as goals among which trade-offs are allowed (that is, neither is a hard nor inviolable constraint), the problem is not, strictly, one of optimization. The heuristic and metaheuristic algorithms encoded into software planning tools discussed in section 4 implicitly forgo strict optimization because they allow suboptimal solutions.

3.2. Conservation Area Network Selection Problems

Many optimization problems can be formalized as mathematical programming problems (10). A family of formal problems associated with the "set cover" (138–140), and the "maximal cover" (52, 141–143) problems from operations research also occur in conservation area network design (5, 21, 137, 144). The inputs for these problems are a set of sites and a list of the surrogates present in each such site. In the set cover problem, the objective is to minimize the total cost of sites such that each surrogate is represented at or above its target within the selected set. In the maximal cover problem, the objective is to maximize the number of surrogates that satisfy their targets subject to a ceiling on the total cost of selected sites. Both problems can be represented as deterministic integer programs (21, 45). Variants can be formulated to incorporate other objectives as further constraints, such as shape or minimal size of each contiguous set of selected sites (137, 145). Multiple optimal solutions may exist for both the set and maximal cover problems, and standard algorithms can find all of them (45, 146), allowing the possibility of comparing these solutions with respect to additional criteria.

3.3. Conservation Action Scheduling Problems

With the sole exception of Kirkpatrick's plan for Tasmania (19), we are not aware of a case that implemented an entire set of selected sites (17). Commonly, plans are implemented partially and in stages over a planning period with the number of sites acquired at each stage constrained by a budget. Typically, planning regions are at least partly exposed to threats from expanding agriculture, mineral resource extraction, urbanization, and other sources. So at each stage, there is a risk of losing sites within the selected set as well as unselected sites that might serve as their replacements. Under these circumstances, the goal is to take such vulnerability into account while identifying sets of sites to be acquired at each stage so that representation of biodiversity is maximized at the end of the process. This is known as the conservation action scheduling problem. Conservation action scheduling can be represented as multistage constrained optimization problem. The parameter being optimized (maximized) is the number of biodiversity surrogates that have met their targets at the end. The constraints are the budgets at each stage.

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This optimization problem can be formalized as a stochastic dynamic programming problem (147–149) with computationally intractable optimal methods of solution. It has also been formalized as a stochastic programming problem (150–152). There has been recent progress in identifying heuristic methods that give near-optimal solutions (149).

A heuristic approach to scheduling that has been widely advocated uses both the irreplaceability and vulnerability of sites (103, 153, 154). The rationale is that early protection of sites that are both highly vulnerable and highly irreplaceable will minimize the extent to which conservation targets are compromised before they can be secured (155). Several studies have addressed the interplay of conservation action and loss of areas (156). These studies have dealt only with biodiversity pattern; a major challenge for conservation planners is to develop strategies that combine planning for biodiversity processes with implementation constrained by land-use dynamics.

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3.4. Multicriteria Analysis

Though the focus of existing conservation planning tools has typically been placed on the representation of biodiversity surrogates, effective planning must take sociopolitical factors into account (5). These can be incorporated into the planning process using multicriteria analysis. Moreover, criteria relevant to the spatial configuration of conservation area networks—such as size, shape, alignment, replication, connectivity, and dispersion, which are often critical to the persistence of biodiversity (12)—can also be incorporated in the same way.

Two types of protocols have been developed to incorporate multiple criteria into the selection of sites for a conservation area network. The first type consists of *iterative* stage protocols, in which multiple criteria are considered as each individual site or small set of sites is selected for inclusion (91, 157–159). The second type consists of *terminal* stage protocols, in which multiple criteria are considered for the selection of an entire network after the formulation of a set of potential networks, all satisfying a given criterion, typically biodiversity representation (160). Both iterative- and terminal-stage protocols can be used simultaneously, with some criteria incorporated during site selection and others at the end.

There have been many attempts to use multicriteria analysis in the design of conservation area networks (reviewed in Reference 136). A wide variety of methods exist, ranging from the well-developed multiattribute value and utility theories (161–164) to purely heuristic procedures (165). Selecting an appropriate method depends on (*a*) whether the alternative sites or conservation networks can be ordinally or quantitatively ranked by each criterion; (*b*) whether the criteria for evaluating alternatives can be ranked at all and, if so, whether they can be ordinally or quantitatively ranked; (*c*) whether the criteria are independent of each other; and (*d*) whether the criteria can be compounded. Problems with ranking and compounding criteria have long been recognized in the decision theory community (166). Ranking criteria is often arbitrary and must be accompanied by sensitivity analyses to test whether results are unstable with even slight changes in ranking (11, 167). Additionally, once criteria begin to be aggregated, there is potential for a loss of transparency; it is no longer clear what motivates a choice. Compounding has some theoretical basis within multiattribute value and utility theories. However, these theories make strong independence assumptions about each pair of criteria (167). Moffett & Sarkar (136) have pointed out that existing planning tools incorporate a small fraction of the available techniques.

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3.5. Probabilistic Data

Traditionally, conservation planning algorithms have assumed that the data available show whether a surrogate is present or absent and sometimes, if present, how abundant or extensive. These data can be obtained from systematic surveys, niche models, maps of land types, or environmental classes. A typical problem faced is that the data on species are presence only, rather than presence-absence—they show where surrogates are present but not where they have been searched for but not found. In such circumstances, sites with no data (possibly indicating false absences) may have allowed targets to be achieved more economically but do not mitigate the representation achieved within selected cells (24, 168).

However, because planning is essentially a matter of comparing sites with one another, it is better to have comparable data across all candidate sites. One way to mitigate problems caused by presence-only data is to use them to model the expected geographical distribution of surrogates in the planning region. Many modeling techniques are available (169), and these typically report probabilities for the presence of surrogates. Similarly when the future distributions of surrogates are incorporated into a plan, we rely on models that typically make probabilistic predictions. Examples include models assessing the vulnerability of biota because of anthropogenic factors, range shifts due to climate change, and patterns of dispersion.

Probabilistic data may be converted to binary data using a threshold probability (38, 170). However, this procedure is open to the objection that any threshold must be arbitrary (21). Two different strategies allow the use of probabilistic data directly. First, probabilities of occurrence or persistence in individual sites may be compounded to obtain the corresponding probabilities for the entire landscape (171, 172). The goal is to ensure that the probability in the network is higher than some specified value, similar to a target of representation. Although this strategy is often followed, it requires the assumptions that the probabilities of different surrogates within a site are independent of each other and that the probabilities for each surrogate are independent from one site to another. Because of ecological relationships between surrogates and the spatial correlations of their distributions (173), both assumptions are unrealistic. Moreover, the associated computational problems are often nonlinear, although they can sometimes be linearized and made tractable (143). According to the second strategy, alternative probabilities are interpreted as expectations (or the expected number of occurrences) of surrogates in

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sets of sites. This technique for handling uncertainty uses the logic of expectations, an alternative to the more common probability calculus (174). The expected values for the occurrences of surrogates may be summed across landscapes and surrogate sets without requiring independence assumptions (21). The total expected number must then be higher than some specified target of representation, as in the case of binary data.

The use of expectations also allows computational problems to be linearized (21). Moreover, the use of probabilistic data does not require any modification of the formalism used for binary data (10). The simultaneous use of probabilistic and binary data is also not problematic. That some existing tools are restricted to binary data is an unnecessary limitation.

4. ALGORITHMS AND SOFTWARE

In discussing algorithmic issues encountered in the design of software tools, though all criteria in Table 1 are important, we are concerned mainly with efficiency. The importance of computational efficiency depends on how planning tools are to be used. As decision support systems, they may be used to develop decision scenarios that require scores of alternative plans to be formulated for appraisal by decision makers. They may also be used in real-time negotiations during which stakeholders need rapid information about the implications of proceeding in alternative ways. In such scenarios, planning tools must ensure that certain minimal criteria (such as representation targets) continue to be met in each plan. Tools that take large amounts of time to analyze a data set or to produce a scenario (say, $\geq$5 h) are likely to be ineffective; in such cases, computational efficiency is critical. Conversely, in a decision scenario in which only a single or a few alternative plans are sufficient, efficiency may be less important than (spatial) economy. In recent years, an increase in the efficiency of planning tools has led to a trend toward the use of multiple scenarios (148, 152, 175). The incorporation of multiple criteria in terminal stage protocols can also involve the formulation of many alternative plans (47, 176).

4.1. Computational Complexity

Because there has been recent controversy over the efficiency and economy of different algorithms (see § 4.4), we introduce relevant terminology from computer science. Computational complexity can either be (*a*) temporal complexity or the time required for a computation, with complexity being the inverse of efficiency; or (*b*) spatial complexity, or the amount of memory that is required for a computation. Both are relevant to the design of conservation planning tools.

With respect to temporal complexity, a computational problem belongs to the class P (for polynomial time) if the number of elementary operations (additions, subtractions, multiplications, and divisions) required to obtain an answer grows as a polynomial function of the size of the input (preferably a low-order polynomial)

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(177). What is important here is that such algorithms are tractable: the time required to execute them (a polynomial function) does not grow inordinately fast as the size of the problem increases compared to an algorithm growing at an exponential rate. The class NP (nondeterministic polynomial) time consists of problems for which the number of operations required to verify a solution grows as a polynomial function of the size of the input (178). [The contrast here is between the time required to produce a solution (in the case of P) and the time required to verify that a solution is correct (in the case of NP).] Obviously, P is a subclass of NP. One of the most important open questions in computer science is whether P = NP.

Given these definitions, a problem is NP-complete if (*a*) it is in NP and (*b*) every other problem in NP is reducible to it; that is, any such problem can be transformed into the NP-complete problem using a P algorithm. Thus, NP-complete problems are the hardest problems in NP. Finally, an NP-hard problem is one that satisfies clause (*b*) above but not (*a*); that is, it is not necessarily in NP. Thus, NP-hard problems are at least as hard as NP-complete problems, possibly harder. The most salient aspect of NP-hard and NP-complete problems is that increasing the speed of computer processors does not significantly affect the tractability of these problems (179). However, this does not mean that every or even most instances of such problems cannot be solved efficiently. All it means is that there are instances for which a solution cannot be obtained in a reasonable amount of time, which is a serious constraint if the goal is to design generic software tools.

4.2. Heuristic Algorithms

For the design of conservation area networks, the set cover and maximal cover problems, which are the simplest problems to be solved, are both NP-hard (143, 178). Consequently, exact or optimal (see § 4.4 below) algorithms guaranteed to produce the optimal (or most economical) solutions may be intractable in many instances. However, for binary data (where surrogates are either present or absent in areas), with definite targets of representation, the function to be optimized can be linearized, reducing temporal complexity. For probabilistic data, some nonlinear problems can also be represented as linear problems (21, 143). Nevertheless, because of NP-hardness of even the linear problems from a computational perspective, it is important to devise efficient heuristic algorithms.

A variety of stepwise or "single pass" heuristic algorithms have been developed. For both conservation area network selection and the scheduling problem, a stepwise heuristic algorithm consists of a rule (or a series of rules) that is applied successively to select sites for inclusion in the selected set, with recalculation of dynamically changing measures such as complementarity at each iteration. Although stepwise heuristic algorithms have in practice achieved efficiency because of the simplicity of the rules incorporated in them, most of them were originally motivated by the goals of economy and transparency, which was achieved by the latter through the incorporation of biologically interpretable criteria such as complementarity, rarity, and adjacency.

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The most commonly used heuristic rules that have been designed to select sites are (*a*) to maximize the complementarity of surrogates (the "complementarity rule"); and (*b*) to maximize the rarity of surrogates occurring at a site, with rarity being interpreted as the inverse of the frequency or area of occurrence of a surrogate (the "rarity rule"). Extensive testing on a large variety of artificial and empirical data sets indicates that, for binary data, using both rules leads to the best results (45, 180). For probabilistic data, complementarity alone performs best (21). The complementarity rule has been incorporated into several planning tools including C-Plan (23, 181) and WorldMap (40, 182). Both the complementarity and rarity rules have been implemented in ResNet (21, 183, 184). Target (185) implements complementarity but includes cost trade-offs.

Stepwise heuristic rules are implemented hierarchically. Should one heuristic rule lead to a tie between several sites for potential inclusion, a second is used, and this process is repeated over the group of rules. For instance, if rarity leads to a tie, then an adjacency rule giving preference to a site adjacent to one already selected can be used to try to break this tie. The adjacency rule leads to the selection of larger contiguous areas (157). Thus, hierarchical rules allow an intuitive incorporation of multiple criteria. However, the relative importance of the rules is determined by their sequence, with frequency of rule use largely determined by the number of ties. This can lead to weightings of the rules that are not explicit.

4.3. Metaheuristic Algorithms

Metaheuristic algorithms control the use of heuristic rules by permitting their repeated use, with an independent criterion determining exit from the algorithm. Metaheuristic algorithms can also be used to incorporate multiple criteria. For instance, the selection of an initial set of sites can be followed by repeated random substitution of sites to see if better spatial configuration can be obtained without sacrificing representation targets. A time limit can be stipulated to force an eventual exit from such a metaheuristic algorithm. Metaheuristic algorithms are becoming the preferred technique for solving NP-hard problems (186, 187). In the design of conservation area networks, metaheuristic algorithms potentially enable greater spatial economy than heuristic algorithms but without sacrificing computational efficiency.

There exists a wide variety of metaheuristic algorithms (188, 189)—most of which are yet to be used in systematic conservation planning. Simulated annealing (190) has been used extensively [with the Marxan software package and its predecessors (159)] to incorporate spatial criteria along with representation (144). It is less computationally efficient than stepwise heuristic rules, but the two can be used together to achieve spatial coherence of network design without excessive loss of computational efficiency (184). C-Plan (with heuristic rules) has recently been adapted to work interactively with Marxan. Tabu search (187) has also been used and shows promise (191, 192).

Metaheuristics can provide a solution to the limitations of sequential applications of rules in stepwise heuristics. For instance, simulated annealing can be used with an objective function, incorporating achievement of targets, minimization of costs, and a function to achieve spatial compactness (47, 176, 193). These criteria are then implemented simultaneously, not hierarchically, and their relative influence on the solutions can be adjusted using weights. However, such weights may be criticized as being arbitrary, and sensitivity analysis should be used to test the robustness of results.

4.4. Optimal Algorithms

Optimal algorithms necessarily perform better than heuristic and metaheuristic algorithms with respect to economy, but because the problems are NP-hard, these algorithms suffer from poor computational efficiency; that is, they may take inordinate amounts of time to resolve realistically sized data sets. Consequently, the gain in economy may not offset the cost in efficiency and the lack of transparency in most practical contexts (50). Numerous computational studies have analyzed the efficiency and economy of stepwise heuristics compared to optimal algorithms (21, 45, 47, 50, 100, 184, 194). Heuristic algorithms achieve computational efficiency and transparency at a potential loss of economy, although this loss has not been rigorously quantified (see, however, References 178 and 195). Extensive numerical tests in the 1990s underscored the conclusion that, compared to heuristic rules, optimal algorithms only achieve a minor increase in economy with a significant loss of efficiency (45, 196).

Rodrigues and coworkers (100, 145) questioned these results and claimed that new software solvers produced optimal solutions with as much computational efficiency as heuristic algorithms. Sarkar et al. (21) examined these claims systematically. Using the industry-standard CPLEX and other integer programming solvers, they found more efficient optimal solutions than Rodrigues & Gaston (100). However, Sarkar et al. (21) found that heuristic algorithms uniformly outperformed optimal solvers with respect to efficiency with only a marginal loss of economy for realistically sized data sets, especially with probabilistic data. In an extreme case, with a data set from Ecuador (37,727 sites and 46 vegetation types as surrogates), the CPLEX and XPRESS optimal solvers found solutions with 65 and 56 sites in 16,018 and 532 seconds, respectively, whereas heuristic rules found solutions with 50–62 sites in 17–23 seconds. Rodrigues & Gaston's (100) negative results for heuristic rules were apparently due to poor implementation of heuristic algorithms. Importantly, they also reflected the simplistic nature of the problems they addressed. Most involved binary data and a target of one representation of each surrogate. Problems of this sort have little practical relevance.

For the scheduling problem, optimal algorithms have also proved computationally intractable because of spatial complexity. The standard method for stochastic dynamic programming is to use backward recursion. However, the number of possible states of the landscape (which sites are selected, which are available, and which have been lost) is so large that the computation becomes impossible for data sets with more than about 25 sites (147, 148, 175). Recent attempts to solve

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the scheduling problem have, therefore, relied on heuristic methods (149, 153, 181, 197). Some of these have been tested using realistic simulations of parallel, incremental conservation and loss of native vegetation (155).

5. FRONTIERS OF RESEARCH

Our purpose in this review is not only to summarize the present state of conservation planning tools but also to identify priorities for future research. This section discusses those priorities.

5.1. Complex Decisions

To date, conservation planning tools have only implemented relatively simplistic decision support protocols compared to the large array of methods available. Most conservation decisions are typically made by groups of stakeholders (25, 198). Nonetheless, existing planning tools, with very few exceptions [e.g., C-Plan (22, 23) and the methods developed by Regan et al. (199)], only support individual decision making. Although a variety of methods exist for group decision support (162, 200), very little work has been done to examine the suitability of these methods for conservation planning. Performing such an analysis and the subsequent design of appropriate tools remain important future tasks.

Similarly, planning is an iterative process with the results of initial planning exercises being used not only to determine what further data and analyses are necessary, but also to refine and devise new policy alternatives. Several software tools are designed to be used iteratively [e.g., C-Plan (22, 23) and MultCSync (201)], but they do not fully implement the iterative process in the sense that they do not provide explicit protocols for the formulation of new policy alternatives. Rather, that task is left to the user. The next generation of planning tools should provide additional support at this stage.

It is also widely recognized that conservation decision making occurs under conditions of risk and uncertainty. Some forms of future risk and uncertainty are beginning to be addressed in conservation planning tools (148, 175). There has also been extensive work on these topics in the context of the management of individual species, both from classical (202) and Bayesian viewpoints (203, 204). However, much more remains to be done even in these contexts. Other forms of uncertainty—for instance, dynamic changes in the available sites or changes in criteria—have had limited consideration in the design of conservation planning tools.

Finally, as noted above (§ 2.1), conservation planning must occur simultaneously at multiple spatial scales. Moreover, the biodiversity features that must be conserved include groups from all taxonomic levels with varying amounts of reliable information available at each level. Thus, conservation planning tools of the future must incorporate systematic methods for dealing with spatial and taxonomic heterogeneity of scale in the data available. A related problem is that the spatial

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and taxonomic scales at which analyses may be reliably performed, as constrained by the available data, may not be the scale of implementation. Few studies have compared the distribution of priority areas derived from coarse-scale (regional) and fine-scale (local) data, but these have demonstrated significant differences (53, 71, 94). At many spatial scales, decisions are likely to be under the purview of groups rather than individuals, and the size, composition, and organization of groups are likely to vary with geographical scale. Different types of uncertainty and risk pertain to different scales and percolate between scales in ways that are difficult to quantify.

5.2. Targets and Surrogates

Issues connected with the choice of targets and surrogates have been recently reviewed in discussions about biodiversity data for conservation planning (27, 42, 71, 88, 93, 205–207). We mention two important unresolved issues.

- Partial protection—planning tools should take into account contributions from partially protected off-reserve areas. This requires explicit information on the likelihood of persistence and contribution to targets for each surrogate under different management regimes. Although conservation planning tools can use such data (in binary or probabilistic form), these remain difficult to obtain. Problems of predicting surrogate distributions and persistence likelihoods relative to a variety of management regimes remain unsolved.
- Beyond species to other levels of variation—phylogenetic diversity (PD) (208) has long been incorporated in planning tools (209), but it has not yet had much impact on conservation planning. Applications face limitations of available data on phylogenetic pattern. In the near future, new approaches may vastly increase available information for many taxa and many sites. For example, it has recently (and controversially) been suggested that a mitochondrial gene (cytochrome *c* oxidase subunit I, COI) can potentially distinguish related species across a broad range of taxa, and rapid COI assessment may enable a general "barcoding" approach for assigning unidentified individuals to species (210–212). Application of conservation planning tools could benefit from such information (213). Other promising prospects include the use of PD for rapid conservation assessment by applying PD measures to molecular (for instance, COI-based) phylogenetic patterns (214). This prospect raises other unresolved surrogacy problems—How predictive is variation in PD of other variation patterns? And can this be estimated by barcoding?

5.3. Planning without Targets or Sets

Biological justification of representation targets is often lacking, although they do offer bench marks for comparison of representation achievement (§ 2.3). Targets

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can be avoided to some degree in many cases. For instance, marginal representation methods, such as those used for surrogacy analysis by Sarkar et al. (71) do not use targets. A range of little-explored approaches exist that use continuous surrogates (as, for instance, obtained using ordination) and do not use targets. Applications include those that explore shifts in frontier curves under different scenarios (11).

One approach was explored in conservation planning for Papua New Guinea (98). The amount of continuous variation that could be represented in 10% of the total area with no constraints was recorded. This amount was then matched in the set of priority areas identified in the presence of fixed existing protected areas, costs, and other constraints. Such an approach required an arbitrary target only for use as a bench mark.

There has been only one case in which an entire set of selected sites has been fully implemented (§ 3.3). An alternative to the selected set approach is to develop a continuously scaled measure of conservation value that can be constantly updated as the conservation landscape changes (98, 215). All sites are prioritized by their current value, and a site can still be acquired from those that are currently available to maximize biodiversity representation within the available budget. Having a continuous conservation value for every site also has an educational benefit by showing that most sites have value, whereas the selection of sets may unintentionally convey the message that sites not in the set have no value.

Finally, the dynamic realities of planning may put targets, discrete attributes, and sets into question to such an extent that some have questioned the use of computer algorithms (28). Policy-based algorithms may mimic the iterative approaches of multicriteria analysis, as in ongoing selection of landowners for conservation payments in Western Australia (89). Tools for strategies such as these remain to be developed in the future.

5.4. Planning for Biodiversity Processes

Section 2.4 summarized the contributions of ecological research to an understanding of biodiversity persistence in conservation area networks. This section covers the ways in which this knowledge can be incorporated into decisions using planning tools.

For much of its development, systematic conservation planning has been dominated by considerations of biodiversity patterns or features, such as species locality records and vegetation types, that can be mapped, treated as static, and sampled in conservation areas (12). But an important role of conservation areas is the maintenance of ecological and evolutionary processes.

Although quantitative targets for pattern-based features can go some way to promoting the persistence of processes, the conservation area networks that result are unlikely to support biodiversity processes that require large areas or particular spatial configurations (96). Four types of approaches have been envisioned to promote the persistence of processes. First, moveable priority areas can track movements of biota of interest or resources necessary for their survival.

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In terrestrial environments, such areas are generally easiest to consider and implement if they cover publicly owned small areas because of potential constraints imposed by protective management of extractive uses in privately owned land. Moveable areas can be valuable for protecting features such as bird breeding colonies, bat roosts, or populations of disturbance-dependent rare plants that periodically shift within a region (216). They have also been proposed to protect successional processes after disturbances (116). A special case is the temporary but repeated application of management restrictions or hunting closures to specific areas to protect species when they are particularly vulnerable (217). In the marine environment, where use rights are generally less restrictive, there is more scope for shifting priority areas, even extensive ones, to track features of interest or to apply temporary protection (218).

Second, biophysical templates associated with specific processes may be targeted for protection. Some recent published work comes from the Cape Floristic Region of South Africa (96, 126, 197). One example is the protection of river gorges important for movement of plants and animals between regions and as refugia. A less obvious example concerns interfaces between acid and alkaline soils believed to be associated with historical and ongoing diversification of some plant taxa. Most regions have areas that are important for the persistence of species of interest. The reasons might include habitat quality and associated high densities and/or reproductive output (219, 220) or areas that include drought refugia, defined by topography and drainage characteristics, and stopover sites for migratory birds. Templates can also be defined as combinations of features that provide complementary habitats used at different times (117) or for different functions, e.g., feeding, breeding, or roosting. Information on templates that represent dispersal barriers, such as wide rivers or mountain ranges (221, 222), can be used to subdivide regions to reflect the influence of ecological and evolutionary history on biotic composition. Lists of templates and methods for identifying them are likely to vary widely between regions owing to the idiosyncrasies of species' life histories, biogeographic history, climate, and physical environments.

Third, qualitative and quantitative design criteria may be used to indicate preferences of planners when choices are available. Design criteria include size, shape, connectivity, replication, spacing, and width of buffers in conservation area networks, which all influence the persistence of species and the maintenance of processes. When applied qualitatively, they are expressed as preferences (e.g., bigger is better). Qualitative criteria have influenced decisions about the design of conservation areas for decades (13, 223) and have guided assessments of existing reserves (224). Preferences for higher compactness and connectivity have been implemented with rule sequences in heuristic algorithms (157) or through objective functions (194, 225). A key limitation of these approaches is that, because they are qualitative, there is no explicit link between the expressed preferences of planners and the configuration requirements of individual processes. Quantitative design criteria interpret the spatial requirements of particular processes as explicit targets. These criteria include those listed above, but the requirements are stated quantitatively. They require planners to interpret knowledge of specific processes as quantitative targets for size, connectivity, and other considerations sufficient to promote the persistence of those processes. This is difficult and constitutes an area of innovative research in conservation planning (226–228).

There is some overlap between the methods grouped under these categories. Most existing planning tools allow at least partial incorporation of qualitative design criteria, and some can use quantitative design criteria. But none systematically implements all features associated with the persistence of processes.

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5.5. Vulnerability

The purpose of conservation areas is to mitigate at least some of the processes that threaten biodiversity. Incorporating information on threatening processes and the relative vulnerability of areas and features to these processes into planning tools is therefore crucial for effective conservation planning. Pressey et al. (50) defined vulnerability as the likelihood or imminence of biodiversity loss caused by current or impending threatening processes (229). Wilson et al. (49) referred to this as "exposure," one of three dimensions of vulnerability in their broader definition. Their other two dimensions are the intensity of a threatening process and its impact, reflecting the response of species or other biodiversity features. Areas of particular concern for conservation planners have high exposure to highly intense threatening processes. Features of concern are those occurring in such areas and experiencing strongly negative impacts. Polasky et al. (230) deal with all three dimensions of vulnerability.

Spatially explicit predictions about vulnerability most commonly deal with exposure because intensity and impact are more difficult to map (49). Exposure is related to environmental factors, e.g., topography and fertility, and to spatial factors, e.g., infrastructure or source areas of invasive species. Conservation areas may also attract development because of the added amenity value of being adjacent to perpetual open space, which also increases the land value (231). Many methods have been used to predict exposure, but there have been few comparisons of their results (but see References 232 and 233) and little or no validation of predictions against actual events.

Another unresolved difficulty in predicting vulnerability concerns how information on different threatening processes should be combined (for example agriculture, urbanization, and invasion by weeds). Few studies have attempted this (32, 234), and there is considerable scope for refinement. Conservation planners have also only begun to consider how uncertainty should be incorporated into vulnerability assessments. Overestimates of vulnerability may direct scarce resources to areas and features that are, in fact, relatively secure. Underestimates may lead to imminently threatened areas and features being given inadequate protection. Information on the bounds around estimates of vulnerability for particular areas or features would allow planners to refine their responses.

Considerations of vulnerability are important throughout the planning process (49) but are particularly apparent in three stages: formulating targets, designing conservation area networks, and scheduling implementation of conservation action. Some planners have argued that larger targets are needed for more vulnerable species and other features (24, 95, 96). Where options exist for achieving targets, new conservation areas can be located to avoid more vulnerable sites and so minimize liabilities for implementation and management (32, 235, 236). Of course, planners do not have options for all sites, so some highly vulnerable sites might have to be included and managed to mitigate their vulnerability even if this entails difficulties and expense. During implementation when resources are typically sufficient for only incremental establishment of sites identified for conservation, vulnerability can provide a guide to scheduling action (§ 3.3).

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6. DISCUSSION

Conservation planning tools are intended for decision support [or decision aid (237)], not for decision making that excludes human expertise. Decisions made using these tools are necessarily constrained by the range and quality of the available data and human expertise (28–30), although the rapid recent growth of biological and environmental databases has improved data quality and availability. Planning tools cannot further solve the problem of inadequate data. However, by easing some tasks such as surrogacy analysis or the tedious computation of complementarity or irreplaceability, they enable the best use of available data. However, poor decisions can also be made if the limitations of software tools are not understood and if they are used inappropriately. By explicitly noting the assumptions incorporated into various planning tools and by emphasizing limitations, this review should help prevent their inappropriate use. Additionally, the analysis of computational performance in the design of planning tools should help the proper implementation of biological and other types of principles in such tools so as to ensure flexibility and efficiency.

We emphasize that the use of software tools in conservation planning must be adapted to the local contexts of individual plans. Ideally, specific tools tailored for each context should be developed. However, software design and testing takes considerable effort and time. Consequently, the use of generic tools [that is, software intended for use in a variety of contexts, for instance, C-Plan (51), Marxan (159), MultCSync (201), ResNet (180), Target (185), and WorldMap (182)] is usually unavoidable. If generic tools are being used, local contexts should determine how they are deployed. A forthcoming review (R.L. Pressey, S. Andelman, M. Bakarr, P. Comer, R. Cowling, P. Crist, F. Davis, D. Faith, C. Groves, R. Machado, S. Polasky, H. Possingham, A. Rodrigues, S. Sarkar, D. Stoms, P. Williams, and K. Wilson, in preparation) provides more detail on this issue.

One theme that has recurred throughout this review is the importance of incorporating biological principles into conservation planning tools. When these tools began to be developed in the 1980s, they applied heuristic principles based on biological intuitions about (*a*) economical representation of biodiversity surrogates (e.g., by the use of complementarity); (*b*) potential threats to such surrogates (e.g.,

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by the use of rarity to select sites or the imposition of higher representation targets for taxa perceived to be at risk); and (*c*) a few qualitative rules about spatial organization of conservation areas (e.g., by the use of an adjacency preference rule to generate larger conservation areas). Advances in our understanding of factors influencing the persistence of biodiversity must be incorporated into planning tools.

We have also emphasized how sociopolitical considerations must be an integral part of conservation planning, and therefore, planning tools must enable their incorporation in the decision making process. Support for group decision making and multicriteria analysis is critical to planning tools of the future. Here, as elsewhere, adequate planning tools must also address issues related to risk and uncertainty.

Several of the issues facing conservation planning for marine environments are similar to the challenges faced in terrestrial environments (47, 238). The planning tools discussed in this review were all developed with terrestrial biodiversity conservation in mind but have occasionally been adapted for use in marine contexts. However, marine conservation also poses some specific problems (239–241). Some areas of current research particularly relevant to planning in the marine environment include (*a*) dealing with marine/terrestrial interfaces, (*b*) reformulating the conservation planning problem to assess adequately the contributions to conservation goals of the different protection regimes that exist in the marine context, and (*c*) accounting for the substantial connectivity between marine sites and the dispersal of biodiversity features among them. It is an open question whether systematic marine conservation planning will be significantly aided by the development of planning tools specifically dedicated to it.

Finally, most conservation planning tools discussed above presuppose a static, closed ecosystem, unaffected by inputs from elsewhere. In many cases, particularly at very large spatial scales, this assumption may be inadequate for selecting conservation areas that ensure the persistence of biodiversity. For instance, in coastal environments, the linkages between ecosystems must be considered if biodiversity is to be sustained: a marine protected area established at a tropical coral reef may become imperiled by human activities onshore that change the flow of sediments, nutrients, or pathogens. There is some work in recent ecological theory on a dynamic, nonequilibrium view in which effects in open ecosystems are created by an off-site disturbance (242). In addition to coastal environments, linkages are also crucial in other settings where conservation planning tools have not found much use, such as agricultural landscapes and freshwater ecosystems (but see Reference 243). Stoms et al. (244) have suggested an approach that accounts for off-site effects and then employs existing multiobjective programming methods to meet targets at least cost and with least harm to the other ecosystem. However, this proposed approach constitutes only one possible short-term solution and has not yet been implemented in a planning tool. It is likely that planning tools for the future, which are based on such a dynamic model of ecosystem change, will be quite different from the suite of tools available today.

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ACKNOWLEDGMENTS

Work on this review began at a meeting of a Working Group on Conservation Planning Tools in July 2003, funded and hosted by the National Center for Ecological Analysis and Synthesis (a center funded by NSF grant # DEB-94–21535); the University of California, Santa Barbara; the California Resources Agency; and the California Environmental Protection Agency. We would especially like to acknowledge the contribution of ideas and information from members of that Working Group who are not authors of the review.

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Annual Review of Environment and Resources
Volume 31, 2006

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