Global conservation priorities that maximize biodiversity return-on-investment

Jonathan M. Hoekstra[1], Bill Murdoch[2], Stephen Polasky[3], Hugh Possingham[4], Rebecca Shaw[5], and Kerrie Wilson[4]

[1]The Nature Conservancy, 1917 First Avenue, Seattle, WA 98101 USA. [2]Department of Ecology, Evolution and Marine Biology, University of California, Santa Barbara, CA 93106, USA. [3] Applied Economics & Ecology, Evolution and Behavior, University of Minnesota, St. Paul, MN 55108, USA. [4] The Ecology Centre, The University of Queensland, Brisbane QLD 4072, Australia. [5]The Nature Conservancy.

Conventional priority-setting approaches for conservation ignore the cost of conservation[1], yet cost considerations are essential if conservation investments are to be efficient [2]. One way to incorporate costs into conservation priority-setting is to apply return-on-investment (ROI) thinking. Here we identify global conservation priorities that maximize the number of plant species protected for a given investment budget. We use an ROI model that integrates data on species richness and estimates of management costs to determine optimal allocations of spending among 794 of the world's 825 terrestrial ecoregions. Comparison of the world's current protected area network to a cost-efficient network suggests that twice as much biodiversity could be protected for the same money if an ROI framework had been applied. For new investment budgets of $200 million to $10 billion that could be spent anywhere, we identify where and how much should be invested to add the greatest biodiversity value to the current protected area network. Cost-efficient global priorities add 13% more plant species for a $1 billion investment, and are distributed across every terrestrial biome and biogeographic realm, thus promoting greater ecological representativeness too. Investment in these global conservation priorities would yield biodiversity returns substantially greater than investments constrained to conventional priority places like hotspots[3] or crisis ecoregions[4]. This ROI approach facilitates dynamic revision of conservation priorities as ecological and economic conditions change, and can be adapted to maximize ROI for other taxa, within smaller geographies, or to account for practical constraints on where, when and how money can be spent.

Conservationists face difficult choices about where to invest limited resources. Habitat loss, unsustainable resource use, global climate change and myriad other anthropogenic forces combine to threaten a sixth mass extinction[5]. Yet three of the largest international conservation organizations -- The Nature Conservancy, World Wildlife Fund and Conservation International -- have combined annual revenues less than one-tenth those of the smallest company listed in the Fortune Global 500[6-9]. Faced with this disparity between needs and resources, it is essential that conservation organizations seek to maximize their "bang for the buck" or biodiversity return on conservation investments.

In setting global conservation priorities, conservation organizations seek to direct resources to the places that need them most. Over the past 20 years, conservation biologists have put forward a variety of approaches such as biodiversity hotspots[3], high biodiversity wilderness areas[10] , the Global 200 ecoregions[15], and crisis ecoregions[4].

Each of these selects a set of priority places based on explicit criteria like vulnerability or irreplaceability of biodiversity, but all ignore the cost of conservation[1].

Economic analyses suggest that ignoring costs can result in significant inefficiencies. Up to twice as many endangered species in the United States could be protected for the same level of investment[12]. Internationally, the same level of protection could be achieved for a fraction of the cost[13]assuming no constraints on where money can be spent on conservation.

One way to dramatically increase the cost-efficiency of conservation spending is to apply a simple return-on-investment (ROI) approach built around species-area curves that seeks to maximize the number of species represented in a protected area network for a given budget[2]. In this paper, we use such an approach to contrast the world's current protected area network against an optimally cost-efficient network, and to identify global conservation priorities where further investments would yield the largest marginal gains in biodiversity. We assume that money could be spent anywhere.

Our conservation objective in these analyses is to maximize the total number of plant species represented within the world's protected area network for some fixed total of management costs. We construct a model of conservation return-on-investment by combining a familiar species-area curve with an estimate of the cost per unit area of conservation management[14]. Our approach is based on a "species-investment" relationship that predicts the accumulation of species protected in an ecoregion as a function of the total amount of money spent on habitat protection:

$$S_i = b_i (x_i / c_i)^z , \tag{1}$$

where S_i is the number of species represented in ecoregion i, x_i is the amount of money invested in ecoregion i, b_i is the species-area constant in ecoregion i, and c_i is the management cost per unit area in ecoregion i, and z is the species-area exponent that we assume is the same for all regions (Figure 1).

The derivative of equation (1) with respect to spending (x_i) is the marginal rate of return-on-investment – the change in species protected per unit of additional spending in a region:

$$\frac{dS_i}{dx_i} = \frac{z \cdot b_i}{c_i^z} x_i^{(z-1)} . \tag{2}$$

The average ROI over all ecoregions is:

$$ROI = \sum_i S_i \Big/ \sum_i x_i . \tag{3}$$

We parameterized species-investment curves for 794 of the world's 825 terrestrial ecoregions[15] using plant species richness data[16] and estimates of annual costs of managing areas for biodiversity (see methods). We did not incorporate one-time acquisition costs into this analysis due to a lack of data. Such costs tend to be positively correlated with management costs but can be highly variable[17].

The "value," "cost," and realized ROI of the world's current protected area network were estimated by calculating the percent area of each ecoregion that has been designated as a protected area[18-20], substituting those data into equation (1) to estimate the number of plant species protected and annual management costs required, and summing over all ecoregions (Table 1). Only protected areas in IUCN categories I-IV were included in these calculations[21]. It is important to note that our species tallies do not account for duplication across ecoregions.

As benchmarks for comparison, we estimated the value, cost and expected ROI of two idealized protected area networks: a cost-efficient optimum in which protected areas were distributed to maximize the number of plant species protected for the same total management cost (about $20 billion), and an area-efficient optimum in which protected areas were distributed to maximize the number of plant species protected in the same total area (about 6 million sq. km) without regard to management costs (see methods).

Compared to the current configuration of the world's protected area network, an optimal allocation of conservation investments could have protected more than twice as many plant species for the same $20 billion commitment of management costs. Even an area-efficient strategy that focused only on maximizing the number of species protected would yield a larger ROI, though at a greater cost of $23 billion (Table 1, supplemental materials).

These comparisons suggest that future conservation investment could yield much larger biodiversity returns than have been realized in the past. To identify those opportunities, we used our approach to direct incremental investments of $200 million, $1 billion, $5 billion and $10 billion that maximize the number of additional plant species protected. For these analyses, annual management cost estimates were converted to an endowment cost, assuming a 5% discount rate (effectively multiplying by a factor of 20). Solutions were constrained such that current protected area coverage could not be diminished (see methods).

Larger increments of new investment achieve larger returns in terms of plant species represented and new areas protected (Table 2). However, average ROI declines from 201 spp/$MM on $200MM invested to 16 spp/$MM on $10 billion invested. Even though ROI diminishes as cumulative investment grows, investments up to about $5 billion yield returns greater than the realized world average to-date.

Larger increments of investment provide for new protected areas across a broader portfolio of ecoregions, and allocate greater sums to many individual ecoregions (Figure 2). A subtle but important feature of ROI-based priority-setting is that the *order* of investment does not necessarily coincide with the *amount* of investment in individual ecoregions. Early investments in small ecoregions or ecoregions with limited habitat still available for conservation may yield high initial returns that quickly diminish and are eclipsed by greater investment in larger ecoregions.

Global conservation priorities that maximize ROI are economically smart AND ecologically diverse. Even initial investments of $200MM would be distributed across all terrestrial biomes and biogeographic realms. The majority of spending is still directed to high-biodiversity ecoregions in the tropics, but "coldspots[22]" like tundra and boreal forest are also targeted for investment (see supplemental material). This happens because, all else equal, greatest returns are expected where existing protection is most limited. Thus, maximizing ROI offers the collateral benefit of increasing ecological representativeness of the world's protected area network, even though that was not an explicit objective.

Many of the ecoregions prioritized by this ROI analysis have also been flagged by conventional priority-setting analyses. Cost-efficient investments would target between one-quarter and one-third of biodiversity hotspots[3], high-biodiversity wilderness areas[10], global 200 ecoregions[11] and crisis ecoregions[4] (see supplemental materials). However, unlike prioritization analyses that omit cost considerations, our return-on-investment approach distinguishes those places where future investments are likely to yield the greatest conservation returns, and avoids places where the biodiversity may be significant, but expected returns are lower than could be achieved elsewhere. As a result, the return-on-investment in cost-efficient global priorities is projected to be from 50 to 100% greater than if investments were constrained to conventional priority places (Table 3, supplemental materials).

Cost-efficient priority-setting offers a dynamic tool for informing conservation investment decisions. Recommendations for where to invest are accompanied by recommendations about how much to invest, and are tailored to the total budget available. Furthermore, the models can be constrained to account for real-world limitations on where, when and how money can be spent. In this way, ROI analyses serve as practical tools without sacrificing analytical transparency and rigor. Prioritization recommendations can and *should* be revised to account for changing economic and ecological conditions such as changes in the cost of conservation, ongoing habitat loss, and the action of others to increase protected area coverage. Conventional analyses identify static priorities that do not change despite changing conservation conditions.

Our ROI model can also be adapted for different conservation objectives, smaller geographies, or even to different conservation strategies, each of which would lead to different prioritizations. The essential requirements are a clear objective that can be optimized, an appropriate model that links conservation investment to biodiversity returns with an appropriate functional form, and suitable cost and biodiversity data for parameterizing the model. Numerous elaborations and variations are then possible, for example to prioritize investment among different strategies as well as places[23], to account for species complementarity among ecoregions in the objective function[24], or to factor in considerations about ongoing habitat loss[2], investment risks or other uncertainties.

Conservationists often feel that they are trying to save the world on a shoestring budget. By accounting for costs explicitly with analyses like these, conservationists can better prioritize conservation opportunities around the world, and use their precious resources to maximize biodiversity return-on-investment.

Methods.

Model parameterization and input data. Species-area constants, b_i, were quantified by rearranging equation (1) and substituting total land area[15], and total plant species richness[16] for x_i/c_i and S_i, respectively. Management costs were estimated by country according to ref 17 as:

$$\log(\text{cost, \$-km}^{-2}\text{-y}^{-1}) = 1.61 + 0.57\log(GNI) - 0.70\log(PPP) - 0.46\log(area)$$

where GNI = Gross national income per unit area[25], and PPP = purchasing power parity[25]. We used a constant average protected area size of 160 km^2 (ref 18). Cost estimates for each ecoregion, c_i, were then calculated as area-weighted averages of national estimates. We assumed z=0.3 for all ecoregions based on central tendencies of field-derived estimates[14]. While the choice of this value is arbitrary, overall results of the analysis are insensitive to it. See supplemental materials for tables of model parameters and input data.

Optimization formulation. Cost-efficient investing seeks to allocate spending among ecoregions so as to maximize the total number of plant species protected for a fixed management budget. This optimum occurs when the marginal rate of return on any additional spending in each ecoregion is equalized (hence one could not improve the allocation by moving resources from one region to another). The logic of this solution is analogous to optimal foraging theory predictions of when animals should switch resources patches[26].

We thus formulated the optimization problem as seeking an allocation of spending in each ecoregion, x_i*, that

maximized $\sum_i S_i = b_i\left(x_i^*/c_i\right)^z$

subject to a total budget $\sum_i x_i^* \le budget$, and $0 \le x_i^* \le x_{im}$

where x_{im} is a maximum cap on possible investment. The latter constraint was imposed because habitat loss limits how much habitat can be protected in any given ecoregion. The maximum "conservable" area (and thus maximum investment) in each ecoregion was calculated as total ecoregion area minus converted area as estimated from summaries of global land cover data (after ref. 4). Optimal spending in each ecoregion was predicted by rearranging equation (2):

$$x_i^* = \left(\frac{R^* \cdot c_i^z}{z \cdot b_i} \right)^{\frac{1}{(z-1)}} \tag{4}$$

where R^* is the marginal rate of return across all regions at which the whole budget is spent, and any spending limits in individual ecoregions are satisfied. The species "value" of these investments were found by substituting x_i^* into equations (1) and (3) for every region.

Benchmark comparisons. The cost-efficient benchmark was determined by solving the optimization problem for a total budget of $19.9 billion. The area-efficient benchmark was determined by modifying the optimization problem to exclude the cost parameters, c_i, and solving for a total "budget" of 6 million hectares of protected area. Solutions are detailed in the supplemental materials.

New investment allocations. Optimal allocation of new conservation investments were determined by solving the optimization problem for a total budget of $19.9 billion plus the expected annual output of new investment endowments. We also stipulated that all existing protected areas are maintained by imposing an additional constraint that $x_i^* \geq x_{i0}$, where x_{i0} are the management costs associated with existing protected areas. Scenarios that constrain new investment to conventional priority places were similarly determined by further constraining $x_i^* = 0$ for all ecoregions, *i*, not among the conventional priority sets. Solutions are detailed in the supplemental materials.

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Supplementary Information accompanies the paper on **www.nature.com/nature**.

<ack> Style tag for the Acknowledgements, the Competing Interests statement and the Authors' Contributions statement.

Correspondence and requests for materials should be addressed to J. H. (jhoekstra@tnc.org).

Table 1. Current conservation return-on-investment could have been doubled.

Comparisons of value, cost, and average ROI of the world's current protected area network against two optimal benchmarks suggest that significantly greater cost-efficiencies are possible. The cost-effective benchmark optimizes allocation of protected areas to maximize the number of plant species that could be protected for the same total management cost. The area-efficient benchmark optimizes allocation of protected areas to maximize the number of plant species protected in the same total area without regard to management costs. Note that total numbers of species do not account for duplication among ecoregions as this requires species lists that are unavailable.

	VALUE		COST	ROI
	Plant species protected	Area protected	Annual management costs	Average return-on-investment
	(number)	(sq. km)	($billions US)	(Species/$MM)
Current protected area network	518,340	6,006,284	19.9	26.0
Cost-efficient optimum	1,054,026	17,882,320	19.9	52.9
Area-efficient optimum	911,330	6,006,284	23.0	39.6

Table 2. Expected return-on-investment of cost-efficient conservation spending.

New conservation investments of $200 million to $10 billion could protect a large number of additional plant species by endowing management of additional protected areas. Increments of new investment are scaled to approximate 1%, 5%, 25% and 50% of estimated annual costs for management of the current protected area network. Percentages are calculated relative to the total number of plant species protected and total land area in the world's current protected area network.

NEW INVESTMENT	VALUE ADDED				ROI
Management endowment	Plant species		Protected Areas		Average return-on-investment
	(occurrences)	(%)	(sq. km)	(%)	(Species/$MM)
$200 million	40,240	7.76%	19,218	0.32%	201
$1 billion	68,833	13.28%	81,246	1.35%	69
$5 billion	123,555	23.84%	337,639	5.62%	25
$10 billion	161,640	31.18%	663,863	11.05%	16

Table 3. Return-on-investment prioritization outperforms conventional conservation priorities.

The added value and expected ROI of $1 billion in new cost-efficient conservation investments are substantially greater than if those same investments were constrained to biodiversity hotspots, high-biodiversity wilderness areas, global 200 ecoregions, or crisis ecoregions. Percentages are calculated relative to the total number of plant species protected and total land area in the world's current protected area network.

PRIORITIZATION	VALUE ADDED				ROI
	Plant species (occurrences)	(%)	Protected Areas (sq. km)	(%)	Average return-on-investment (Species/$MM)
ROI priorities	68,833	13.28%	81,246	1.35%	69
Biodiversity hotspots[3]	47,383	9.14%	58,051	0.97%	47
High-biodiversity wilderness areas[10]	28,688	5.53%	106,699	1.78%	29
Global 200 Ecoregions[11]	48,941	9.44%	80,107	1.33%	49
Crisis Ecoregions[4]	35,533	6.86%	53,182	0.89%	36

Figure 1. Species-investment curves predict the cumulative and marginal biodiversity return-on-investment. Equations (1) and (2) specify the parameterization used in this analysis.

Figure 2. Prioritization of ecoregions for new conservation investments totalling \$200 million (a), \$1 billion (b), \$5 billion (c), and \$10 billion (d), respectively. Labels in (a) indicate first 25 ecoregions recommended for investment. Shading indicates the optimal amount of money to allocate to each ecoregion from each budget. Note that the order of investment does not necessarily coincide with the allocations recommend by our ROI model.

Figure 1

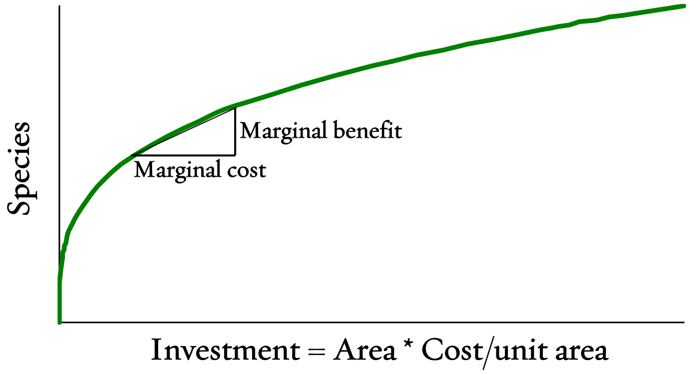
Species
Marginal benefit
Marginal cost
Investment = Area * Cost/unit area

Figure 2a

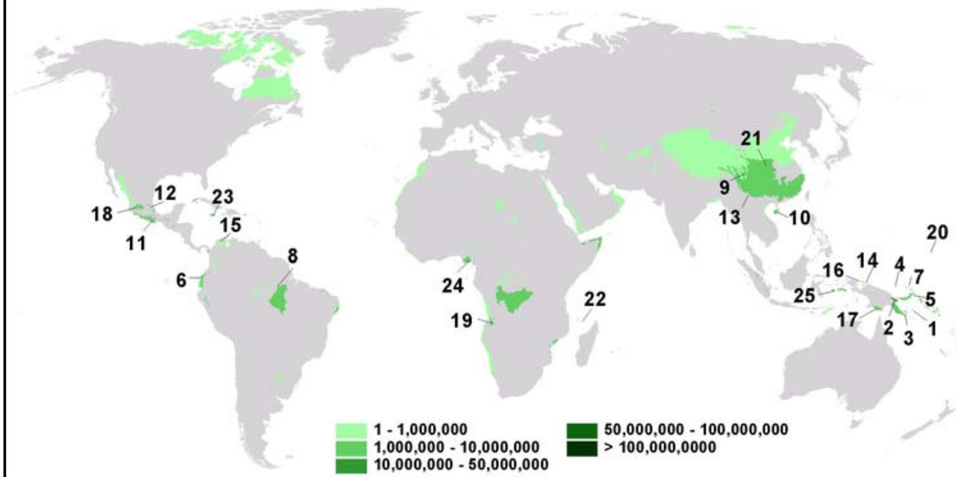

Figure 2b

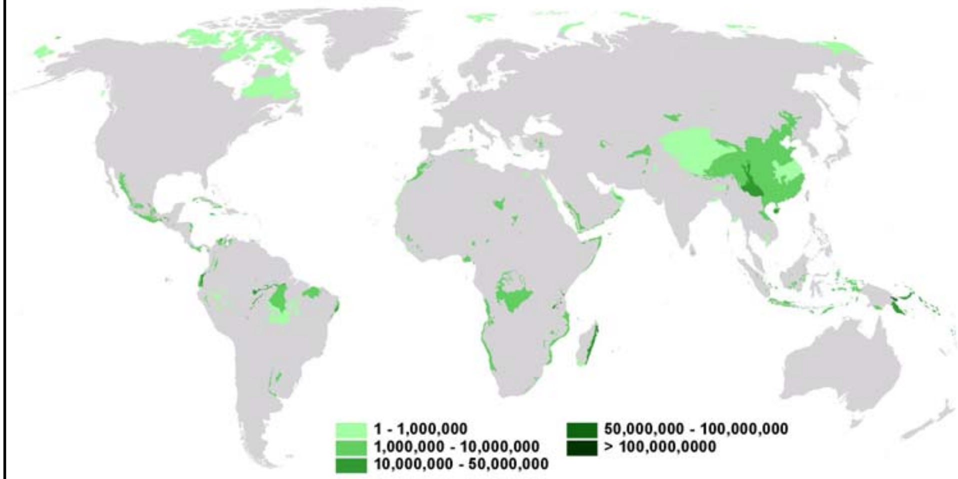

Figure 2c

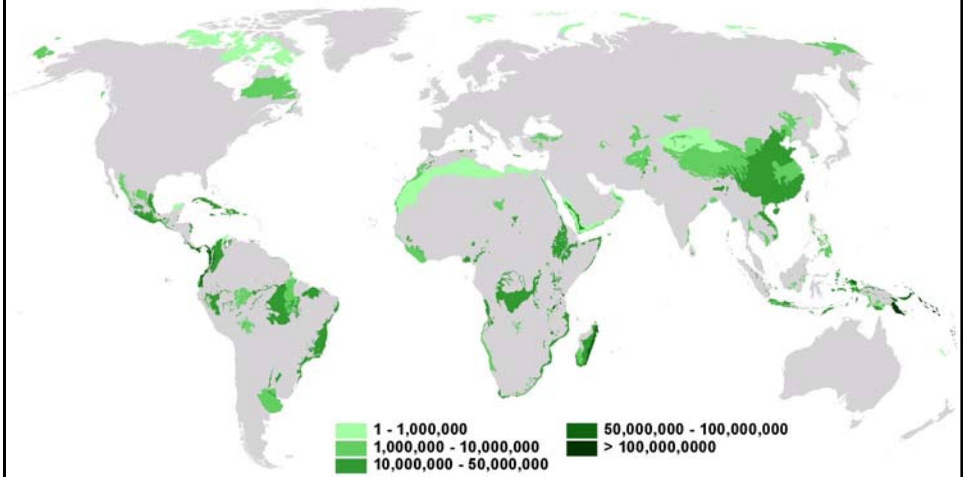

Figure 2d