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Gap analysis: concepts, methods, and recent results*

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Abstract

Rapid progress is being made in the conceptual, technical, and organizational requirements for generating synoptic multi-scale views of the earth's surface and its biological content. Using the spatially comprehensive data that are now available, researchers, land managers, and land-use planners can, for the first time, quantitatively place landscape units – from general categories such as 'Forests' or 'Cold-Deciduous Shrubland Formation' to more categories such as 'Picea glauca-Abies balsamea-Populus spp. Forest Alliance' – in their large-area contexts. The National Gap Analysis Program (GAP) has developed the technical and organizational capabilities necessary for the regular production and analysis of such information. This paper provides a brief overview of concepts and methods as well as some recent results from the GAP projects. Clearly, new frameworks for biogeographic information and organizational cooperation are needed if we are to have any hope of documenting the full range of species occurrences and ecological processes in ways meaningful to their management. The GAP experience provides one model for achieving these new frameworks.

Introduction

As the abundance of humans continues to increase and the current species extinction event extensifies, biogeographic information that is both spatially comprehensive and of appropriate resolution is becoming more vital for effective management of our biological resources. Although this tenet may seem obvious to some, its articulation and broad acceptance are recent, responding in part to the perceived conservation imperative and in part to emerging principles and knowledge of landscape ecology. In the USA, some of the most rapid progress in the development of such information has been accomplished through the National Gap Analysis Program (GAP). Gap analysis is a method for identifying 'gaps' in the network of conservation land and water areas. The conceptual, technical, and organizational bases needed for this work have been developing since the underlying principles of gap analysis were discussed in 1987 (Scott et al. 1987). As methods, data, and a massive cooperative experience emerged over the past decade, demand for and applications of GAP information expanded beyond the original intent of 'a quick overview of the distribution and conservation status of several components of biodiversity' (Scott et al. 1993).

While there is debate about the number of species being lost or at risk of extinction (e.g., Lugo 1988; Mann and Plummer 1995; Lawton and May 1995), the number of species at risk has increased since the USA Endangered Species Act was enacted in 1976 (Smith 1996), and it is likely that this trend will continue (Pimm et al. 1995). So far, conservation efforts in the USA have not been effective in slowing the rate of species endangerment. One reason is that most conservation programs are designed to conserve species already at the verge of extinction and do not address the ultimate problem of continued habitat loss for most species not adapted to human-configured environments. Until recently no concerted effort was being made to develop spatial information on the actual distributions of 'ordinary' species (not endangered or

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threatened with extinction) and their habitats or on the effectiveness of contemporary conservation land and water areas for species conservation. Neither has there been a previous effort to determine, element-by-element, gaps in the current mix of conservation land and water areas as well as other conservation activities.

Without spatially explicit data, it is unlikely that the forces causing habitat losses (e.g., invasive species, logging, grazing, mining, infrastructure development, recreation) can be managed effectively or that a network of conservation areas can be successfully designed. These data must include maps and other spatial information, at resolutions usable by land managers, of (a) species distributions (not to be confused with delineations of general range limits), (b) dominant vegetation cover types (or vegetation alliances; FGDC 1997, Grossman et al. 1998), and (c) conservation areas. The lack of this information for states and large regions has, until now, been due partly to a lack of the science and technology needed to create such maps. For example, remotely sensed imagery has not been available, an accepted classification system for vegetation based on community ecology has only been recently developed, and technical capabilities for creating, assessing the accuracy of, and analysing large spatial data sets has only been available for the past several years. During 1994, the first full set of Landsat Thematic Mapper (TM) satellite imagery of the 48 contiguous states was assembled for state-by-state mapping of floristically defined vegetation types. Contemporaneously, a suitable vegetation classification has been established (Grossman et al. 1998; FGDC 1997; Jennings 1993), and computing capabilities have been vastly improved. Of particular importance, the skill pool has been expanded greatly, primarily through support of graduate students associated with GAP projects.

In addition to a lack of science and technology, there previously was no organizational or institutional catalyst for the development of the information needed. The task is a massive one and impractical for any single organization to achieve. Working as cooperators in GAP, professional biologists, ecologists, computer scientists, geographers, and others have crossed disciplinary and institutional boundaries to address conservation needs (Jennings 1995).

Significant concepts

Burley (1988) first described a concept for identification of 'conservation gaps' as a process to identify and classify the various elements of biodiversity and examine the existing system of protected areas. Then the process was to determine which elements (e.g., vegetation types, habitat types, species) are not represented or poorly represented in existing conservation areas. Finally, this information was to be used as a way to set priorities for the next steps of conservation actions, such as designing future reserves and planning land acquisitions.

Gap analysis is based on Burley's rather simple concept, yet it requires sophisticated, novel approaches in generating the large amounts of new data that are required. It is a coarse-filter (*sensu* Noss 1987) information strategy for protecting biodiversity (Scott et al. 1987, 1993) in that it focuses on both community-based units of habitat as well as on each individual species. This approach is intended to work in concert with 'fine-filter' conservation, which focuses on localized actions for those species in danger of extinction. The method assesses these distributions relative to existing conservation areas and other categories of land and water management, at spatial resolutions useful for understanding and describing the ecological and conservation contexts of a given biodiversity 'element' (vegetation alliance, habitat, or species) or suite of elements, or of any given land tract of interest. With this information, GAP seeks to identify elements of biodiversity not sufficiently represented in conservation areas. These are considered 'conservation gaps' that may be closed through changes in land or water management practices. (For example, in New Mexico, approximately 93% of Grace's warbler (*Dendroica graciae*) habitat occurs on land where the species' habitat needs are not a management consideration (Thompson et al. 1996). Incorporating its habitat needs with existing land-use planning and management may close this conservation gap.) The program also seeks to produce biogeographic information that may be used in regular planning and management of land-based resources. The work is carried out by academic, nongovemment, and agency institutions on a state-by-state basis. GAP is the only USA program attempting to assess the conservation status of all components of the nation's biodiversity.

Proactive rather than reactive management

A fundamental assumption GAP makes is that the best time to decrease the probability of a species' extinction due to human activities is well before its population is diminished to the point of endangerment. Waiting until a species is actually endangered or threatened with extinction results in reactive management activities that are expensive, exhibit a low probability of success (Tear et al. 1993), and are often socially divisive.

The GAP approach is predicated on the assumption that a dual focus on the conservation of habitats and multiple species will be both cheaper and more likely to succeed than conservation programs focused on any single species or population (Scott et al. 1993). At the same time, this approach is intended to provide a biogeography-based stratification for more detailed studies of, for example, composition, structure, and function of individual species, groups of species of interest, and vegetation alliances that are needed for site-level reserve design.

The cost of maintaining species in their natural state when they are relatively common and part of self-sustaining ecosystems is less than the cost of intensive management programs needed to save species that are at the brink of extinction (Scott et al. 1987). An efficient way to avoid extinction crises is to work with the many different institutions – private and public – that are involved with land-use management and land-use planning to develop large-area geographic information for overall biodiversity. This information can then be applied to land-use and resource management decisions, whether incrementally small everyday decisions such as zoning permits or decisions of broader scope such as state land-use planning.

Setting priorities for treating elements of biodiversity

Because we cannot practically model all elements of biodiversity in the near tenn, we must set priorities for which elements to treat first (Margules and Austin 1991; Scott et al. 1993; Gap Analysis Program 1998; Csuti and Kiester 1996; Noss and Cooperrider 1994; Jennings et al. 1996). At the same time we must continue to improve assessment capabilities by developing better information about each element and by continually increasing the number of taxa that we develop maps of. Initially, gap analysis methods focused on vegetation alliances along with all native species of amphibians, birds, mammals, and reptiles as surrogates for biodiversity. We began with this group of vertebrate species because they play a major role in community patterns and processes (Terborgh 1989), and because mapping their distributions at a practical and useful scale was tractable. Vegetation alliances are used because patterns of natural terrestrial land cover are an integrated reflection of the physical and chemical factors that shape the environment of a given land area (Whittaker 1973). They also are determinants for overall biological diversity (Franklin 1993; Noss 1990) as their structure and composition significantly affect species-level interactions. Vegetation alliances are the finest level of biotic assemblages that can be described and mapped over large areas using remotely sensed imagery (though technical limitations to mapping certain alliance types remain). They are constituent parts of landscapes and can be used as a set of equivalence classes in conservation evaluations (Fenner 1974; Austin 1991).

In recent years methods have been developed to extend GAP to include ant species (Allen et al. 1998), crayfish, fish, mussels, and snail species (Sowa 1998), and research is under way to develop methods for predicting distributions of plant species (Fertig et al. 1998). These predictive models have broad application for planning, management, and research far beyond GAP conservation assessments, and we anticipate including additional taxa in the future.

Clearly, focusing on a limited number of phyla will result in conclusions that are biased toward the mapped elements. Within that limitation, the approach will provide a synoptic spatial framework for linking information which is finer as well as coarser in both thematic description and spatial resolution. For example, maps of species distributions or habitat types produced for GAP can provide an ecological and geographical context for stand or plot data measuring population or genetic criteria while directly linking these representations to continent-level measurement of biome criteria.

Hotspots and reserve selection

An early gap analysis hypothesis was that species and alliance maps would allow for identification of biodiversity 'hotspots' (areas of maximal element co-occurrence, or richness), which might offer efficient conservation opportunities. Work done since that time has tested the concept and changed our understanding of its utility. For example, Prendergast et al. (1993) studied the potential overlap of biodiversity hotspots among birds, butterflies, dragonflies, liverworts, and aquatic plants and found only low correlation of hotspots among these taxa. Reid (1998) found that the utility of the hotspot approach was scale dependent.

Richness of certain biodiversity elements, however, remains necessarily central to the development of design methods for conservation reserve networks that adequately represent existing biodiversity. For example, the concepts of complementarity, flexibility, and irreplaceability developed by Pressey et al. (1993) require stepwise element accumulation processes for (a) establishing a mix of existing and potential reserve areas, (b) choosing efficient combinations of reserve areas to establish a reserve network, and (c) accounting for irreplaceable elements as network configurations are sorted. Algorithms for choosing efficient sets of reserve areas that represent mapped elements of biodiversity have also been the source of substantial testing and discussion (e.g., Csuti et al. 1997). All such approaches, theoretical as well as actual, depend on spatially explicit data for the elements of biodiversity. Presently, it seems unlikely that any single method or algorithm will be adequate for establishing biodiversity conservation areas.

The goal of maintaining a viable complement of existing biodiversity elements underlies most national and international policy today and is the basis for a whole new field of study, conservation biology. While gap analysis does not prescribe methods for reserve design, it focuses first on developing the basic information needed, and second on assessing the degree to which mapped elements are represented in the existing set of conservation areas. Substantial research on reserve design has been made possible by the development of basic GAP data, especially their synoptic and range-wide coverage of element distributions (e.g., Caicco et al. 1995; Csuti et al. 1997; Davis et al. 1990; Duever and Noss 1990; Kareiva 1993; Merrill et al. 1995; Noss 1991; Wright et al. 1994).

Hierarchy theory for ecology

A central concept for gap analysis is that hierarchical relationships exist between ecological systems of differing spatiotemporal extents (such as organisms, populations, species, communities, or landscapes [*sensu* Forman and Godron 1986]). Further, alterations to land and water characteristics, formerly limited in extent to populations and species, are now manifest at the levels by which natural communities and landscapes function (Noss et al. 1995).

Because the dynamics of larger systems (e.g., a landscape) constrain the behaviors and occurrences of the smaller systems that they encompass (e.g., a population within that landscape) by means that are independent of the smaller systems (O'Neill et al. 1986), conservation efforts implemented at the population or single-species level will not be effective when entire landscapes are largely converted to other forms and functionally different ecological systems. Furthermore, the mechanisms, or emergent properties, by which a system interacts with the forcing variables cannot necessarily be identified by a simple aggregation of its smaller components nor by a reduction of its larger components (Allen and Starr 1982). In order to slow the loss of our biological resources, the basis for solving problems and implementing decisions must be predicated on information that is extracted from the level at which the changes are being induced, in this case communities and landscapes. This is a critical basis for the large-area synoptic approach, and it represents an ambitious application of the hierarchical concept to conservation problems (O'Neill 1996).

Terrestrial versus aquatic environments

Because initial focus was on amphibian, bird, mammal, and reptile species, some have come to see gap analysis as lacking a focus on aquatic biodiversity. Although funding limitations impose the need to set taxonomic priorities (as discussed previously), the issue of treating terrestrial and aquatic environments separately is a diversion that runs counter to GAP's underlying phylogenetic approach toward biodiversity (mapping biota rather than environmental factors), and it warrants brief discussion. The line of thinking that separates resource management into terrestrial and aquatic categories derives from traditional commercial and recreational mandate-driven approaches toward natural resources management based on one organizational sector for fishery management, another for game, and yet another for horticulture (among still others), none of which consider all species of equal value. It may be that the greater losses to biodiversity among noncommercial or nonrecreational species living in submerged environments (see The Nature Conservancy 1996) is related to this traditional administrative separation of land and water. One opportunity before us now is the generation, synthesis, and representation of information in ways that treat the terrestrial and aquatic elements of biodiversity in an interrelated manner. Rather than segmenting the GAP effort into 'land' and 'water' categories (and even separate national programs as some have attempted to do), GAP attempts to treat biodiversity by taxonomic groupings.

Effects of cooperative data development

Developing the spatial data needed for gap analysis is an enormous task. It turns out that the process of developing these data may have a greater constructive effect on conservation than the various derived analyses. This is because, first, the data development phases of GAP have resulted in major increases in capabilities and capacities of hardware, software, and skills among groups of institutions operating at the state level. Second, development of the data requires a massive cooperative effort among academic, state, federal, and nongovernment institutions, and this activity has resulted in positive changes in institutional relationships, including clearer and more efficient divisions of labor and longer-term coordination for future data development. Third, the data, and interpretations of it, are put to many other uses far beyond the basic identification of conservation gaps, such as localized natural resources decision making, statewide planning, preserve system planning, and basic research. Fourth, GAP has created a context for discussing proactive biodiversity conservation among agency land managers, scientists, and policy makers.

Methods

The basic process of gap analysis is to compare the distributions of species and vegetation types of interest with the distribution of conservation areas (Figure 1). The following provides some background and a brief review of the methods used to develop the land cover, species, and land stewardship data sets. More detailed description of these methods can be found in 'A Handbook for Conducting Gap Analysis.' (Gap Analysis Program 1998), Scott and Jennings (1998), Scott et al. (1993), and Jennings et al. (1996).

Land cover maps

The land cover mapping process for a GAP state project begins with adoption, evaluation, and perhaps modifications to the vegetation types of the National Vegetation Classification (NVC; Grossman et al. 1998; Sneddon et al. 1994; Weakley et al. 1997; Drake and Faber-Langendoen 1997; Reid et al. unpublished; Bourgeron and Engelking 1994; FGDC 1997). The current GAP activity is the first attempt in the USA at mapping a detailed floristics-based classification of existing vegetation across entire states at a mesoscale (nominally 1:100,000), and the NVC itself is, today, a first approximation. Despite decades of conflicts over the management of biological resources and demand for an ecosystems approach to research, planning, and management, until recently there was not a consistent and widely accepted set of defined categories for naturally occurring assemblages of species for characterizing ecosystems and landscapes. The lack of a common classification for assemblages of plant species has had a limiting effect on the application of ecology to problems such as loss of biodiversity (Loucks 1996; ESA Vegetation Panel, unpublished), and the development of the NVC and mapping of vegetation alliances is overcoming such limitations (see FGDC 1997; Grossman et al. 1998; Jennings 1993, 1996a, b, 1997).

Acquisition of digital data for rendering the land cover map is the next step. This begins with obtaining a set of TM imagery covering the state. Other important data that are assembled include but are not limited to digital elevation models (DEMs), soil maps, larger-scale vegetation maps, field reconnaissance data (both from earlier work and as part of the GAP effort as necessary), and National Wetlands Inventory (NWI) maps. One set of material that has become commonly used is high resolution aerial imagery, providing samples of vegetation along a transect. While there has been rapid development of technology for acquiring and interpreting aerial videography (see Slaymaker et al. 1996), aerial still photos are also used.

Areas of relative homogeneity must then be delineated from the TM and labeled with the categories defined by the classification system. In an iterative process, more detailed attributes of delineated vegetation types and revisions to their boundaries are added as more information is developed from sources such as other maps, aerial photos or videos, and field reconnaissance. Methods that have been applied to pattern delineation include manual delineation of patterns from false color TM-derived images using techniques of photogrammetry (e.g., context, texture, color; Davis et al. 1991), and spectral classification using both supervised and unsupervised techniques (Lillesand and Kiefer 1987; Jennings et al. 1996).

Finally, an assessment of the overall accuracy of the data is conducted (Crist and Deitner 1998). The

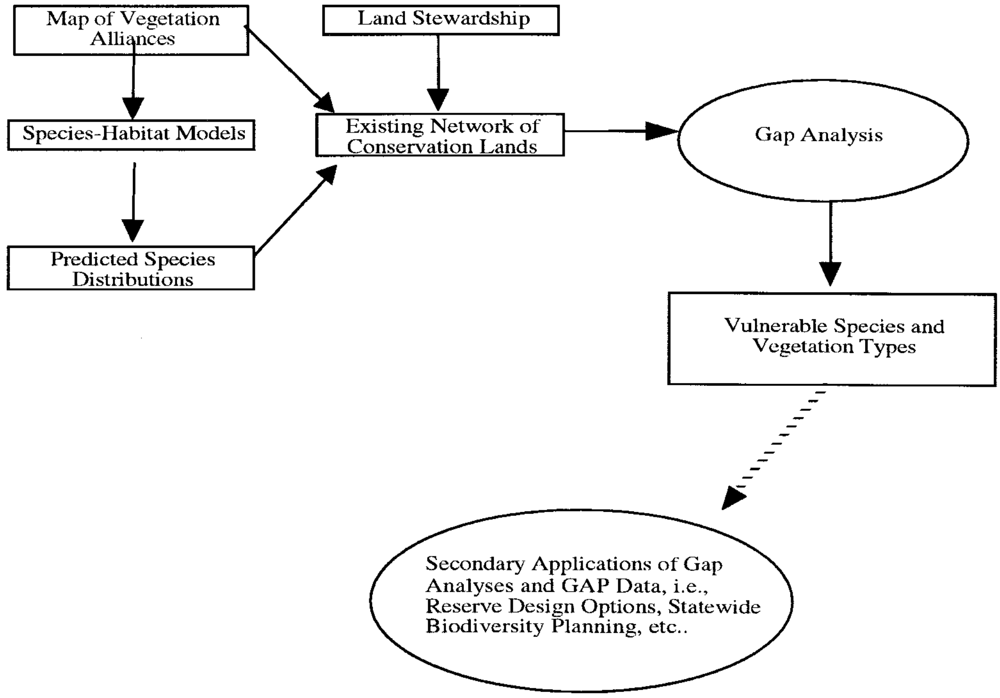

Figure 1. The gap analysis process. Vegetation alliances are mapped, then these maps are used in modeling species distributions. In the gap analysis, maps of vegetation and species distributions are combined with the maps of conservation areas to show how well vegetation alliances and species are represented in the existing network of conservation lands, those that are neither adapted to human-dominated environments nor adequately represented in conservation lands are identified as 'gaps', or vulnerable. These, then become the focus for further conservation work.

first step in assessing thematic accuracy is acquiring an independent set of reference data. These data consist of point samples acquired either on the ground or from aerial video or still photos with a subsample of each mapped vegetation type verified by field reconnaissance. The accuracy assessment objective is to determine the thematic accuracy of each map class within an 8% standard error (e.g., accuracies for lower mountain conifer forests in New Mexico, made up of Ponderosa Pine, Pinyon Pine, and Juniper alliances, were 63% with a 6.3% standard error; Thompson et al. 1996). Assessment of all but very rare map categories are based on 40 samples. The interpreted results from each of the reference data samples are compared with the mapped land cover type. This comparison is expressed in a table showing the probabilities of every possible correct or incorrect classification. The tabulation of user accuracy and their associated errors (Congalton 1991) is emphasized because this is usually the type of error a user of the map is interested in. Where the database is appropriately maintained, the final assessment of accuracy will reveal where improvements should be made in the next update (Stoms et al. 1994).

Vertebrate species maps

All maps of species are predictions about the occurrence of that species within a particular area (Csuti and Crist 1998a). Gap Analysis species maps predict the distributions of species at a landscape scale (a large area made up of more than one kind of natural community, generally covering several thousand hectares; Forman and Godron 1986). Because the occurrences of most species must be sampled by collections made at individual locations, and these point samples are usually compiled into general small-scale maps (e.g., 1:10,000,000) in field guides, landscape-scale information on species distributions, and thus awareness, is often lacking in land management decisions.

The process of modeling species distributions begins with establishing a list of species to be mapped. Names of species follow the Integrated Taxonomic Information System (1998) or Natural Heritage Central Databases taxonomic names (The Nature Conservancy 1998). Researchers then obtain location records for each species and record their sources in a database which may also include date of collection and collector. The range extent of each species is delineated and subdivided into units of recent known occurrences and extrapolated or predicted occurrences. Frequently the 635 km^2 hexagon grid developed by the Environmental Monitoring & Assessment Program (EMAP) is used as tessellation units for this purpose (see 'Building Hexagon Range Maps,' Csuti and Crist 1998a, Appendix 1). A database of habitat association information for each species is developed from an exhaustive review of literature. Species-habitat relationship models are constructed from this knowledge base for each species using existing GIS data sets of the environment (beginning with the GAP land cover map and then using DEMS, NWI, soils, and others as appropriate). For many species this knowledge base is the first compilation of published literature on their habitat preferences. When the habitat affinities of a species change across their range, the range area is stratified by the National Hierarchical Framework of Ecological Units (ECOMAP) sections or subsections (e.g., Keys et al. 1995). Species-habitat models are reviewed by experts, and the adjusted species-habitat models are then intersected with the general range maps. The resulting draft of a predicted distribution map is again reviewed and revised as appropriate (Csuti and Crist 1998a).

All species distribution maps are assessed for their accuracy (Csuti and Crist 1998b). As with the land cover maps, this is done by comparing the predicted distributions with independent reference data. Some assumptions basic to the generation of the maps that must be considered in the assessment process are: (a) species are predicted to occur within a map polygon representing potential habitat but are not predicted to occur at any particular point within that polygon, (b) no predictions are made about the abundance of the species within the mapped polygon, (c) species are assumed to be present in a polygon at least once in the last 10 years but not necessarily in every year, and (d) species are assumed to be present during some portion of their life cycle, not necessarily throughout the entire year.

Unlike the land cover maps, species occupation of habitat varies diurnally, seasonally, and annually, requiring repeated visits over many years to detect all species (Cooperrider et al. 1986; Gibbons et al. 1997). Because most state GAP projects develop maps of 300 to 700 species over millions of hectares, it is not possible to conduct a thorough, field-based assessment of each species map. Rather than randomly sampling locations for all possible species, investigators identify locations where high-confidence lists of species occurrences have been compiled over many years. Species known to occur at these locations are compared with the predicted species distributions. Limitations of this method are: (a) it only provides a measure of agreement between the predicted distribution and a set of known locations, (b) it depends on the availability of existing check lists for a reasonable number of areas (5 or more), and (c) it requires that reliable check lists of species not be used to build the distribution maps. Because a group of check lists from localities around a given state is not a statewide probability sample, inferences about accuracy of a species distribution outside of the cheek fist area is open to interpretation. There is always a danger of circularity between the map creation and validation if the experts that developed the range maps were aware of the check list contents. Although there may be no practical way to prevent this type of circularity, if the condition exists it is documented as a limitation. As with all GAP results, in situ verification is needed for any individual, localized application of data.

Development of consolidated digital biogeographic data (e.g., maps, specimen locality records, literature on habitat affiliation) for each native species (amphibians, birds, mammals, and reptiles to date) is one important result from the process of mapping species distributions. Such data are of fundamental utility to resource planners, managers, and researchers and have not been available previously.

Land stewardship maps

A land steward is the actual land manager regardless of ownership. Mapping land stewardship requires a spatial data set of the geographic boundaries of public lands and some private lands (such as large private preserves). This data set includes attributes about the land owner and managing institution. Each parcel is classified into a biodiversity management category. Most states do not have a previous statewide map of land stewardship. In addition to providing a view of the existing network of conservation areas, this map is the basis for future design of a more effective set of conservation areas.

All lands are classified into one of the following four biodiversity management categories. Status 1: An area having permanent protection from conversion of natural land cover and a mandated management plan in operation to maintain a natural state within which disturbance events (of natural type, frequency, intensity, and legacy) are allowed to proceed without interference or are mimicked through management. Status 2: An area having permanent protection from conversion of natural land cover and a mandated management plan in operation to maintain a primarily natural state, but which may receive uses or management practices that degrade the quality of existing natural communities, including suppression of natural disturbance. Status 3: An area having protection from permanent conversion of natural land cover for the majority of the area, but subject to extractive uses of either a broad, low-intensity type (e.g., logging) or localized intense type (e.g., mining). It also confers protection to federally listed endangered and threatened species throughout the area. Status 4: There are no known public or private institutional mandates or legally recognized easements or deed restrictions held by the managing entity to prevent conversion of natural habitat types to anthropogenic habitat types. The area generally allows conversion to unnatural land cover throughout.

Mapped land units are assigned ownership and management codes (see Table 1 for some examples). All land units are classified for biodiversity management status using GAP status levels 1–4. Subcategories of these categories may be mapped if desired by the state project cooperators.

Analysis

The objective of GAP is to identify biotic elements (species or alliances) that are either underrepresented or not represented in the existing network of conservation areas. Once the land cover, animal distribution, and stewardship data sets are prepared, the land cover and species distribution (element) coverages are intersected with the stewardship coverage so that the element coverages incorporate the stewardship boundaries and attributes (Crist and Csuti 1997). The statistical results from this are reported in tabular form, showing the number of hectares of each element's distribution that occur within each stewardship and management category. A narrative interpretation is prepared, with a focus on those underrepresented elements that may be especially vulnerable to habitat conversions. Maps detailing the relationship between species distributions and conservation areas are then produced.

For example, almost 87% of the Picea Glauca Forest Alliance in New Mexico occurs on land that is either Status 3 (having protection from permanent conversion of natural land cover, but subject to extractive uses) or Status 4 (no known requirements to prevent conversion of natural habitat types to anthropogenic habitat types; generally allows conversion; Table 2). Approximately 13% of its occurrence is either status 1 (having permanent protection from conversion and a mandated management plan in operation to maintain a natural state) or status 2 (having permanent protection from conversion of natural land cover and a mandated management plan in operation to maintain a primarily natural state, but which may receive uses or management practices that degrade the quality of existing natural communities, including suppression of natural disturbance). In this case, the U.S. Forest Service is the steward of about 86% of this element (Table 2).

The issue of how much of any element's distribution needs to be represented in conservation areas is unresolved. A GAP workshop convened in fall 1995 concluded that methods for establishing adequate levels of conservation representation are lacking. Arbitrary levels of 10%, 20%, and 50% of an element's distribution in management status 1 or 2 have been published in the literature as possible conservation targets (Noss and Cooperrider 1994; Noss 1991; Specht et al. 1974), and these may allow some estimation of risk on a case-by-case basis. Establishing the amount and configuration of land and water needed by each element remains a critical yet daunting task. Additional analyses that may be undertaken include assessments of species important to a given state (e.g., migratory birds, statewide endemics), special features (e.g., riparian vegetation types), or evaluations by ecoregion using sections (Bailey 1995) or subsections (McNab and Avers 1994).

One current limitation to the analyses is that no independent assessments are being made of the findings themselves. For example, Smith et al. (1998) found that approximately 4% of ovenbird (*Seiurus aurocuillus*) habitat is represented in conservation lands of Arkansas. However, that amount has not been evaluated for accuracy. There has not yet been enough research on the reliability of such results, especially the relationship between assessments of the accuracy of the data sets used as inputs and the results of the analyses. Scale remains a persistent issue, especially when inferences are made from analyses done at a larger cartographic scale than the scale that the data were produced at. Higher resolution on-the-ground surveys are needed for localized areas before implementing management decisions.

Table 1. Examples of management coding system for land stewardship (from Crist et al. 1998).

Codes			Management descriptors		
1000			Federal lands		
	1300			Fish and wildlife service	
		1301			National wildlife refuge
3000			State lands		
	3200			School lands	
5000			Local lands		
	5200			County parks	
6000			Non-gov. organization		
	6300			The nature conservancy	
		6301			TNC easement

Table 2. An example of tabular conservation analysis of a GAP biodiversity element, in this case a vegetation type from Crist and Csuti (1997).

Element code, name, and GAP biodiversity management categories	Percent, map accuracy for this element	Total km^2 of distribution in the state	Percent of total state distribution	Total km^2 by manager category Example: USFS as the manager	Percent of total state distribution on USFS land
IA8Nc3, Picea Glauca Forest Alliance,	73	330.54	0.07	285.22	86.2
Status 1		28.07	8.5	23.09	6.9
Status 2		16.00	4.8	0.00	0.0
Status 3		196.34	59.4	196.07.	59.4
Status 4		90.13	27.3	66.06	20.0

A second limitation is that these results do not reveal previous habitat losses. The historic distribution of an element is rarely known. Results from gap analysis that show the amount of an element's distribution in conservation areas today may be misleading in terms of historical context. If an element has already been extirpated from 70% of its previous distribution and the gap analysis shows a 10% representation in conservation areas today, actually only 3% of the element's previous distribution is represented. The implications of this are significant, for example, affecting potential for adaptation to changing environments, or likelihood of metapopulation persistence.

A third limitation is that gap analysis currently does not predict element viability. For most species and plant communities, viability measures (e.g., habitat quality, species abundance, population trends) are unknown. Only information on representation, with the objective of identifying at-risk species and vegetation types, is provided.

Analyses of animal species must be regarded with more caution than analyses of vegetation types because land cover maps are of observed distributions whereas animal distributions are predicted. Land cover types are sessile while animal species are mobile, usually having a more dynamic biogeography. Also, the effects of management practices on vegetation types are often easier to predict than effects on animal species.

A limitation of state-level analyses is the truncation of element distributions by state boundaries, resulting in a lack of rangewide context. This limitation will be overcome as state data sets are assembled into larger regional data sets and analyses are performed on these data. Results from the first regional analyses have been completed by Stoms et al. (1998) and Wright et al. (unpublished).

The limitations described above demonstrate the generally primitive state of present-day knowledge on species and vegetation alliances and their conservation needs. They can, however, serve as a research agenda for future progress.

Organization and Status of GAP

Business model

The single most significant organizational assumption that GAP makes is that the work is best carried out state-by-state (although in a few cases GAP projects cover more than one state, state-level implementation is still the primary level of GAP organization) and that each state project is supported by the mutual cooperation of natural resources institutions (state, federal, private) from within each state. The program is coordinated by and receives core funding from the U.S. Geological Survey (USGS). When averaged for all states, these funds are roughly equalled in matching funds and in-kind contributions from the approximately 500 organizations operating as state-level cooperators. Major national partners include the Department of Defense, the Environmental Protection Agency, and The Nature Conservancy.

Status

Currently, state projects are either under way, completed, or in an organizing phase in each of the 48 contiguous USA states. The program moved from a research and development status within the USGS to an operational status early in 1998. A second-generation effort was launched for the five southwestern states (Arizona, Colorado, New Mexico, Nevada, and Utah) in 1999. Although funding remains the single limiting factor (core funding has declined steadily each year for the past five years), future directions include: (a) developing biogeographic data for additional species, (b) synchronizing the production of state data by large regions, (c) regional and range-wide analysis of data, (d) using social science to both promote the adoption and diffusion of gap analysis as a technical innovation as well as a means for incorporating measures of human activities into analyses, and (e) developing biodiversity decision support systems for land use planners and managers.

Some recent results

The following are examples of some results from GAP projects in Wyoming, New Mexico, and Arkansas, intended to illustrate ways in which GAP data can be interpreted. The results presented below indicate a general pattern of adequate conservation of high elevation areas and other areas of relatively low biomass productivity (also supported in unpublished analyses by J. Michael Scott et al.). Most importantly, they show how an accounting of conservation status for both habitats and species can be achieved, leading to a systematic process for biodiversity conservation, element-by-element.

Wyoming

In Wyoming (Merrill et al. 1996) seven of the 41 classes of mapped vegetation occur at high elevations and are well protected (>50% of their area is represented in conservation areas) because they occur in national parks and wilderness areas. Sixteen (44%) of 36 natural (e.g., not agricultural or infrastructure) land cover types have either <1% or <50,000 ha of their total area in status 1 and 2 lands.

The highest priority for further protection is recommended for vegetated dunes, active dunes, forest-dominated riparian, shrub-dominated riparian and grass-dominated wetlands because their current protection is low and they are the most vulnerable to ongoing land management practices. Bur oak woodland, Great Basin foothills grassland, xeric upland shrub, limber pine woodland, saltbush fans and flats, desert shrub, greasewood fans and flats, and nonvegetated playas were identified as second in priority. Management of the last four types could easily be accommodated in conjunction with one another along topographic gradients, and the Bureau of Land Management (BLM) should play an important role in their conservation because they are largely under BLM's stewardship.

Because of their restricted distributions, opportunities for the conservation of bur oak and Great Basin foothills grasslands are more limited and are likely to reside with the U.S. Forest Service (USFS). Shortgrass prairie, mesic shrubland, and ponderosa pine communities were identified as a third priority for conservation, which, because of land tenure patterns, will require working cooperatively with private landowners.

On average, status 1 and 2 lands contain a smaller percentage of habitat for amphibians (8.8%) and reptiles (2.6%) than for either birds (14.4%) or mammals (14.5%). Species that have a high level of habitat protection (>50%) were restricted to the greater Yellowstone ecosystem. Among species not considered peripheral in Wyoming, the number identified as conservation gaps (80) consist of 6 amphibians (50% of all amphibians), 8 reptiles (31%), 25 mammals (22%), and 41 birds (14%). The habitats of most of these species are mostly in the eastern or south-central portions of the state where status 1 and 2 lands are uncommon. For example, *Lampropeltis triangulum*, the pale milk snake, occurs in scarp woodlands and foothills of the Great Plains region of eastern Wyoming, generally from 900–950 m elevation in association with the Limber Pine Woodland Alliance, Ponderosa Pine Woodland Alliance, Aspen Woodland Alliance, all classes of riparian, as well as dry cropland (Figure 2). Approximately 0.43% of its predicted distribution occurs within conservation areas (status 1 and status 2). However, the exact amount of this species' habitat that should be represented in conservation areas to ensure its long-term survival remains unknown. What is needed for the next step is more specific information about this and other elements identified as conservation gaps, such as their sensitivity to human activities, genetic potential for inbreeding depression, and population demographics, in order to avoid future conservation crises. This case illustrates how conservation of biodiversity can be approached element-by-element in an efficient manner. In Wyoming, management on public multiple-use lands (status 3, which are under the stewardship of USFS and BLM) and cooperative efforts with private land owners will be important to the long-term conservation of a large number of the species identified as conservation gaps. By planning for the conservation needs of these species now, which requires development of higher-resolution information, future conservation crises and the costs they incur may be avoided.

New Mexico

In New Mexico (Thompson et al. 1996) about 7% of the surface area is in management status 1 and 2 (conservation areas). Eleven of the 42 mapped classes of noncultivated vegetation each have small total areas (>10,000 ha) and of these, six have >10% of their total areas represented within status 1 or 2 lands. These six vegetation types have both limited occurrences and are not well represented in conservation areas. Overall, 20 classes of mapped vegetation each had >10% of their total area represented in conservation areas. Like in Wyoming, vegetation types that occur at higher elevations are better protected than those at lower elevations. More than 30% of the vegetation types having any of their areas in status 1 or 2 lands are high-elevation forests and alpine types. Most status 1 and 2 lands are owned by federal agencies, primarily the Forest Service, Park Service, and Department of Defense.

Among all vertebrate species (except fish), the predicted distributions of nine (1.5%) are not represented in any conservation areas. Twenty-six (4.5%) have no more than 1% of their predicted total distribution in status 1 or 2 lands. Almost 45% of these 35 species (those with 0–1% of their predicted distributions in conservation areas) are reptiles and amphibians, yet reptiles and amphibians make up 21% of all mapped species. Most (73.6%) of amphibian, bird, mammal, and reptile species have <10% of their predicted distributions represented in status 1 and 2 lands. One fifth of the 584 non-fish vertebrate species in the state have 10–50% of their predicted distributions in conservation areas. Only three species, one reptile and two mammals, have >50% of their total predicted distributions in status 1 or 2 lands. Each of these 3 species have very limited distributions that coincide with conservation areas.

Arkansas

In Arkansas (Smith et al. 1998) about 1.3% of the surface area is in management status 1 and 2. However, 53% of the state's surface area is dominated by agriculture (20%), water (25%), infrastructure (6%), and areas having <5% vegetation (2%). The remaining 47% of the state's surface area is dominated by natural or semi-natural vegetation which is where almost all status 1 and 2 lands are located. In the 47% of the state dominated by natural vegetation, 16 (49%) of the 33 mapped classes of non-cultivated vegetation each have total areas <10,000 ha, and of these,

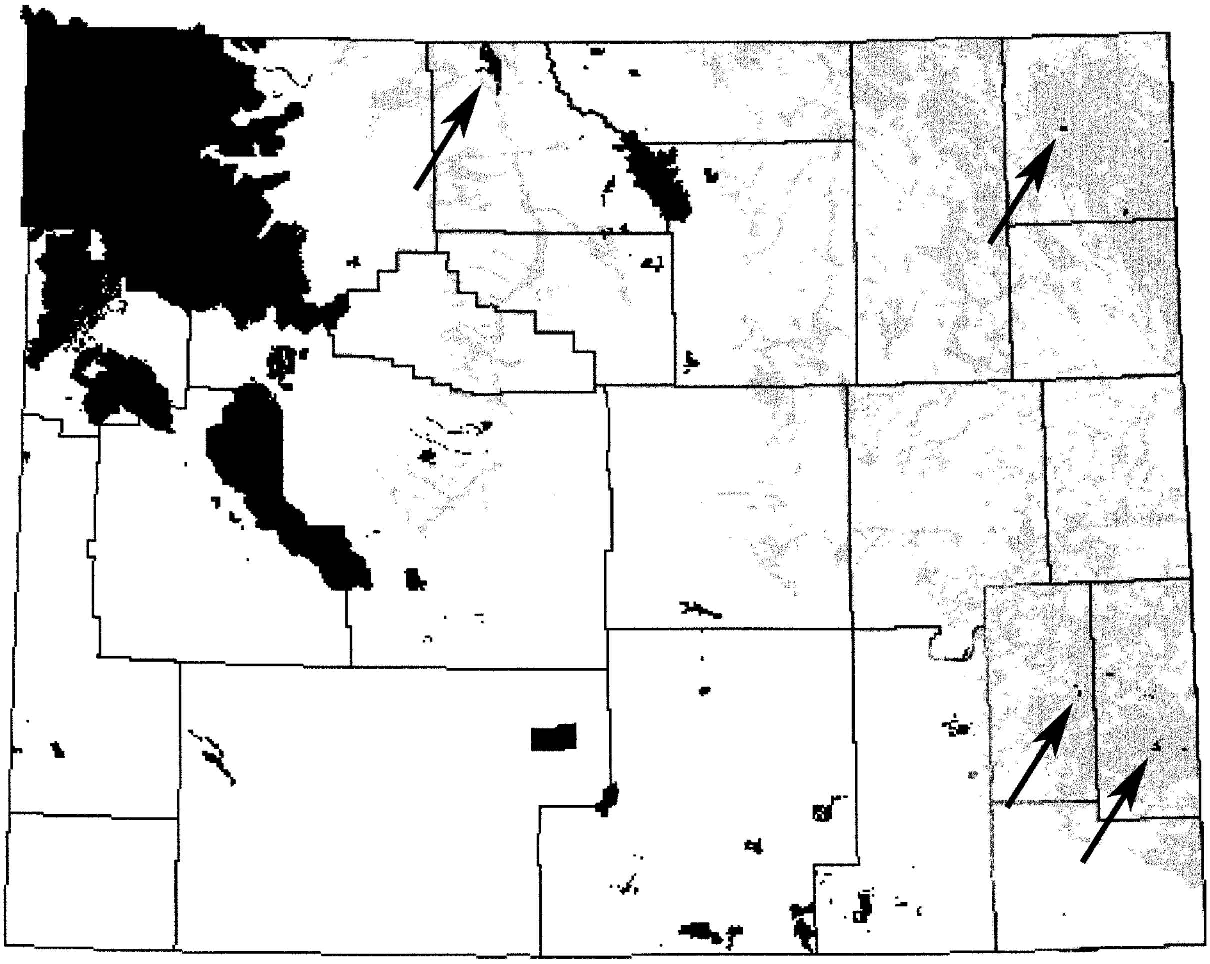

Figure 2. Conservation areas (GAP status 1 and 2) of Wyoming, shown in black, relative to the predicted distribution of *Lampropeltis triangulum*, pale milk snake, shown in grey. Some examples of the overlap between conservation areas and the snake's distribution are indicated with arrows.

12 (75%) have <10% of their total areas represented within status 1 or 2 lands. These vegetation types have both limited occurrences and are not well represented in conservation areas. Overall, 7 (21%) of all classes of noncultivated mapped vegetation have no representation within conservation areas, 18 (54%) have 0.1–10% of their occurrences within conservation areas, and 6 (18%) have >10% represented in conservation areas. Most (75%) of the mapped natural vegetation types in Arkansas either are not represented in conservation areas or have <10% of their occurrence within conservation areas.

Among all vertebrate species (except fish), the predicted distributions of 42 (13%) are not represented in any conservation areas. Twenty six (8%) have no more than 1% of their predicted total distribution in status 1 or 2 lands. Of these 68 species that have 0–1% of their predicted distributions in conservation areas, 20% are reptiles and amphibian, 25% are birds, and 46% are mammals. Most (85%) of amphibian, bird, mammal, and reptile species have <10% of their predicted distributions represented in status 1 and 2 lands. Of the 322 non-fish vertebrate species in the state, 321 (99%) have <20% of their predicted distributions in conservation areas.

Discussion

Information as a catalyst

State projects are viewed as events in progress, having to do with the development of powerful new information about biological resources as well as the formation of new technical capabilities. The process of developing the information catalyses integration among the cooperating institutions and results in important new institutional relationships and structures (e.g., the Missouri Resource Assessment Partnership). As centralized environmental management and regulation is de-emphasized, scientifically sound biogeographic information shared among institutions for managing resources becomes ever more important for effective and meaningful decision making.

Standards

Benefits will be derived from a more unified approach to the management of biological resources not only among institutions within a state, but among such institutions across state boundaries. The GAP strategy corresponding to this is to foster the development and use of consistent definitions and classification of species assemblages and other basic sets of information as well as the use of consistent technical methods wherever possible. At the same time, for some methods such as land cover pattern delineation, singular methods have not been proven to be applicable to all environments. Flexibility in methods has been vital to the development of GAP. Standardization of all methods for the sake of standardization alone is self-limiting, especially where innovation and discovery are central to achieving the objectives, as they have been with the Gap Analysis Program.

Operations

The first-generation gap analysis effort has resulted in major gains in the science, technology, and institutional capabilities needed for developing and applying information to the overall management of biodiversity. Of primary importance, we have learned the operational level of effort that is required. We have also learned that our knowledge base of most species and vegetation alliances is minimal. A substantially larger effort will be required to systematically document habitat affinities for most species, and this must include a much greater amount of specimen field collecting and survey of vegetation types. The program has contributed significantly to increases in the number of GIS- and remote sensing-capable biodiversity practitioners and researchers. Much greater expansion of the skill pool in vegetation science, community ecology, and landscape ecology is still needed.

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