Journal of Conservation Planning Vol 3 (2007) 1 — 16

Assessing tradeoffs in biodiversity, vulnerability and cost when prioritizing conservation sites

Holly E. Copeland, Johanna M. Ward, & Joseph M. Kiesecker

Holly E. Copeland
The Nature Conservancy, Wyoming Field Office
258 Main Street, Suite 200
Lander, WY 82520
Phone: (307) 335-2129
Fax: (307) 332-2974
hcopeland@tnc.org

Johanna M. Ward
The Nature Conservancy, Regional Office
2424 Spruce Street
Boulder, CO 80302
Phone: (303) 541-0339
jward@tnc.org

Joseph M. Kiesecker
The Nature Conservancy, Wyoming Field Office
258 Main Street, Suite 200
Lander, WY 82520
Phone: (307) 335-2130
Fax: (307) 332-2974
jkiesecker@tnc.org

ABSTRACT: The ability to identify areas of biodiversity importance and assess the potential for adverse habitat alteration is a component of a preventative rather than a reactive approach to conservation (Davis et al. 1990). However, focusing solely on the most threatened areas often results in concentrating on the most expensive conservation work. We used The Nature Conservancy's (TNC) existing conservation sites within the state of Wyoming to identify biologically important areas that varied with respect to potential vulnerability and then examined the likely costs associated with conserving these places. We assigned a biodiversity index to each conservation site by assessing biological richness and identifying the current state of dominant transforming land uses. We measured vulnerability by identifying the future risk of additional land-transforming uses. This information, once combined, resulted in a map that highlighted areas of high biodiversity that varied in the degree to which they are vulnerable. We also analyzed the relationship between cost of conservation and vulnerability, and determined that vulnerability is positively correlated with conservation costs. The cost (in dollars) needed to reverse impacts associated with future threats in all the low-vulnerability sites (650,000 ha) would only accomplish conservation within 26% (401,000 ha) of medium- and 5% (121,000 ha) of high-vulnerability sites. We propose that our analysis will aid in implementation of conservation action by providing a methodology that includes estimates of cost in addition to urgency and can be applied effectively at any scale by land trusts and other institutions implementing conservation programs.

Keywords: conservation planning, biodiversity, vulnerability, cost, prioritization, Wyoming

INTRODUCTION

The limited resources allocated to the conservation of biodiversity profoundly influence the planning methods and conservation strategies of governmental and non-governmental organizations alike. Critical to successful conservation is defining where and when to work. There is no doubt that the number of places in need of conservation action far exceeds available resources. This places a premium on identifying priorities. Moreover, there is an urgent need for strategic, proactive approaches to complement the costly, reactive measures of many approaches once species and systems become threatened or endangered. Synthesizing spatial data on the distribution of biologically important areas with data assessing potential habitat degradation and resource development encourages a preventative rather than a reactive approach to conservation (Davis et al. 1990). With GIS data becoming more readily available and accessible on a variety of subjects (biological and natural resources, land management, resource extraction, and census statistics), multi-criteria spatial analyses, such as completed in this paper, are also more feasible and robust.

The scientific literature is replete with alternative ideas of how to identify priority conservation areas (sites) (e.g. Margules & Pressey 2000; Myers et al. 2000; Noss et al. 2002; Kareiva & Marvier 2003). Most often, planners use area-constraining algorithms that seek to maximize biodiversity while limiting the area needed for conservation (Davis et al. 1996, Lawler et al. 2003). It is now commonplace to incorporate threats into these assessments, although despite the call for proactive conservation, few have attempted a comprehensive assessment of all major current and future threats (Wilson et al. 2005). And few, if any, analyses consider how alternative valuations of variables ultimately influence the outcome of the prioritization. For example, a survey of papers published in the journals Conservation Biology, Biological Conservation, and Ecological Applications from 2000-2005 found that all papers published on protected area planning and prioritizations consider areas of high threat as priorities for conservation action (H.C. & J.K., unpublished data). Prioritizing areas with the highest threat may result in a strategy that focuses on the most expensive conservation work. Moreover, a focus on high-threat areas may limit the utility of conservation planning exercises, because implementation often is constrained by cost as well as other factors that are outside the control of most practitioners (Groves 2003).

Relevance of the theory behind conservation prioritizations can best be illustrated through the extent to which they are implemented. In fact, a very low percentage of plans show evidence of implementation, which reflects a disconnect between planners and practitioners (Prendergast et al. 1999; Polasky et al. 2001). The gap between conservation planning and implementation may be bridged when cost is considered in conservation prioritization approaches (Frazee et al. 2003; Pence et al. 2003). Conservation biologists are increasingly recognizing the need to incorporate socioeconomic considerations such as cost into prioritization analyses if they are going to be put into practice (Balmford 2006; Sarukhan 2006). Progress has already been made. Several researchers have examined tradeoffs in species conservation and cost (Ando 1998; Polasky et al. 2001; Polasky et al. 2005), but few have applied their work to existing conservation areas, and examined tradeoffs among biodiversity, vulnerability and cost.

To illustrate the process of priority site selection and contrast opposing selection strategies, we focused on the conservation sites delineated through The Nature Conservancy's (TNC) planning process within the state of Wyoming. Nature Conservancy planners use a multi-scaled planning approach, beginning with broad-scale ecoregional planning. Ecoregions are large units of land and water defined by climate, geology, topography and associations of plants and animals (Bailey 1995). Ecoregional planning is a methodical and comprehensive process for identifying a set of places or areas that together represent the majority of species, natural communities, and ecological systems found within an ecoregion. A portfolio of priority sites is the end product of ecoregional planning, and should represent the full distribution of biodiversity in the area (e.g. Noss et al. 2002). Site selection is guided primarily by biological targets, which are representative plants, animals or biological communities that, when conserved, provide a high probability that the ecoregion's biodiversity will be maintained. While the process of ecoregional planning identifies biologically important sites and threats, when prioritization is addressed, conservation action is typically directed at the highest-threat sites. Our goal here is to build a GIS-based model to address the following questions using readily available spatial data: (1) Where are the sites of highest biodiversity?; (2) How do sites differ with respect to vulnerability?; and (3) How does variation in vulnerability affect the potential costs of implementation?.

Our analysis has been applied to conservation areas in Wyoming, but is intended to describe a general method that could easily be adapted to conservation areas in other areas. This is especially true for Western states, where land transformations, such as oil and gas, water development, and residential development, similar to Wyoming are occurring, and thus would have similar costs for conservation. If this analysis were to be adapted for areas with different threats, cost measures would need to be developed that reflect these threats. Also, those wishing to complete this analysis for sites with more of an aquatic emphasis may want to alter the weighting to account for this.

METHODS

We built a GIS-based model to integrate multiple measures of a site's biodiversity and vulnerability (Fig. 1, page 4). Our biodiversity index was based on conservation target information from existing ecoregional assessments and by developing a spatial measure of landscape integrity and aquatic health using readily available data from federal and state agencies. Our vulnerability index was based on the likelihood for a site to be impacted in the future by mineral extraction, residential development and new water projects. In this paper, we define a site's vulnerability as its susceptibility to land use activities likely to have the most future impact to Wyoming's ecosystems: mineral extraction, residential development, and new water projects. A prioritization of portfolio sites developed for six ecoregions (TNC 1998; TNC 1999; Freilich et al. 2001; Neely et al. 2001; Noss et al 2001; Hall et al. 2002) was achieved by ranking each site by the biodiversity and vulnerability indices. We then examined the relationship between vulnerability and cost by estimating the potential costs associated with preventing or reversing the impacts of the threats, should they be realized on the ground.

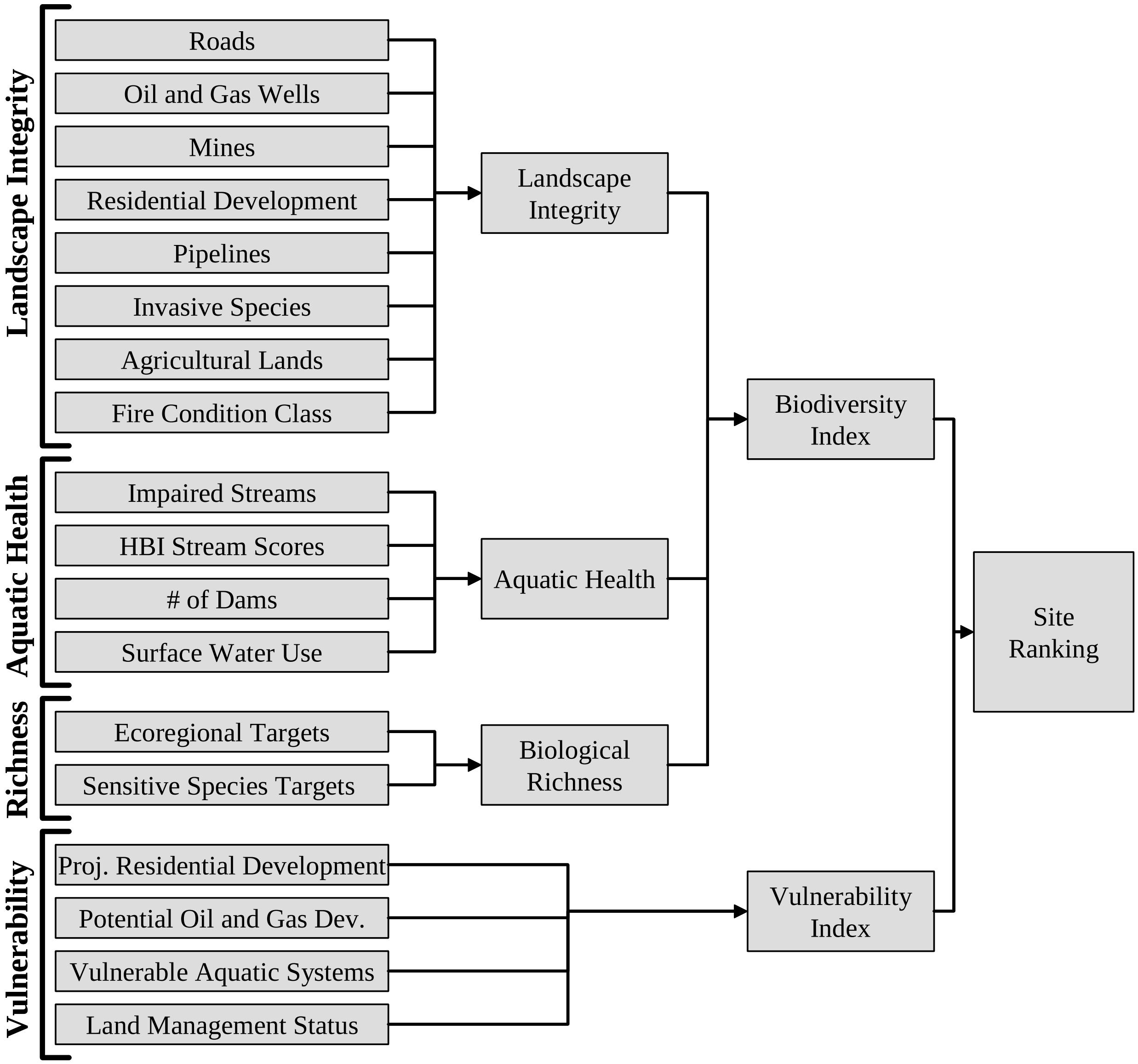
Study Area

Six ecoregions (Bailey 1995) intersect Wyoming (from largest to smallest): Wyoming Basins, Northern Great Plains Steppe, Utah-Wyoming Rocky Mountains, Southern Rocky Mountains, Central Shortgrass Prairie, and the Black Hills. All of the boundaries of these ecoregions extend beyond Wyoming, but only the sites (or portions thereof) within Wyoming and larger than 5000 acres (2024 ha) were considered for our analysis. We made the decision to clip our analysis at the state boundary recognizing that while ecological phenomena do not respect political boundaries, political boundaries clearly influence how and where decisions are made for conservation organizations like The Nature Conservancy. We used terrestrial biomes (clusters of ecoregions) as delineated by Olson et al. (2001) for analysis and reporting.

Biodiversity Index

The biodiversity index was based on a combination of landscape integrity, aquatic health, and biological richness at the site. Landscape integrity was calculated by combining socioeconomic data that measures the impact of human activities on the land and data showing the distribution of invasive species and fire condition. We calculated aquatic health using four factors: dams, impaired streams, Hilsenhoff Biotic Index (HBI) stream scores, and surface-water use. We calculated biological

FIGURE 1 A schematic representation of data and workflow for the biodiversity and vulnerability analyses.



richness from data on species and sensitive species presence in portfolio sites from ecoregional planning. In most cases we either reclassified or normalized these data to values ranging from zero to one using linear-scale transformation (maximum-score procedure) (Malczewski 1999), unless the data dictated differently to gain a normal fit.

Landscape Integrity

We acquired eight datasets to represent landscape integrity; ones that we believe best represent the cumulative impact of human activities on the land. We combined eight factors, all from readily available datasets from federal and state agencies. The eight factors were: roads, mines, oil and gas pipelines, oil and gas wells, residential development, agricultural lands, invasive species, and fire condition class (Table 1, page 6). We summed and normalized all landscape integrity factors and calculated the mean value for each portfolio site (Fig. 2, page 7)

Aquatic Health

We acquired four datasets to represent stream condition or aquatic health: dams, impaired streams, HBI scores, and surface water diversion. We estimated the impact of dam-water diversion by summing the number of dams in each portfolio site. (Army Corps of Engineers 2005). We used 303(d) data on impaired streams from the Environmental Protection Agency (2002) to measure general pollution issues. Lengths of impaired streams, in meters, were summarized for each portfolio site. We used stream point samples provided by the Wyoming Department of Environmental Quality (2005) and averaged Hilsenhoff's Biotic Index (HBI) scores across each portfolio site. Hilsenhoff's Biotic Index measures stream health by assessing the composition of macroinvertebrate communities; higher index values indicate a more pollution-tolerant macroinvertebrate community and generally a lesser degree of water quality. In cases where we lacked sample data for a site, we assigned the mean score. We acquired data from the U.S. Geological Survey (1995) on surface-water usage, a measure of how much water is diverted for human uses by watershed. We intersected the watersheds and our sites, and calculated a weighted-area average by site. Finally, we summed and normalized all four measures of aquatic health to produce a single score for each site.

Biological Richness

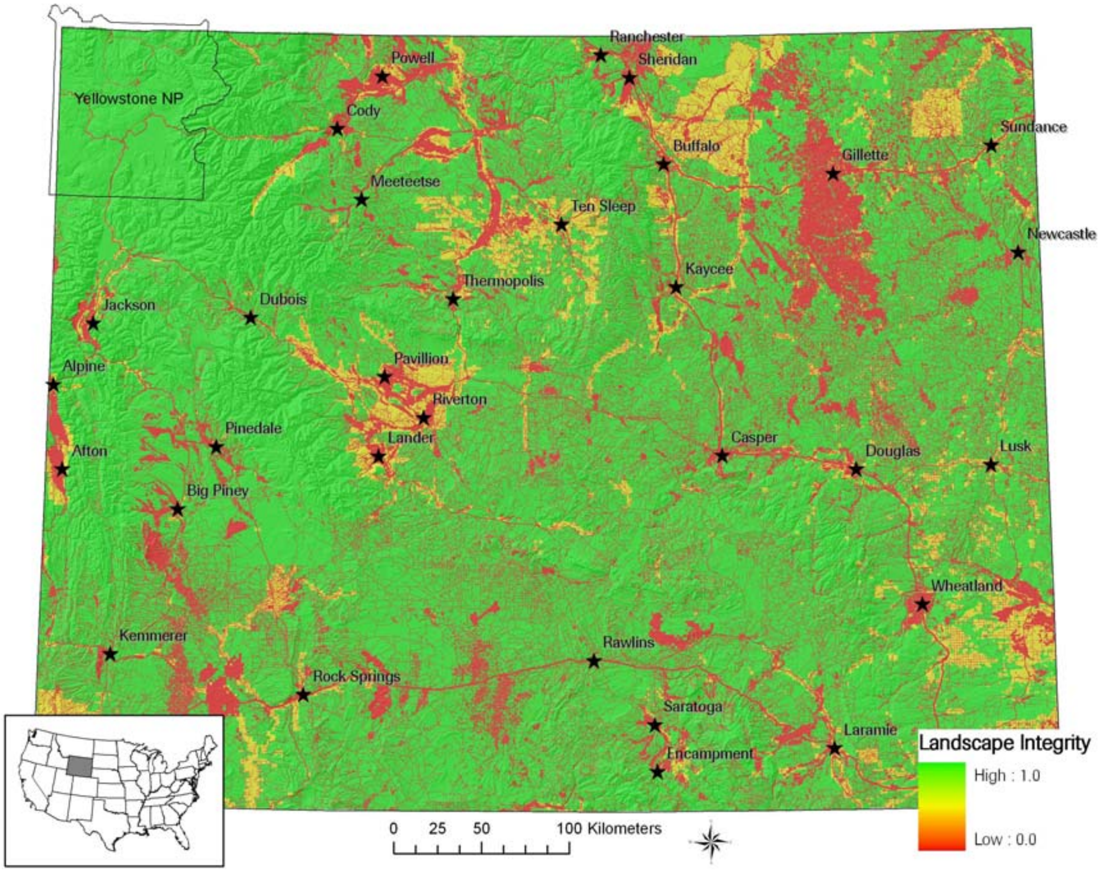
A product of all TNC's ecoregional plans are portfolios of sites with lists of "conservation targets" representing all species, communities, and ecosystems important to each site. However, methodologies for ecoregional planning within TNC are not consistent, and the range of the number of conservation targets varies widely by plan. To account for this, we normalized these data to each ecoregion. We counted the number of conservation targets in each portfolio site and calculated the mean divided by the standard deviation of conservation targets within each ecoregion and then normalized to one by dividing by the maximum value. As a further measure of a site's biodiversity, we tabulated the number of sensitive species from federal and state agencies that are represented as biological targets in each portfolio site. In Wyoming, the U.S. Fish and Wildlife Service, the U.S. Forest Service, Bureau of Land Management, the Wyoming Game and Fish Departments, and the Wyoming Natural Diversity Database (Keinath et al. 2003) maintain lists of "sensitive species". We cross-walked the conservation targets for each site with sensitive species information from all five agencies to create sensitive species richness lists for each site. We summed and normalized the number of sensitive species in each site. Finally, we summed and normalized the two measures—counts of conservation targets and counts of sensitive species—to create a single value for biological richness.

TABLE 1 Data Sources, Dates, and Methods Used in the Analysis for Calculating Landscape Integrity

Data Title	Source	Source Date	Procedure
Roads	U.S. Census Bureau	2000	We buffered roads based on road class size using methods similar to Theobald (2003), where interstate highways, for example, are buffered by 500 meters (from the centerline of the highway) and four-wheel drive roads are buffered 25 meters. *
Mines	Wyoming Department of Environmental Quality	2001	We selected all mines from the Wyoming DEQ dataset containing the outlines of all surface mines.
Oil and Gas Wells	Wyoming Oil and Gas Conservation Commission	2005	To account for disturbance from oil and gas wells, each well was buffered 0.40 km (0.25 mile) for active wells and 0.2 km (0.125 mile) for inactive wells, values based on sage grouse sensitivity (Braun et al. 2002).
Oil and Gas Pipelines	Wyoming Department of Revenue	2001	The typical right of way given for oil and gas pipelines is 7.6 meters (25 feet) on either side of the pipeline (U.S. Department of Transportation 2006). We buffered each side of the pipeline by 30 meters to ensure that they would be captured since we were using a pixel size of 30 meters.
Residential Development	Census Bureau	2000	We used block-level census units polygons and the housing count attribute to classify the data into urban, suburban, and rural categories (Theobald 2003). We classified blocks greater or equal to 0.06 units per ha (0.025 units/acre) as residential. We removed public lands from consideration by intersecting these polygons with public lands data from the Wyoming GAP Assessment (Merrill et al. 1996).
Agricultural lands	Wyoming Water Resources Center	1998	We selected irrigated and non-irrigated croplands from the original dataset, and weighted the data based on our perceived value of impact (irrigated croplands were weighted twice non-irrigated croplands.
Invasive Species	University of Wyoming Cooperative Agricultural Pest Survey	1998	We summarized data on all 20 invasive species in the survey into a single raster dataset denoting presence or absence of an invasive species.
Fire Condition Class	Fire Sciences Laboratory of the US Forest Service Rocky Mountain Research Station	2000	We selected three fire condition classes (class 1 (within or near historical range), class 2 (moderately altered from historical range), or class 3 (significantly altered from historical range)) and used linear scaling to weight the data based on perceived degree of impact. **

* A known limitation of this dataset is the absence of new roads as a result of recent oil and gas development.
** Data are photo-interpreted data from the National High Altitude Aerial Photography Program.

FIGURE 2 Map of landscape integrity for Wyoming. We combined eight factors to calculate landscape integrity: roads, mines, oil and gas pipelines, oil and gas wells, residential development, agricultural lands, invasive species, and fire condition class. Higher (green) values indicate higher landscape integrity. Inset map (lower left) shows the location of Wyoming within the conterminous United States.



Calculating the Biodiversity Index

Our biodiversity index consisted of the three factors described above: landscape integrity, aquatic health, and biological richness. The ecoregional plans which produced these conservation sites, were largely terrestrial focused; therefore, we weighted both of these factors twice that of the aquatics health factor. The three factors were weighted and summed to produce the final biodiversity index.

Vulnerability Index

We measured a site's vulnerability by summing and normalizing data on four factors for which we had readily available data and considered most likely to impact Wyoming's biodiversity in the future: projected rural residential development, potential energy development, potential water diversion projects, and land protection status. To map projected rural residential development we used census block-level data on housing counts from the 2000 U.S. Census, for all developable (private) lands. We calculated the housing density per block and assumed a total of 20% growth in all blocks over 25 years (2000 to 2025) based on historic growth projections (State of Wyoming, Economic Analysis Division 2005). If the density was greater than 0.06 units per ha (0.025 units/acre) for a given block, we categorized having high potential for residential development (Theobald 2003) and gave it a score of 1. All other blocks were given a score of 0.

We estimated potential oil and gas development by merging data from both the Bureau of Mines (Anderson et al. 1990) and the Wyoming State Geological Survey. The final values were categorized based on potential for development (high potential = 1, medium potential = .5, low potential = 0) and the mean value estimating future oil and gas development calculated for each site.

Basin-wide water plans were recently completed for all the major drainages in Wyoming (Wyoming State Water Plan 2002). A product of these plans was an assessment of potential for future surface-water diversions, a measure of how much water may be diverted as a result of human uses. We acquired and merged each basin's data. We removed projects from consideration deemed to be conservation related and projected to have a positive impact on the watershed. The basin plans classify potential projects into two categories based on potential for occurrence: short-list (higher probability) or long-list (lower probability); we selected all the short-list projects, given the higher degree of potential for these projects to actually occur, and summed the number of these projects by site. We scored each conservation site from 0 (low potential) to 1 (high potential) based on the number of potential projects in the conservation site, and normalized and categorized the data into five equal-sized bins.

We included land protection status to measure the level of land protection in the site, an indicator of both the possibility for residential development and a measure of land management status in line with conservation. We used data from the Wyoming GAP Analysis (Merrill et al. 1996) and conservation easement data, where available, from all Wyoming land trusts and the Wyoming Game and Fish Department. Values were given to each land management category based on the intended stewardship and management (Merrill et al. 1996). We considered GAP classes one and two as protected, and therefore not vulnerable. Conversely, we considered GAP classes three and four as not protected, and therefore highly vulnerable (Theobald 2003).

Calculating the Vulnerability Index

The four vulnerability measures (projected rural residential development, potential oil and gas development, potential water development, and land protection status) were summed and normalized into a single index from 0 to 1 for each site, and binned into three equal-sized classes and ranked low, medium, and high.

Determining the Priority Sites

We sorted all sites by the biodiversity index and selected the 45 highest-ranked sites, thus ensuring that all priority sites were of the highest biodiversity. Then we sorted these 45 sites according to low-, medium-, and high-vulnerability based on their respective status. These final 45 sites became our priority sites.

Vulnerability-Costs Assessment

Once we selected the priority sites, we estimated the implementation or restoration costs associated with abating the potential threats to those sites. We assigned a cost function to the threats of residential development, water development and oil and gas extraction. We spilt the vulnerability costs into ones where we felt we could engage proactively to prevent them from occurring (residential development) and those where we would act more reactively and work to reverse impacts once they have occurred (oil and gas development and water development projects). With the exception of potential residential development (because real estate costs vary significantly by region), we assumed that costs associated with abating threats (i.e. reclamation) were the same throughout the state. We then compared the relationship between cost and vulnerability using a simple linear regression.

To measure the cost of conservation associated with abating residential development, we gathered information on the purchase cost per hectare for each portfolio site from real-estate experts and recent land sales made by the Wyoming Chapter of TNC. The costs were then weighted by the area of estimated density of future residential development and categorized into three groups: low density at less than 0.0004 units per ha (0.001 units per acre), medium density between 0.0004 units per ha and 0.004 units per ha (0.001 units/acre to 0.01 units/acre), and high density at greater than 0.04 units per ha (0.01 units/acre). Areas of high vulnerability were multiplied by the full estimated land values, areas of medium vulnerability were multiplied by half the estimated land values, and areas of low vulnerability were multiplied by one-tenth the estimated land values. Finally, we summed these values to arrive at the cost to conserve the site from residential development.

We estimated the costs of restoration after oil and gas development on a per well basis ($20,000/well), based on data provided by Western Organization of Resource Councils (2004). We assumed a density of 1 well every 16.2 ha (40 acres) in areas with a high vulnerability to oil and gas development, based on well-spacing guidelines provided by the Wyoming Oil and Gas Conservation Commission (2005). Costs associated with restoration were then weighted for each site based on the calculated vulnerability. Sites were scored the full projected costs for each 16.2 ha (40 acres) area with a high vulnerability to potential oil and gas development. Areas with medium vulnerability to oil and gas were scored half the cost, (=32.4 ha (80 acres)) spacing for wells to reflect the reduced likelihood of development), and sites with low vulnerability to oil and gas were scored with no cost. All costs were summed to produce an estimated cost of oil and gas development restoration per site.

We also estimated costs associated with restoration of water development projects based on a sample of 36 small dam (mean length = 120 meters, mean height = 10 meters, mean cost $398,000) removals in the United States (American Rivers et al. 1999; Trout Unlimited 2001; H. John Heinz III Center for Science, Economics and the Environment 2002; Graf 2003). Costs associated with water development restoration were summed based on the number of projects proposed for each site.

We summed the costs associated with each of the vulnerability indicators, rounding to the nearest thousand, to arrive at a single restoration/conservation cost estimate for each of the 45 priority sites. To further illustrate the relationship between vulnerability and cost, we compared costs between low-, medium- and high-vulnerability sites and assessed how much conservation, in hectares, could be accomplished with the same dollar amount by working at sites with differing vulnerability scores.

RESULTS

Of the roughly 8.5 million hectares of portfolio sites found within the six Wyoming ecoregions, we identified 51% of the area (45 out 123 sites) as high priority (Fig. 3). We observed distinct patterns in the geographic distribution of the biodiversity and vulnerability of priority sites across terrestrial biomes. High biodiversity areas were most often found in the xeric shrublands (1.9 million ha), followed by forests (1.3 million ha) and grasslands (1.1 million ha). The high-vulnerability sites were dominated by grassland and xeric shrubland biomes, which likely results from the widespread potential for future mineral extraction, while the low- and medium-vulnerability sites were dominated by forested biomes (Table 2, page 11).

Vulnerability scores appear to reliably predict projected costs of abating future threats. Sites with high vulnerability scores were more likely to have higher costs associated with abating these same threats (β = .130, *t* (43) = 1.75, *p* = <0.001, Table 2, page 11). The costs associated with restoring or abating all future threats for all of the 650,000 hectares (1.6 million acres) of low-vulnerability sites is 161 million dollars. This same dollar

FIGURE 3 Conservation prioritization of portfolio sites in Wyoming. The 45 priority sites are indicated in green (high biodiversity-low vulnerability), orange (high biodiversity-medium vulnerability) or red (high biodiversity-high vulnerability). Relative cost is shown on a bar chart for each site; minimum cost is $0 at Snowy Range; maximum cost is $1.4 billion at Greys River. Remaining portfolio sites are stippled.

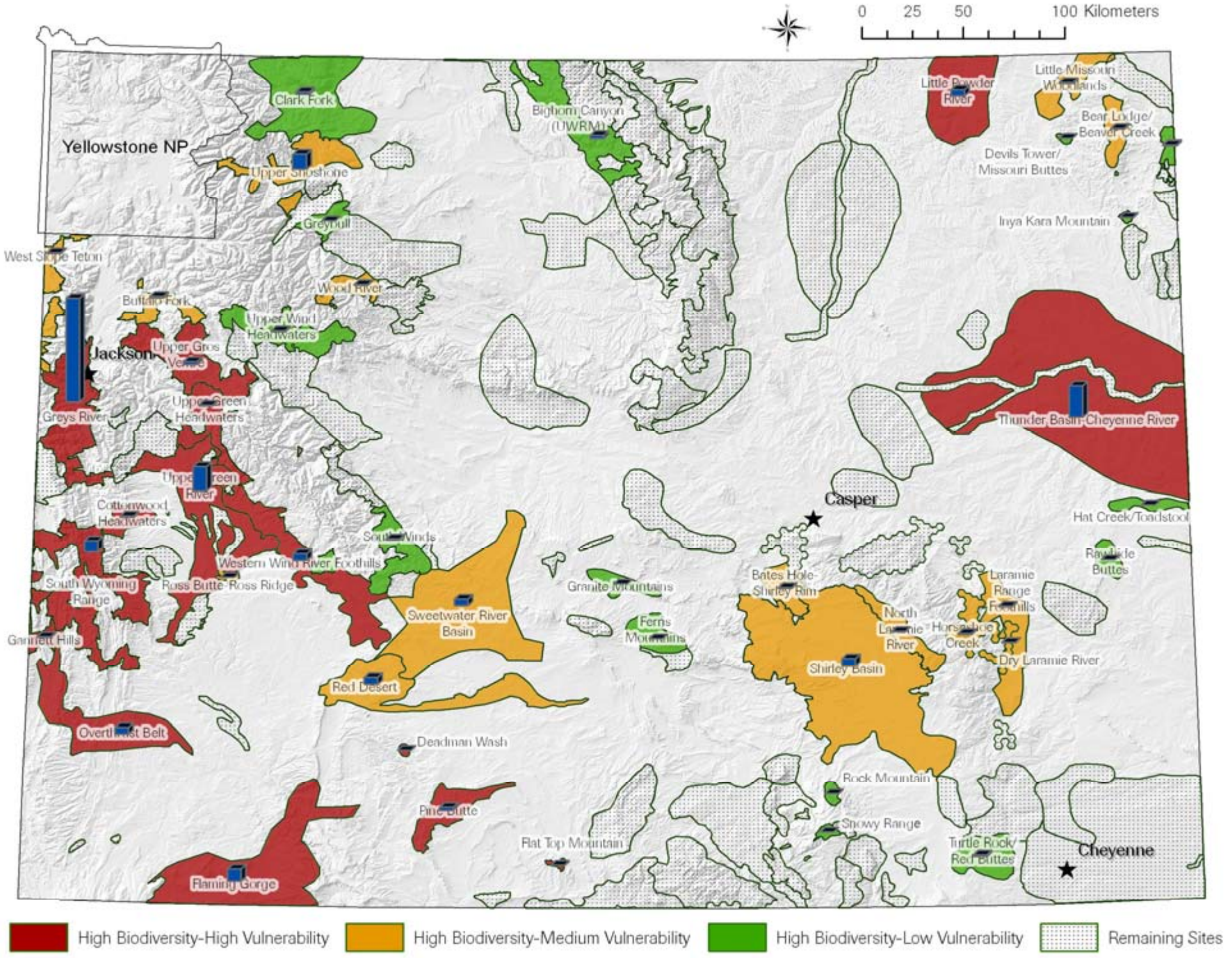


TABLE 2 Summary Data (hectares, vulnerability, and costs in USD) for the 45 Priority Sites

Biomes	Name	Hectares	Vulnerability[a]	Cost (USD) [b]
Xerics and Shrublands	Cottonwood Headwaters	28,151	High	18,600,000
	Deadman Wash	2,787	High	1,880,000
	Ferris Mountains	37,514	Low	644,000
	Flaming Gorge	264,064	High	173,000,000
	Flat Top Mountain	3,189	High	2,280,000
	Granite Mountains	25,633	Low	111,000
	Overthrust Belt	138,339	High	95,900,000
	Pine Butte	56,172	High	42,200,000
	Red Desert	147,311	Medium	97,900,000
	Ross Butte-Ross Ridge	4,724	Medium	2,910,000
	Shirley Basin	565,866	Medium	98,500,000
	Sweetwater River Basin	318,184	Medium	94,700,000
	Upper Green River	201,750	High	341,000,000
	Western Wind River Foothills	149,036	High	99,400,000
Grasslands	Bates Hole-Shirley Rim	35,783	Medium	12,900,000
	Hat Creek/Toadstool	18,822	Low	728,000
	Laramie Range Foothills	84,400	Medium	9,520,000
	Little Missouri Woodlands	48,442	Medium	16,900,000
	Little Powder River	130,412	High	87,700,000
	Rawhide Buttes	19,678	Low	480,000
	Thunder Basin-Cheyenne River	776,082	High	438,000,000
Forests	Bear Lodge/Beaver Creek	32,239	Medium	11,100,000
	Bighorn Canyon (UWRM)	108,412	Low	47,500,000
	Buffalo Fork	30,796	Medium	19,000,000
	Clark Fork	181,961	Low	32,000,000
	Devils Tower/Missouri Buttes	2,652	Low	937,000
	Dry Laramie River	15,613	Medium	1,390,000
	Gannett Hills	24,541	High	16,300,000
	Greybull	26,207	Low	33,100
	Greys River	128,700	High	1,440,000,000
	Horseshoe Creek	39,631	Medium	13,500,000
	Inya Kara Mountain	2,655	Low	998,000
	North Laramie River	44,971	Medium	1,060,000
	Northern Hills Spring Creeks	11,601	Low	15,200,000
	Rock Mountain	7,408	Low	1,070,000
	Snowy Range	5,959	Low	0
	South Winds	71,572	Low	18,200,000
	South Wyoming Range	163,365	High	150,000,000
	Turtle Rock/Red Buttes	55,177	Low	23,900,000
	Upper Green Headwaters	61,915	High	16,700,000
	Upper Gros Ventre	105,038	High	39,700,000
	Upper Shoshone	83,843	Medium	211,000,000
	Upper Wind Headwaters	76,057	Low	19,700,000
	West Slope Teton	39,290	Medium	11,900,000
	Wood River	29,508	Medium	10,100,000

aVulnerability estimates projected future impacts to Wyoming's biodiversity using four factors: projected rural residential development, potential energy development, potential water diversion projects, and land protection status.

bCost was estimated by assigning a cost function to three of the four vulnerability factors (projected rural residential development, potential oil and gas development, and potential water development projects) based on the likelihood of its potential threats to occur.

amount would only achieve restoration or abatement of these same threats on 26% (401,000 ha) of medium- and on 5% (121,000 ha) of high-vulnerability sites.

DISCUSSION

Resources available for purposes of conservation invariably are in short supply relative to need. Accordingly, setting priorities for conservation action is a necessary and major task for organizations concerned with the preservation of species and ecosystems. Explicitly combining information about biodiversity and the vulnerability of sites to anthropogenic threats enables conservation planners to consider aspects of urgency and cost in addition to biodiversity. Our analysis identified 45 areas of high biodiversity within Wyoming, and ranked them based on their vulnerability. Our estimate of costs associated with abating threat suggests that our vulnerability ranking provides a reliable surrogate for implementation costs. We believe this type of analysis provides the greatest utility for conservation practitioners. Conservation organizations can use this approach to make decisions about priority sites that would allow them to incorporate an estimate of cost and potentially effect more conservation for less money (Babcock et al. 1997; Wu et al. 2001; Messer 2006). An individual site, although biologically important and highly threatened, may require all of an organization's funds to protect or restore and thus eliminate its ability to address other areas. Sites with relatively low vulnerability may provide a comparatively long window of opportunity and point to lower-cost conservation opportunities. In fact our analysis suggests that the dollar amount needed to reverse impacts associated with in all the low-vulnerability sites would only accomplish conservation within 26% of medium- and 5% of high-vulnerability sites.

The priorities selected by our analysis represent all three biomes (grasslands, xeric shrublands, and forests) recognized in Wyoming. Twenty-four out of 45 priority sites occur in forested habitats. This is likely a reflection of the high degree of formal conservation attention historically given to forested systems over their lowland counterparts in the western U.S. as well as elsewhere (Knight 1994; Knight 1999; Scott et al. 2001). In addition to the disparity in representation, there were strong differences in the vulnerability scores for priority sites representing different biomes. Forested habitats dominated the low- and medium-vulnerability sites, while the grasslands and xeric shrublands habitats dominated the high-vulnerability priority sites (10 of 15 high-vulnerability sites). This is not surprising and follows a well-established trend. Worldwide, grasslands and xeric shrublands are among the most threatened systems (Tarboton 1997; Knight 1999), and in Wyoming, the brunt of current and future oil and gas development is occurring in these systems.

Effective conservation planning not only uses the best available science but also strives to improve on-the-ground conservation. In reality, a low percentage of plans show evidence of implementation, which probably reflects a disconnect between planners and practitioners (Prendergast et al. 1999). One way to help improve this disconnect may be to incorporate some measure of the cost of its execution (Polasky et al. 2001; Frazee et al. 2003; Messer 2006), one of several factors limiting conservation implementation. The potential vulnerability to future degradation may give an accurate estimate of cost and potential for success. For example, the positive correlation between the likelihood of land-use conversion and cost of land acquisition means sites highly vulnerable to residential development are typically more expensive than low-vulnerability sites (Newburn et al. 2005). Moreover, sites composed primarily of private land would also guide action towards more expensive strategies, such as acquisition (Pence et al. 2003). The same can be said for other threats as well. For example, a site with a higher risk of oil and gas development would likely cost more to restore relative to a site with a lower risk of future development.

Our analysis suggests a framework by which cost can be incorporated into the planning process in an objective, repeatable fashion. In our case, the cost analysis was a secondary, additional step to the original site identification process since we used sites from multiple ecoregional plans done at different times with different methods, and worked to prioritize them across a single geography. We could just as easily see these methods embedded in the ecoregional planning process for both the selection and prioritization of sites. For example, MARXAN (Ball et al. 2000, Possingham et al. 2000), a widely used systematic conservation planning tool, has the ability to incorporate cost directly into the planning process. Planners could run different models examining alternative cost scenarios that don't focus solely on the highest-threat/highest-cost places, but seek to find solutions that highlight lower-cost places as well.

Our prioritization selected only 45 of the 123 portfolio sites. Nevertheless, the acreage of these sites represents approximately 51% of the total portfolio area. These 45 sites were selected as "no regrets" sites. Given that half of the portfolio area has been selected, a further refinement based on the feasibility of implementation may be necessary to reduce the acreage to something more manageable. Alternatively, the prioritization may be used differently by various conservation organizations. For example, those with limited funding available may focus on sites with low vulnerability scores, while others with more resources may choose to concentrate on high-vulnerability/high-cost sites. Given the ecoregional planning process from which the portfolio sites were initially selected (TNC 1998; TNC 1999; Freilich et al. 2001; Neely et al. 2001; Noss et al. 2001; Hall et al. 2002), any decision to "walk away" from a site that is highly vulnerable would require that goals for conservation targets found within that portfolio site be captured elsewhere. For example, conservation of the 45 priority sites alone would only protect 57 % of the biodiversity in Wyoming, and 61% (398 of 649) of the populations of sensitive species (H.C., unpublished data).

The approach used here was successful in building a GIS-based model which aggregated data from ecoregional plans and from other publicly available spatial datasets. It can be applied at any scale and in any region with a robustness and accuracy dependent upon data quality. Instead of using a single variable to drive priority selection, we used a multi-criteria approach derived from multiple sources. We are confident in the reliability of data used in the analysis given the scale of our analysis. However, these data sets were derived from a number of sources, some over five years in age. More recent datasets may improve the quality of predictions. We also recognize important data gaps that would impact the outcome of this analysis. For example, we have not included a measure of current grazing condition. Given the abundance of rangelands within Wyoming, this is clearly an important gap that should be filled.

Our analysis only considers cost as it relates to future threats. We recognize that most, if not all sites, are already degraded to some degree and there would likely be costs associated with ameliorating these impacts not considered in our cost analysis. However, the 45 priority sites have, by definition, the highest biodiversity (=highest landscape integrity) and we would expect a lower cost to conserve than if we attempted to protect or restore highly modified or fragmented lands. In addition, our costs include a mix of proactive and reactive approaches due to the nature of the conservation strategies likely to be applied. It is relatively straightforward for a conservation organization to prevent residential development through land acquisition or conservation easements. But, we currently have limited options to prevent oil and gas development or water development projects outright in a similar manner.

The long-term implications of prioritizing low-cost/low-vulnerability sites for conservation are intriguing. In the Western US, we might be able to conserve an entire basin through conservation easements on a few larges ranches at minimal cost long before they are at risk for subdivision. Ecologically, the consequences might be larger, more contiguous areas of protected land, rather than smaller disconnected parcels around suburban landscapes. Conservation of low-vulnerability sites doesn't necessarily preclude conservation of high-vulnerability sites. In fact, the conservation organization that the authors are affiliated with has made a strategic decision to do both. Conservation organizations might also find it necessary to do both to appeal to a donor's sense of urgency at addressing critical threats.

CONCLUSION

The field of conservation biology is increasingly recognizing the importance of conservation plans that will translate into more on-the-ground conservation (Balmford & Cowling 2006). During the implementation phase of conservation, the relevant social, economic and political constraints often dramatically modify scientific recommendations (e.g., Margules & Pressey 2000). An important challenge for conservation practitioners is to develop alternative recommendations that involve objective trade-off analyses of how much biodiversity is captured in each scenario (Freemark 1995). Because most conservation organizations have limited capacity, future work is needed to develop simple models for estimating the total cost of conservation. Our analysis uses a relatively simple GIS-based model for estimating cost of conservation. Being in a position to weigh the potential for future degradation facilitates planning in a way that incorporates more than just the elements of biodiversity (Lubchenco 1995). Such an approach to conservation planning promises better connections between science and the economic and political structure of conservation decision-making.

ACKNOWLEDGMENTS

We gratefully acknowledge J. Lillegraven and D. Knight for their thoughtful review and P. Hunker for assistance with land valuations.

LITERATURE CITED

American Rivers, Friends of the Earth, and Trout Unlimited. 1999. Dam removal success stories: restoring rivers through selective removal of dams that don't make sense. American Rivers, Washington, D.C.

Anderson, N. B., R. A. Beach, A. W. Gray, C. A. Roberts. 1990. Potential exploitable mineral areas in Wyoming including carbon dioxide, coal, geothermal resources, helium, oil and gas, oil shale, phosphate, sulfur, trona, base and precious metals, betonite, gypsum, limestone and zeolites. Department of Interior, U.S. Bureau of Mines, Denver, Colorado.

Ando, A., J. D. Camm, S. Polasky, and A. Solow. 1998. Species distributions, land values, and efficient conservation. Science 279:2126-2128.

Army Corps of Engineers. 2005. National inventory of dams. Available from http://crunch.tec.army.mil/nid/webpages/nid.cfm. Accessed September 2005

Babcock, B.A., P.G. Lakshminarayan, J.J. Wu, and D. Zilberman. 1997. Targeting tools for the purchase of environmental amenities. Land Economics 73(3):325-39.

Bailey, R. G. 1995. Description of the ecoregions of the United States. 2nd edition. U.S. Forest Service Miscellaneous Publication 1391.

Ball, I. R. and H. P. Possingham. 2000. MARXAN (V1.8.2): Marine reserve design using spatially explicit annealing, a manual.

Balmform, A. and R. M. Cowling. 2006. Fusion or failure? The future of conservation biology. Conservation Biology 20:692-695.

Braun, C. E., O. E. Oedekoven, and C. L. Aldridge. 2002. Oil and gas development in western North America: effects on sagebrush steppe avifauna with particular emphasis on sage-grouse. Transactions of the North American Wildlife and Natural Resources Conference 67, Wildlife Management Institute, Washington, D.C.

Davis, F. W., D. M. Stoms, J. E. Estes, and J. Scepan. 1990. An information systems approach to the preservation of biological diversity. International Journal of Geographical Information Systems 4:55-78.

Davis, F. W., D. M. Stoms, R. L. Church, W. J. Okin, and K. N. Johnson. 1996. Selecting biodiversity management areas. Pages 1503-1528 in Sierra Nevada Ecosystem Project: final report to Congress. Vol II. Assessments and scientific basis for management options. Wildlands Resource Center, University of California, Berkeley.

Frazee, S. R., R. M. Cowling, R. L. Pressey, J. K. Turpie, and N. Lindenberg. 2003. Estimating the costs of conserving a biodiversity hotspot: a case study of the Cape Floristic Region, South Africa. Biological Conservation 112:275-290.

Freemark, K. E. 1995. Assessing effects of agriculture on terrestrial wildlife: Developing a hierarchical approach for the U.S. EPA. Landscape and Urban Planning 31:99-115.

Freilich, J., B. Budd, T. Kohley, and B. Hayden. 2001. The Wyoming Basins ecoregional plan. TNC Wyoming Field Office, Lander, Wyoming.

Graf, W. L. (editor) 2003. Dam removal research: status and prospects. H. John Heinz III Center for Science, Economics and the Environment, Washington, D.C.

Groves, C. R. 2003. Drafting a conservation blueprint: a practioner's guide to planning for biodiversity. Island Press, Washington D.C.

Hall, J., H. Marriott, and J. Perot. 2002. Ecoregional conservation in the Black Hills. TNC Midwest Conservation Science Center, Minneapolis, Minnesota.

H. John Heinz III Center for Science, Economics and the Environment (CSEE). 2002. Dam removal: science and decision making. CSEE, Washington, D.C.

Kareiva, P. and M. Marvier. 2003. Conserving biodiversity coldspots. The American Scientist, July/August.

Keinath, D., B. Heidel, and G. Beauvais. 2003. Wyoming plant and animal species of concern. Wyoming Natural Diversity Database, University of Wyoming, Laramie, Wyoming.

Knight, D. 1994. Mountains and plains: the ecology of Wyoming landscapes. Yale University Press, Connecticut.

Knight, R. 1999. Private lands: the neglected geography. Conservation Biology 13:223-224.

Lawler, J. J., D. White, and L. L. Master. 2003. Integrating representation and vulnerability: two approaches for prioritizing areas for conservation. Ecological Applications 13:1762-1772.

Lubchenco, J. 1995. The role of science in formulating a biodiversity strategy. BioScience 45:S7-S9.

Malczewski, J. 1999. GIS and multicriteria decision analysis. Wiley and Sons, New York.

Margules, C. R., and R. L. Pressey. 2000. Systematic conservation planning. Nature 405:243-253.

Merrill, E.H., T.W. Kohley, M.E. Herdendorf, W.A. Reiners, K.L. Driese, R.W. Marrs, and S.H. Anderson. 1996. Wyoming gap analysis: a geographic analysis of biodiversity -- final report. University of Wyoming, Laramie, Wyoming.

Messer, K.D. 2006. The conservation benefits of cost-effective land acquisition: A case study in Maryland. Journal of Environmental Management 79(3): 305-315.

Myers, N., R. A. Mittermeier, C. G. Mittermeier, G. A. B. da Fonseca, and J. Kent. 2000. Biodiversity hotspots for conservation priorities. Nature 403:853-858.

Neely, B. P. Comer, C. Moritz, M. Lammert, R. Rondeau, C. Pague, G. Bell, H. Copeland, J. Humke, S. Spackman, T. Schultz, D. Theobald, and L. Valutis. 2001. Southern Rocky Mountains: an ecoregional assessment and conservation blueprint. TNC Colorado Field Office with support from the U.S. Forest Service, Rocky Mountain Region, Colorado Division of Wildlife, and Bureau of Land Management, Boulder, Colorado.

Newburn, D., S. Reed, P. Berck, and A. Merenlender. 2005. Economics and land-use changes in prioritizing private land conservation. Conservation Biology 19:1411-1420.

Noss, R. F., G. Wuerthner, K. Vance-Borland, and C. Carroll. 2001. A biological assessment for the Utah-Wyoming Rocky Mountains ecoregion: a report to The Nature Conservancy. Conservation Science, Corvallis, Oregon.

Noss, R. F., C. Carroll, K. Vance-Borland, and G. Wuerthner. 2002. A multicriteria assessment of the irreplaceability and vulnerability of sites in the greater Yellowstone ecosystem. Conservation Biology 16:895-908.

Olson, D. M., E. Dinerstein, E. D. Wikramanayake, N. D. Burgess, G. V. N. Powell, E. C. Underwood. 2001. Terrestrial ecoregions of the World: a new map of life on Earth. BioScience 51:933–938.

Pence, G. Q. K., M. A. Botha, and J. K. Turpie. 2003. Evaluating combinations of on- and off-reserve conservation strategies for the Agulhas Plain, South Africa: a financial perspective. Biological Conservation 112:253-273.

Polasky, S., J. D. Camm, B. Garber-Yonts. 2001. Selecting biological reserves cost-effectively: an application to terrestrial vertebrate conservation in Oregon. Land Economics. 77:68-78.

Polasky, S., E. Nelson, E. Lonsdorf, P. Fackler, A. Starfield. 2005. Conserving species in a working landscape: land use with biological and economic objectives. Ecological Applications 15:1387-1401.

Possingham, H. P., I. R. Ball and S. Andelman. 2000). Mathematical methods for identifying representative reserve networks. In: S. Ferson and M. Burgman (eds) Quantitative methods for conservation biology. Springer-Verlag, New York, pp. 291-305.

Prendergast, J. R., R. M. Quinn, and J. H. Lawton. 1999. The gaps between theory and practice in selecting nature reserves. Conservation Biology 13:484-492.

Sarukhan, J. 2006. Conservation biology: views from the ecological sciences. Conservation Biology 20:674-676.

Scott, J. M., F. W. Davis, R. G. McGhie, R. G. Wright, C. Groves, and J. Estes. 2001. Nature reserves: do they capture the full range of America's biological diversity? Ecological Applications 11:999-1007.

State of Wyoming, Economic Analysis Division. 2005. Population estimates and forecasts for Wyoming counties, cities, and towns for 2000-2020. Available from http://eadiv.state.wy.us/pop/pop.asp. Accessed September 2005.

Tarboton, W. R. 1997. Whither grasslands? Birds and Birding 2:149-153.

Theobald, D. M. 2003. Targeting conservation action through assessment of protection and exburban threats. Conservation Biology 17:1624-1637.

TU (Trout Unlimited). 2001. Small dam removal: a review of potential economic benefits. TU, Arlington, VA.

TNC (The Nature Conservancy). 1998. Ecoregion-based conservation in the central shortgrass prairie. TNC Colorado Field Office, Boulder, Colorado.

TNC (The Nature Conservancy). 1999. Ecoregional planning in the northern great plains steppe. TNC Montana Field Office, Helena, Montana.

TNC (The Nature Conservancy). 2000a. Conservation by design: A framework for mission success. TNC, Arlington, Virginia.

TNC (The Nature Conservancy). 2000b. The five-s framework for site conservation: a practitioner's handbook for site conservation planning and measuring success. 2nd edition. TNC, Arlington, Virginia.

U.S. Department of Transportation. 2006. Frequently asked questions. Available from http://primis.phmsa.dot.gov/pipelineInfo/faqs.htm#10 (accessed September 2005).

U.S. Geological Survey. 1995. Surface-water usage. Available from http://water.usgs.gov/watuse. Accessed March 2005.

Western Organization of Resource Councils. 2004. The need for stronger federal oil and gas bonding requirements. Available from: http://www.worc.org. Accessed September 2005.

Wilson, K., R. L. Pressey, A. Newton, M. Burgman, H. Possingham and C. Weston. 2005. Measuring and incorporating vulnerability into conservation planning. Environmental Management 35:527-543.

Wu, J.J., D. Zilberman, and B.A. Babcock. 2001. Environmental and distributional effects of conservation targeting strategies. Journal of Environmental Economics and Management 41:333-350.

Wyoming Department of Environmental Quality (WYDEQ). 2001. Mine permit database. WYDEQ, Cheyenne, Wyoming.

Wyoming Department of Environmental Quality (WYDEQ). 2005. Water quality monitoring database. WYDEQ, Lander, Wyoming.

Wyoming Oil and Gas Conservation Commission. 2005. Rules and regulations, chapter 3. Available from http://wogcc.state.wy.us. Accessed September 2005.

Wyoming State Water Plans. 2002. Statewide water resources data inventory. Available from: http://waterplan.state.wy.us. Accessed May 2005.