LETTERS

Prioritizing global conservation efforts

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One of the most pressing issues facing the global conservation community is how to distribute limited resources between regions identified as priorities for biodiversity conservation[1–3]. Approaches such as biodiversity hotspots[4], endemic bird areas[5] and ecoregions[6] are used by international organizations to prioritize conservation efforts globally[7]. Although identifying priority regions is an important first step in solving this problem, it does not indicate how limited resources should be allocated between regions. Here we formulate how to allocate optimally conservation resources between regions identified as priorities for conservation—the 'conservation resource allocation problem'. Stochastic dynamic programming is used to find the optimal schedule of resource allocation for small problems but is intractable for large problems owing to the "curse of dimensionality"[8]. We identify two easy-to-use and easy-to-interpret heuristics that closely approximate the optimal solution. We also show the importance of both correctly formulating the problem and using information on how investment returns change through time. Our conservation resource allocation approach can be applied at any spatial scale. We demonstrate the approach with an example of optimal resource allocation among five priority regions in Wallacea and Sundaland, the transition zone between Asia and Australasia.

Conservation organizations allocate resources to areas that have been identified as priorities for conservation investment[3,7]. These priority regions are identified using information on relative biodiversity values, past or present threats to these values, and current levels of protection[9]. Species richness, or endemic species richness, is typically used to estimate the biodiversity value of a region[10]. The relative cost of conservation in different regions is ignored in the identification of priority regions despite evidence that its inclusion improves the cost-effectiveness of conservation prioritization[11–15].

Some international organizations rank these regions in terms of their priority for funding, but the approaches used to derive these rankings are not solutions of a properly formulated problem[4,6,16]. If the objective is to maximize the total number of species conserved, then this objective is unlikely to be achieved if regions are prioritized only on the basis of species richness. This is because regions that are highly threatened but marginally less species-rich may lose many species before being considered for conservation investment. Likewise, if the relative cost of investing in different regions is not taken into account, resources may be directed to expensive regions when the same amount of resources might have conserved more species if invested in regions with lower land-acquisition and management costs. The efficient allocation of conservation resources will be achieved only if the problem includes data on biodiversity, threat and cost, and is rigorously formulated.

Allocation of conservation resources, like any problem in decision theory, requires a broad goal, a specific objective, a set of constraints, a set of possible actions that form a strategy, and an understanding of the system dynamics provided by equations that link the actions and constraints to the objective[1] (see Methods). Here, the goal is to maximize biodiversity conservation through the creation of reserves, given ongoing habitat destruction and the constraint of a fixed budget. The best strategy—how much money to spend in each region each year—depends on endemic species richness, forest conversion rates (and the uncertainty associated with these rates), land cost and initial conditions (area of land currently reserved, converted or otherwise; see Table 1 and Supplementary Table). This decision theoretic formulation provides an explicit and transparent statement of the problem, which addresses the essential features of conservation resource allocation: biodiversity values, threats, costs, investment returns and data uncertainty.

We find an optimal resource allocation schedule using stochastic dynamic programming (SDP)[8,17]. The SDP algorithm finds the optimal allocation decision each year given the current state of the system and possible events in the future[17]. Applying SDP to problems with more than a few regions is computationally intractable, so we investigate whether myopic heuristics ('rules of thumb' that look only one time-step ahead) can approximate the optimal solution. The two heuristics that we propose as approximations are 'maximize short-term gain' and 'minimize short-term loss' (see Methods). We compare the performance of these heuristics to priority setting approaches based on simple rankings, using a case study from Southeast Asia.

To illustrate our conservation resource allocation approach, we first compare the allocation of resources between two regions,

Table 1 | Biodiversity, threat and cost data for the five priority regions

Priority region	Area (km^2)	Forested area (km^2) in 1997	Reserved area (km^2) in 2003	No. of endemic bird species		Conversion rate (% yr^{-1})		Cost (US$ km^{-2})	
				Actual	Rank	Actual	Rank	Actual	Rank
Sumatra	475,746	164,303	84,901	18	4	2.3	2	95	2
Borneo	735,372	426,975	173,989	29	2	2.1	3	110	3
Sulawesi	187,530	79,509	68,150	67	1	2.4	1	76	1
Java/Bali	138,787	19,464	8,770	24	3	1.7	4	782	4
Southern peninsular Malaysia	131,598	58,500	29,221	4	5	1.2	5	2,746	5

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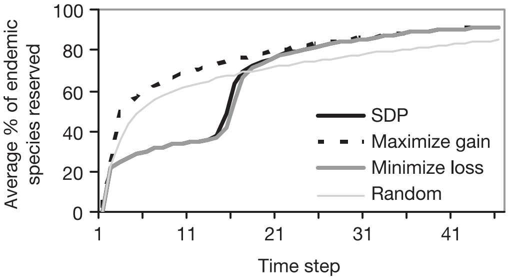

Figure 1 | Proportion of endemic species reserved through time in Borneo and Sumatra. The average proportion is calculated by four different resource allocation approaches: SDP, maximizing short-term gain, minimizing short-term loss, and random allocation between regions. The annual budget is US$ 1 million and assumes no pre-existing reserves. The minimize short-term loss heuristic most closely approximates the optimal SDP solution; however, the maximize short-term gain heuristic results in the greatest number of endemic species reserved at early time steps.

Borneo and Sumatra, using the parameters in Table 1. We find that the optimal schedule is to allocate all resources to Sumatra for over a decade. Once all species occurring in Sumatra are conserved, investment is scheduled for Borneo. For this initial case study, the heuristic that minimizes short-term loss most closely approximates the optimal solution (Fig. 1). However, if there is uncertainty regarding our ability to invest in a region for the whole planning period, for example if funding ceases unexpectedly, then maximizing short-term gains is likely to result in the greatest number of species conserved. When we modify the problem to include a random probability of investment ceasing, the optimal allocation schedule more closely reflects the heuristic that maximizes short-term gain. The heuristic that maximizes short-term gain allocates funding to both regions simultaneously, in proportion to the marginal returns from investment (Fig. 2).

To explore the sensitivity of our results to the parameters, we assess each approach using different combinations of relative threat and relative endemic species richness for two hypothetical regions. Both heuristics perform well, but the heuristic that minimizes short-term loss is most similar to the optimal SDP solution and outperforms the other heuristic for most parameter sets (Fig. 3). The heuristic that maximizes short-term gain performs best when the threat levels of the two regions are similar, and performs poorly when the regions have very different threat levels but similar endemic species richness (Fig. 3a). The heuristic that minimizes short-term loss performs slightly worse than the optimal solution when both the relative level of threat and the endemic species richness of the two regions are very similar (Fig. 3b). If the annual budget is increased, land parcels are reserved at a faster rate. This mitigates forest conversion and, consequently, the difference between the approaches in the number of species conserved is reduced. When the relative cost of land acquisition in each region is varied, the results are similar to those in Fig. 3 once the axes are adjusted to a species gain per dollar basis.

We next evaluate the performance of the heuristic algorithms, which we have shown to be close to optimal, for five priority regions from Southeast Asia. We compare the results of the algorithms with rankings based on endemic species richness, threat and cost (Table 1 and Fig. 4). This case study is used to illustrate our resource allocation approach, which can be applied to any number of priority regions for which a schedule for resource allocation is required. The approach can also be applied at any spatial scale, from global level problems to those at a local level. Our decision theory approach recommends initially investing all resources in Sulawesi and no other place until all the species occurring in Sulawesi are conserved. Only after this should investment proceed in Sumatra, Borneo and Java. After investment in Sulawesi ceases, the heuristic that maximizes short-term gain recommends roughly equal investment in Sumatra, Borneo and Java, and investment is scheduled last for Malaysia (Fig. 4a).

By contrast, ranking the five regions based on individual criteria does not provide an obvious schedule for resource allocation (Table 1). The three ranking criteria suggest that Sulawesi is the highest priority for conservation investment and Malaysia is the lowest. On the basis of only endemic bird richness, the rankings would recommend that investment should occur first in Sulawesi, second in Borneo, third in Java, fourth in Sumatra, and last in Malaysia. Although these simple rankings are not widely different from the results of our decision theory approach, there are discrepancies, which would occur more frequently for problems involving more regions. In addition, these rankings do not indicate the fraction of funds to allocate between the regions (nor whether funds should be allocated totally to a particular region or distributed between them). For example, the rankings could mean that investment should be directed towards Sulawesi until its species are conserved or, alternatively, that investments should be in proportion to the relative number of endemic species occurring in these regions. It is also not clear how these criteria should be combined to provide an allocation schedule that will maximize the protection of biodiversity. For example, if priority is determined only by endemic species richness, ignoring cost and threat, then Borneo's priority is overestimated. Similar confusion can arise if we prioritize only on threat or cost.

We have formulated the conservation resource allocation problem in a clear and transparent manner that involves defining an objective, identifying management actions, acknowledging constraints and incorporating uncertainty. Our problem formulation has five main simplifications. First, we have not accounted for the spatial variability within the priority regions and, consequently, the particular parcels where resources should be allocated are not identified. Second, our economic model is very simple. Third, we have not accounted for the temporally heterogeneous nature of land availability for reservation[18]. Fourth, we have used endemic bird species as a surrogate for biodiversity and assumed that numbers of endemic species reserved

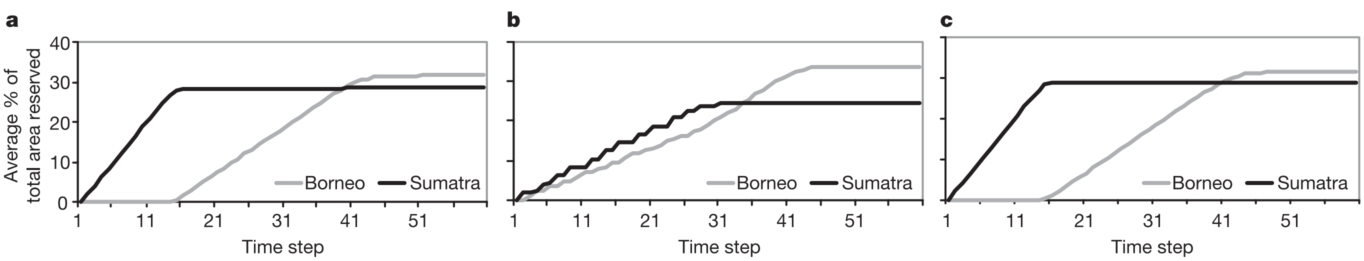

Figure 2 | Proportion of the total area of Borneo and Sumatra reserved through time. The average proportion of the total area reserved is calculated by three different resource allocation approaches. **a**, SDP. **b**, The heuristic that maximizes short-term gain. **c**, The heuristic that minimizes short-term loss. The annual budget is US$ 1 million and assumes no pre-existing reserves. The approach that maximizes short-term gain tends to allocate resources to both regions simultaneously, whereas the other, slightly superior, approaches allocate sequentially between regions.

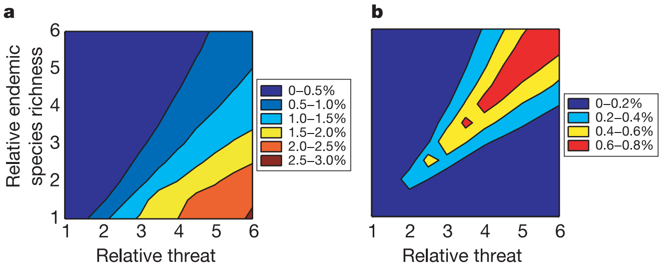

Figure 3 | Comparison of conservation performance of heuristic algorithms to the optimal solution. Two hypothetical regions are compared that differ in relative threat and number of endemic species. The performance of each heuristic is the percentage of endemic species not reserved relative to the optimum solution. **a**, Performance of the heuristic that maximizes short-term gain as compared with the optimal SDP solution. **b**, Performance of the heuristic that minimizes short-term loss as compared with the optimal SDP solution. The heuristic that minimizes short-term loss outperforms the heuristic that maximizes short-term gain for most parameter sets.

follows a species–area relationship. Last, we have assumed that the amount of resources invested in a region is directly proportional to the probability of species persisting. These assumptions can be relaxed within the framework that we present.

There is a need for computationally feasible and understandable algorithms that can deliver near-optimal solutions for large conservation resource allocation problems. The simple heuristics that we explore were developed to solve a properly formulated problem, perform surprisingly well relative to the optimal SDP solution, and are superior to simple ranking approaches. Minimizing short-term loss most closely approximates the optimal allocation schedule and maximizing short-term gain is close to optimal despite ignoring threat, although it underperforms if threat levels are very different. Under extreme uncertainty, maximizing short-term gain is the most risk-averse approach as it provides a buffer against an uncertain investment future.

We recommend that conservation organizations maximize short-term gain, unless the regions of concern have similar endemic species richness and very different levels of threat. In such circumstances,

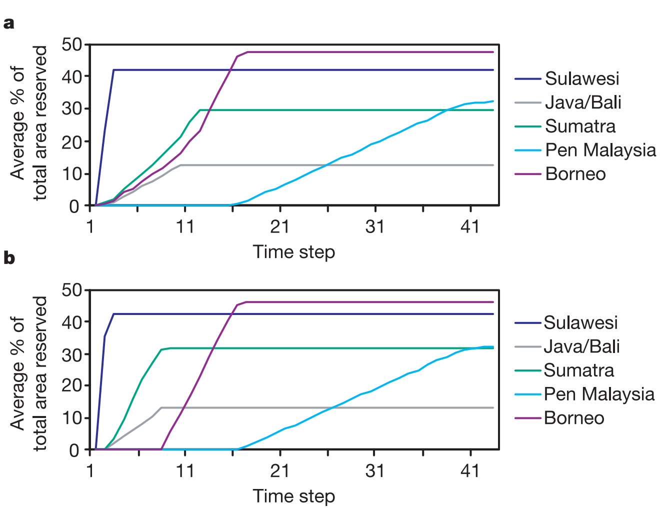

Figure 4 | Proportion of five priority regions from Southeast Asia reserved through time. The average proportion of the total area reserved is determined using two resource allocation heuristics. **a**, Heuristic that maximizes short-term gain. **b**, Heuristic that minimizes short-term loss. The annual budget is US$ 1 million and assumes no pre-existing reserves. In both cases resources are initially allocated completely to Sulawesi and investment is directed to southern peninsular Malaysia only after investment has occurred in Sumatra, Java/Bali and Borneo.

resource allocation should minimize short-term loss. We argue that conservation investments should be evaluated as any investment is evaluated: that is, with a clearly defined objective and an assessment of how well the returns from the investment meet this objective. Responsible conservation organizations and international agencies should consider embracing a decision theoretic approach when scheduling the allocation of conservation resources.

METHODS

The first step in formulating the conservation resource allocation problem is to define a quantifiable objective. Our objective is to maximize the number of endemic species remaining across all regions when habitat conversion ceases because there is no unreserved or unconverted land (see Supplementary Methods 'Problem formulation'). We assume that, for each region, the number of endemic species conserved per unit area is a monotonically decreasing function of the area reserved. Therefore, our conservation returns in each region diminish with increasing investment. We model this relationship using a species–area curve[19–21] (see Supplementary Methods (ii)). In principle, any relationship between area and endemic species conserved could be used. The next step in formulating the problem is determining what actions are possible, in this case what fraction of the budget to allocate to each region each year. Our decisions are thus constrained by a fixed annual budget. Although we recognize that funds for conservation can be directed towards many kinds of activity (for example, restoration programs, the purchase of forestry concessions and species recovery programs), we focus on the acquisition of land for reservation. We assume that each land parcel can be classified as reserved, available for reservation or converted (anthropogenically altered and assumed no longer suitable habitat for the endemic species of the region). Threat is modelled by assuming that a constant proportion of available parcels in each region are converted each year. To incorporate the uncertainty associated with parcel loss[22–24] (see Supplementary Methods (iii)), conversion is represented as a stochastic process with a binomial distribution. We estimate the cost of reservation in each region using statistical models[12,25] (see Supplementary Methods (iv)).

We use SDP and two myopic heuristics to determine how many parcels to reserve in each region each year. We compare these results to a random acquisition process. Once the optimal solution is obtained, we forward-simulate the resulting acquisition schedule 10,000 times for each parameter set to calculate the expected number of species conserved. The solutions found using SDP are optimal in the face of uncertainty[18,26–28]. Owing to an exponentially increasing state space, however, 'the curse of dimensionality' limits SDP to problems with few regions. The maximize short-term gain heuristic selects parcels for reservation that result in the greatest increase in the number of endemic species conserved. This heuristic ignores threat and is myopic, considering only the short-term future when selecting the next parcel to reserve and not all possible futures as the SDP algorithm does. The minimize short-term loss heuristic is also myopic: it selects parcels that will minimize the expected loss of species from the system in the next time step (see Supplementary Methods (i)).

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Supplementary Information is linked to the online version of the paper at www.nature.com/nature.

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