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Efficiently targeting resources to deter illegal activities in protected areas

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Summary

1. In many countries, areas delineated for conservation purposes can only achieve their objectives if effective law enforcement occurs within them. However, there is no method currently available to allocate law enforcement effort in a way that protects species and habitats in a cost-effective manner. Law enforcement is expensive and effort is usually concentrated near the locations of patrol stations where rangers are based. This hampers effective conservation, particularly in large protected areas, or regions with limited enforcement capacity.
2. Using the spatial planning tool Marxan, we demonstrate a method for prioritizing law enforcement in a globally important conservation landscape (the Greater Virunga Landscape, GVL, in central Africa) using data on the spatial distribution of illegal activities and conservation features within the landscape.
3. Our analysis of current patrol data shows that law enforcement activity is inadequate with only 22% of the landscape being effectively patrolled and most of this activity occurring within 3 km of a patrol post. We show that the current patrol effort does not deter illegal activities beyond this distance.
4. We discover that when we account for the costs of effective patrolling and set targets for covering key species populations and habitats, we can reduce the costs of meeting all conservation targets in the landscape by 63%, to \$2·2–3·0 million USD, relative to the cost of patrolling the entire landscape. This cost is well within the current expenditure of approximately \$5·9 million USD for the GVL but would better target effort from both patrol posts and mobile patrol units in the landscape.
5. *Synthesis and applications*. Our results demonstrate a method that can be used to plan enforcement patrolling, resulting in more cost-efficient prevention of illegal activities in a way that is targeted at halting declines in species of conservation concern.

Key-words: costing ranger patrols, law enforcement effectiveness, Marxan, planning patrol effort, threats mapping

Introduction

The primary threats to vertebrates in tropical countries are loss of habitat and overharvesting (Robinson & Bennett 2004; Hillborn *et al*. 2006; Fa & Brown 2009; Tranquilli *et al*. 2012), with the main strategies used to conserve such species being the creation of protected areas and law enforcement to ensure that these areas are well protected (Pfeifer *et al*. 2012). Studies assessing the efficacy of conservation methods regularly identify effective law enforcement as a key factor in the conservation of large mammals in particular (Bruner *et al*. 2001; Hillborn *et al*. 2006; Craigie, Baillie & Balmford 2010; Tranquilli *et al*. 2012). Where there is poor law enforcement, biodiversity can rapidly

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diminish (Peres & & Terborgh 1995). As a result, effective law enforcement is paramount for effective conservation, particularly in countries where poverty is high amongst rural populations and there is potential to increase income through illegal activities (Jachmann 1998; Rowcliffe, de Merode & Cowlinshaw 2004).

Research on law enforcement has primarily focused on monitoring law enforcement effort in relation to the levels of illegal activities (Leader-Williams, Albon & Berry 1990; Jachmann & Billiouw 1997; Jachmann 1998), measuring the impacts of increasing patrol effort or penalties (Leader-Williams & Albon 1988; Leader-Williams, Albon & Berry 1990; Milner-Gulland & Leader-Williams 1992; Hofer *et al.* 2000) and assessing the numbers of rangers per unit area or budget needed to minimize illegal activities, at least to a level where conservation objectives are not greatly impacted (Leader-Williams, Albon & Berry 1990; Jachmann & Billiouw 1997; Jachmann 1998, 2008). More recently, law enforcement research has begun to be used to assess the management effectiveness of protected areas (Jachmann 2008), the links between protected area performance and tourism (Jachmann *et al.* 2011) and the incentives that can be used to encourage compliance with wildlife laws (Keane *et al.* 2008). These studies suggest that the best way to improve law enforcement is to increase the probability of detecting illegal activities, particularly identifying the people involved and penalizing them (Milner-Gulland & Leader-Williams 1992; Arcese, Hando & Campbell 1995). While ‘catching the crook’ is an intuitive way to overcome illegal activities, rarely has the spatial nature of illegal activities and how this affects law enforcement strategies in conservation been assessed. One study from the Serengeti concluded that mapping where poaching activity is likely to occur was an effective way of proactively identifying where enforcement activities should be targeted (Campbell & Hofer 1995; Hofer *et al.* 2000). Another study used predictions of where deforestation was most likely to occur to target law enforcement effort (Linkie, Rood & Smith 2010).

Here, we develop and test a method to determine where law enforcement activities could be targeted to ensure the long-term viability of conservation features within a landscape of protected areas. We use the decision support software Marxan (Game & Grantham 2008; Ball, Possingham & Watts 2009) to minimize the costs of conserving viable populations of key species and a representative sample of habitats, given the variable costs of law enforcement and expected poaching threats at different sites. Using examples from the Greater Virunga Landscape (GVL), a region of exceptional vertebrate diversity (Plumptre *et al.* 2007), we show how the method can be used in a real situation to allocate ranger patrol effort spatially.

Materials and methods

We identified where to target law enforcement effort by (i) determining the distribution of conservation features (key species and habitats), (ii) determining the distribution of threats, (iii) identifying current patrol effort, (iv) estimating the cost of patrolling effectively, (v) conducting a spatial prioritization that minimizes the cost of patrolling and maximizes the averted reduction in abundance of hunted species and (vi) measuring the reduction in costs achieved by focusing patrolling effort in areas of high threat. Using this method, we assessed the effectiveness of patrols operating from patrol posts, mobile patrols operating from park headquarters or a combination of both methods, and the effect of changing patrol post location to increase management efficiency in the GVL.

STUDY AREA

The GVL encompasses many habitats, ranging in altitude from 600 to 5100 m above sea level. Twelve contiguous protected areas totalling 13 800 km^2 make up the landscape and we mapped the major vegetation types across each protected area using aerial photography from 2006, coupled with high-resolution satellite imagery for areas where cloud cover was high at the time the photographs were being acquired (Fig. 1). At least 1409 terrestrial vertebrates (mammals, birds, amphibians and reptiles) are known from the landscape and 3755 plant species with probably at least another 100 fish species. Of these, 100 terrestrial vertebrate species are endemic to the Albertine Rift and 56 terrestrial vertebrate species are globally threatened (Plumptre *et al.* 2007). Many of these species can be effectively conserved by maintaining

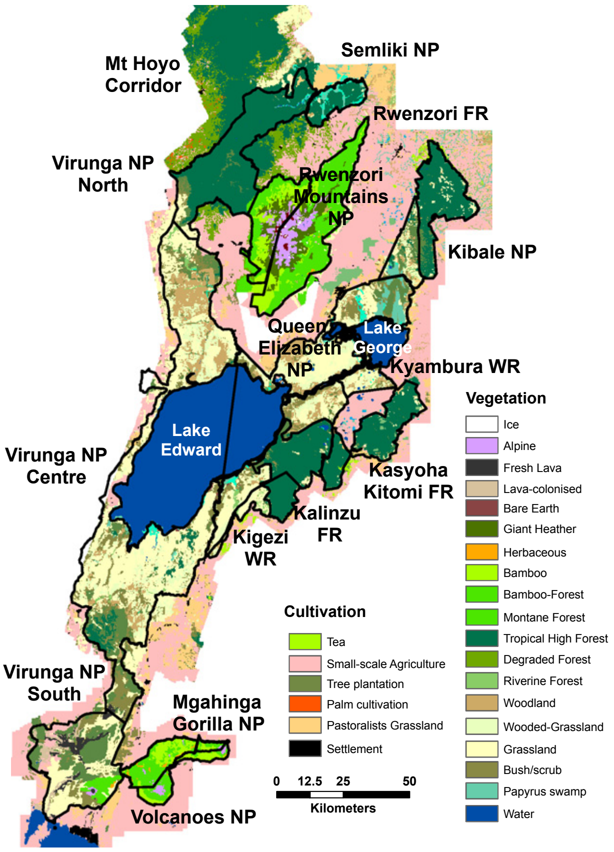

Fig. 1. Vegetation map of the Greater Virunga Landscape created from classifying 250 × 250 m cells across the landscape using aerial photographs and high-resolution satellite imagery. NP, National Park; WR, Wildlife Reserve; FR, Forest Reserve.

the condition and extent of habitat that already exists. Here, we focus our attention on a relatively small set of wide-ranging species likely to be most affected by illegal activities – 'landscape species' (Appendix S1 in Supporting Information) – while using the major vegetation types across the region as surrogates for biodiversity more broadly.

Each of the protected areas in the landscape contains permanent patrol posts from which rangers move to tackle illegal activities, sometimes making multiday patrols (camping at night) to cover areas further from the post. At some sites, mobile patrols also are used to patrol the protected areas. These patrol rangers are based at a park headquarters, or major substations, and travel by vehicle to sites where they are dropped to undertake foot patrols. The main illegal activities the patrols are trying to locate include: snaring for large ungulates, armed poaching of large mammals, pitsawing for timber, harvesting non-timber forest products, harvesting bamboo poles, charcoal kilns, grazing of domestic livestock in the park, encroachment for cultivation and mining (for gold). The aims of the patrols are not just to locate such activities but to also apprehend the perpetrators and, where appropriate, halt the activity.

DATA ON SPECIES AND THREATS

We collated data on the distribution of landscape species, illegal activities and ranger patrols from a variety of sources. Species sightings data and geolocation information on illegal activities were retrieved from the ranger-based monitoring system within each protected area, which also pinpoints the position of ranger parties every 30 min during patrols (Stokes 2010). We obtained these patrol data from the Uganda Wildlife Authority (UWA) and the Congolese Wildlife Authority Institut Congolais pour la Conservation de la Nature (ICCN) for protected areas in those countries, but did not obtain data from the Rwanda Development Board for Volcanoes park. Additional species and threats data from ground surveys made by UWA were used for Kibale National Park from a survey made in 2005 (Wanyama *et al.* 2010), and species data from aerial surveys of the savannas of the GVL in 2010 were obtained from UWA, ICCN and WCS where total counts of elephant and buffalo were made and GPS positions taken for all herds sighted. Geolocation records of sightings of animals, their signs (e.g. dung, nests) and illegal activities from surveys of large mammals and birds were obtained from the Wildlife Conservation Society Albertine Rift Program's survey data from 1999 to the present (reports available on www.albertine-rift.org). These surveys aimed to visit as much of each forest as possible using a combination of transect and reconnaissance walks.

We used the 56 877 species point locations derived from the above data sets to construct models of the distribution of each species across the GVL. The species modelled included all of the landscape species apart from lappet-faced vulture and Rwenzori duiker because of insufficient data for these species. Instead, we modelled white-backed vulture *Gyps africanus*, which is impacted by many of the same threats as the lappet-faced vulture. The Rwenzori duiker is confined to alpine and subalpine habitat in the Rwenzori massif, and we believe it is captured by conserving this habitat.

MODELLING SPECIES DISTRIBUTIONS

Maxent (Phillips, Anderson & Schapire 2006) was used to model the species distributions as it has been found to be one of the better modelling software packages for presence-only data (Elith *et al.* 2006, 2011). Maxent has been criticized recently for its calculation of an index of habitat suitability rather than a probability of occurrence (Yakulic *et al.* 2013; Fitzpatrick, Gotelli & Ellison 2013). We considered using Maxlike (Royle *et al.* 2012) as an alternative package as this estimates the probability of occurrence from presence-only data. However, unlike Maxent, Maxlike requires randomly sampled data and does not incorporate correction options that can deal with bias (Kramer-Schadt *et al.* 2013). Maxlike in turn has also received some criticism in that it makes assumptions that may not be true in nature (Hastie & Fithian 2013). Given this, we opted to use Maxent and used a bias layer comprising all sampled locations for the pseudoabsence points to correct for the biased sampling (Royle *et al.* 2012; Kramer-Schadt *et al.* 2013).

The environmental variables used to build the distribution models are described in Table 1, and all data were mapped at 250-m resolution. Maxent compares the locations of the sightings with 10 000 points drawn randomly from the whole landscape to estimate relationships between the species and environmental variables (Table 1). Tenfold cross-validation was used to test model performance, which runs the model on each 10% of the data to obtain an average model. We used area under the receiver-operating characteristic curve as a measure of the performance of the models (Phillips, Dudik & Schapire 2004; Phillips, Anderson & Schapire 2006).

We estimated the population size for each species in each grid cell using the habitat suitability indices derived from Maxent coupled with landscape population estimates derived from aerial and ground surveys (UWA and WCS, unpublished data). We assumed that the abundance of each species in each pixel increases with predicted habitat suitability from the Maxent models, and scaled the abundance estimates within each pixel such that they summed to equal our independently derived total population estimate for each species across the entire landscape. Although the outputs from Maxent do not represent probabilities of occurrence, they do represent modelled habitat suitability, and as such should scale positively with occupancy, albeit with this relationship breaking down at high habitat suitability values. Consequently, variations on exactly how this is calculated would be unlikely to drive major differences in the results of the spatial prioritization. Targets for conservation of each species were then set for Marxan based on the estimated population size of each species (see below).

MODELLING THREAT DISTRIBUTION

We modelled the distribution of illegal activities in Maxent using the georeferenced locations of nine illegal activities collected from ranger patrols and surveys: snares (n = 6220), carcasses killed by poachers, poachers camps and gunshot fire with guards (n = 3588), timber harvesting (n = 1232), charcoal making (n = 2712), non-timber forest product (NTFP) collection (n = 3576), bamboo collection (n = 284), cultivation (n = 2963), grazing of livestock (n = 1286) and mining activities (n = 90). Care was taken to select the predictor variables that might plausibly affect illegal activities rather than entering all of them. A map of all human threats was made by summing the Maxent index probability in a cell across each of the nine illegal activities modelled. We took a parsimonious approached and simply summed these to give an index of intensity of threat in each cell.

Table 1. Environmental variables used in the species distribution modelling

Category	Variable
Land cover	Vegetation type: classification from aerial photographs and high-resolution satellite imagery (Fig. 1)
Climate	Rainfall: annual rainfall data from 39 rain gauges across the landscape (measured mainly in the 1960s–1970s) were extrapolated to the landscape using a kriging method
SRTM data	Elevation: mean elevation within each grid cell using 30-m SRTM data (http://srtm.usgs.gov/index.php)
	Slope: – mean slope within each grid cell using 30-m SRTM data (http://srtm.usgs.gov/index.php)
Soil	Soil type: classification from the FAO soil map for Africa downscaled to a 250-m resolution (Source: http://www.grid.unep.ch/data/summary.php?dataid = GNV7&category = lithosphere&dataurl)
Human impacts	Distance from roads: distance between the centroid of each grid cell and the nearest road using road data from the Global GIS Database: Africa (http://www.agiweb.org/pubs/pubdetail.html?item = 624102)
	Distance to edge of protected area: distance between the centroid of each grid cell and the edge of the protected area
	Distance from human settlement: distance between the centroid of each grid cell and the nearest village or other settlement
	Distance from river: distance between the centroid of each grid cell and the nearest permanent river using the Global GIS Database: Africa (http://www.agiweb.org/pubs/pubdetail.html?item = 624102)
	Distance from patrol posts: distance between the centroid of each grid cell and the nearest patrol post using collated data from several sources (see Materials and methods)
	Fire frequency: the number of fires in each grid cell between 2000 and 2009 calculated from burn scars digitized in each dry season (Plumptre *et al.* 2010).
Masks	Agricultural lands: the land cover map was used to identify agricultural lands, which were excluded from the distribution models and projections
	Bias grid: as the input data were biased in the way they were collected (e.g. ranger-based data have more observations near patrol posts than further away), we classified each pixel according to sampling effort (5 = high sample effort to 1 = low sample effort) using quintile ranges across all records for all species and illegal activities. We included this bias grid in the Maxent analysis

ANALYSING CURRENT PATROL EFFORT

While on patrol, rangers take a GPS position every 30 min if they have not sighted anything and so the position locations together with observation of species and illegal activities give a good measure of where the patrol has been. For each park, we assessed the number of GPS positions points taken at 1-km distances from the patrol posts to calculate the percentage of patrol effort at 1-km distances from the patrol posts. We also separated the sightings of illegal activities from the position points and species sightings and compared how the abundance of illegal activities changes with distance from patrol post when corrected for patrol effort. Using data on patrol costs per post, we calculated the current allocation of patrol budgets per square kilometre in relation to patrol posts. This analysis assumes that detection of illegal activities does not change with distance to base or patrol location (see Keane, Jones & Milner-Gulland 2011).

TARGETING LAW ENFORCEMENT INTERVENTIONS

Conservation planning tools are often used to identify where to place new protected areas, but they can be used to allocate any conservation investment spatially (Possingham, Ball & Andelman 2000; Moilanen, Wilson & Possingham 2009). Here, we develop a conservation planning approach to identify where to target law enforcement interventions to protect species and habitats at minimum cost. We explore the allocation of law enforcement effort across the GVL using Marxan as a tool to identify spatially where costs will be minimized while achieving the conservation of target species and habitat. There are three main ways in which law enforcement patrolling can be improved and costs reduced: (i) improve patrolling coverage from existing patrol posts; (ii) increase mobile patrolling with vehicles to take rangers to more remote sites; and (iii) redesign the configuration of existing patrol posts so that rangers patrol critical areas of the landscape.

We constructed three scenarios that assessed how costs in patrolling could be minimized while ensuring efficiency of patrolling was improved to at least one visit per cell per month. Scenario 1 compares the use of two patrol methods: (i) rangers patrolling from fixed patrol posts and (ii) rangers patrolling using mobile vehicle patrols to access the park before walking on foot. Scenario 2 takes the cheapest patrol method for each cell (patrol post or mobile patrol) and assesses the optimum configuration using Marxan. Scenario 3 assesses the option to reconfigure the locations of patrol posts in response to the high costs of patrolling by moving existing patrol posts to areas of poor patrol coverage and high conservation importance with the aim of reducing patrol costs.

Scenario 1: comparison of patrolling from patrol posts or using mobile patrols

This scenario compares the costs of conserving the key species and habitats using mobile patrolling from park headquarters or ranger patrols from patrol posts. First, we modelled the distribution of key species across the landscape and mapped key habitats that were identified as conservation priorities. We then estimated the spatial costs of operating in the landscape from patrol posts and separately from headquarters and/or substations by mobile patrol (see below). These costs were then summed across the whole landscape to estimate the total cost for patrolling anywhere in the landscape under each patrol method. We set targets for conservation of species and habitats and ran Marxan incorporating the costs of operating in each cell from either patrol posts or mobile patrols. We calculated the cost of focusing patrols in the areas identified under the best-case scenario in Marxan. We then identified where threats are greatest in the landscape (from models above) and calculated costs under the best-case scenario from Marxan for targeting patrol effort in areas of most threat only. Costs were then compared with those of patrolling all selected cells in the best-case scenario with those targeting only those cells of greatest threat (where summed Maxent scores >2·0 or where 77% of threat sightings occurred) to estimate the cost reduction that would be achieved by patrol post, or mobile patrolling in these areas of greatest threat.

Scenario 2: improve efficiency of current patrol effort by identifying where mobile patrolling is more cost-effective than patrolling from permanent posts

This scenario combined the best combination of mobile patrolling and patrols from patrol posts to minimize costs using the two methods. We used the same targets and modelled species distributions as in Scenario 1 and identified where mobile patrolling costs are cheaper than patrol costs and combined the two cost layers to produce the most efficient cost layer. Then, we ran Marxan and assessed changes in total costs based on combining fixed and mobile patrols (using the same methods as in Scenario 1 and comparing costs in the best-case scenario and in the areas of greatest threat).

Scenario 3: reallocate patrol posts or mobile patrol bases using the analysis in Scenario 1

This scenario identifies where to potentially re-site a patrol post or mobile patrol headquarters to maximize the reduction in costs of patrolling and assess the cost reduction in this landscape. To be strategic in allocating where these posts should be allocated, we used the following method to identify the most suitable sites: (i) we calculated the percentage of maximum threat-level values for each cell across the landscape to identify areas of high threats; (ii) we counted how many times each cell was selected from the 1000 Marxan runs to identify cells that were consistently important in the solutions; and (iii) we calculated the percentage of the maximum cost for cells across the landscape to identify areas of high cost. We summed these three measures and divided by three to identify those areas with the highest average percentage of threats, selection frequency and cost. We then re-allocated two patrol posts from areas where they were less important (not in areas of high threat, high selection frequency or high operating costs) to these identified sites and recalculated costs of operation using the same method and patrol efficiency as in Scenario 1. We did the same for two mobile patrol bases by adding them to a logical site where mobile patrolling could reduce current costs in high cost areas. We then ran Marxan with the new cost layer and measured the reduction in cost.

MARXAN ANALYSES

We ran Marxan on a grid of 1×1 km cells (combining 250×250 m cells by summing or averaging values as appropriate) to keep the number of planning units manageable and because a 1-km grid is a tractable unit for planning enforcement activity. Marxan was run 1000 times for each scenario, using 1 million iterations in each run. The number of times a cell was selected in the 1000 runs was counted to measure the relative importance of the cells. We used a species penalty factor of 5 to ensure that targets were met for all species and calibrated the boundary length modifier (BLM) to ensure that the analysis identified spatially clumped areas in which to implement enforcement activity (Game & Grantham 2008).

Targets were set as an explicit population size protected by the patrolling activity using the maximum population size if the overall population was smaller than 1000 individuals or at 1000 individuals if larger than this value. For the habitats, a minimum area of 200 km^2 was set as a target if this could be achieved. If not, at least 90% of the area of habitat was selected as a target. More widespread habitats were set larger targets of 500 km^2 except for tropical high forest which was allocated 1500 km^2 (38% of available area) because of its known high biodiversity value.

Costs of enforcement activity were calculated based on the expected time for a patrol of four rangers to move through a habitat under different topographic conditions. Similarly, a layer was created based on costs of moving from park headquarters or substations by road in and around the landscape and combined with the first cost layer to derive a cost layer for mobile patrols (see Appendix S2 Supporting Information for details of methods). Cost distances were calculated to patrol posts and to mobile patrol stations to estimate travel time costs for ranger patrols. Where travel time cost was greater than the costs of 5-h travel time, costs of establishing a camp and multiday patrolling were added (rations and bonuses for rangers) up to the maximum number of patrol nights needed to access a site (four nights). Search costs were estimated as 2 h of ranger time per 1-km^2 cell in the landscape and added to the cost layers. In order to effectively patrol an area, it was estimated that at least one visit per month would be necessary to deter illegal activities. We therefore multiplied the costs by 12 to obtain an annual cost figure for each 1-km^2 cell in the landscape to create the cost surfaces used in the separate Marxan analyses (Appendix S2, Supporting Information). For Scenario 2, we calculated areas where the cost of patrolling from a post was greater than mobile patrol costs and created a cost layer, replacing the patrol post costs by the mobile patrol costs where this was true.

Results

PATROL COVERAGE IN THE GREATER VIRUNGA LANDSCAPE FROM RANGER COLLECTED DATA

The areas patrolled (visited at least once in the patrol data from each protected area) over the periods monitored varied between the different protected areas (Table 2). Throughout the GVL, only 60% of the area had been patrolled over a period of approximately 5–11 years for each site. Much of the unpatrolled area was in the Virunga Park where insecurity and the presence of armed rebels made it difficult to access parts of the park. Patrolling activity was concentrated near to patrol posts, dropping rapidly with increasing distance from the fixed posts (Fig. 2a). For patrolling to be effective in this landscape where snaring is the main poaching method used, we estimated that an area should be patrolled at least once every month, but only 22·9% of the landscape was patrolled with this level of effort (orange areas in Fig. 2a). The intensity of threats in the

Table 2. The area of each protected area, dates of patrol data, area patrolled and percentage area visited

Protected area	Period	Total area (km^2)	Area patrolled (km^2)	Percentage
Virunga	2005–2009	7835	3783	48·29
Queen Elizabeth	2000–2011	2508	2234	89·07
Semuliki	2004–2010	221	203	92·15
Kibale	2000–2010	794	738	92·97
Mgahinga Gorilla	2000–2007	38	38	100·00
Rwenzori	2005–2011	1019	756	74·18
Greater Virunga Landscape	2000–2011	12 918	7799	60·37

landscape was predicted by summing the results of the modelled distribution of the nine threats (Fig. 2b), indicating that many of the threats are predicted to occur near the edge of the protected areas, with only partial overlap between the threats and the current patrolling effort. Illegal activities at other sites also tend to be concentrated nearer the edges of protected areas and closer to human habitation where travel costs are lower and people involved are less easily detected by law enforcement patrols (Campbell & Hofer 1995; Hofer *et al.* 2000). Areas where patrolling effort is markedly low in the presence of high predicted threat include the central Virunga Park and some central areas of Rwenzori Mountains.

PATROL EFFORT WITH DISTANCE FROM PATROL POSTS

Patrol effort declined rapidly with increasing distance from the patrol post (Fig. 3a), although there was some variation between protected areas. About 75% of GPS locations collected by patrol teams occurred within 5 km of the patrol post, and 50% were within 3 km of the post. Sites where overnight patrols are made more regularly such as in Rwenzori Mountains National Park (because of its ruggedness where overnight patrols have to take place) or where mobile patrols commonly occur (Queen Elizabeth National Park) show more regular patrolling at further distances from the patrol posts (Fig. 3a). Most of the patrolling in Mgahinga Gorilla National Park occurs close to patrol posts simply because of the small size of the park.

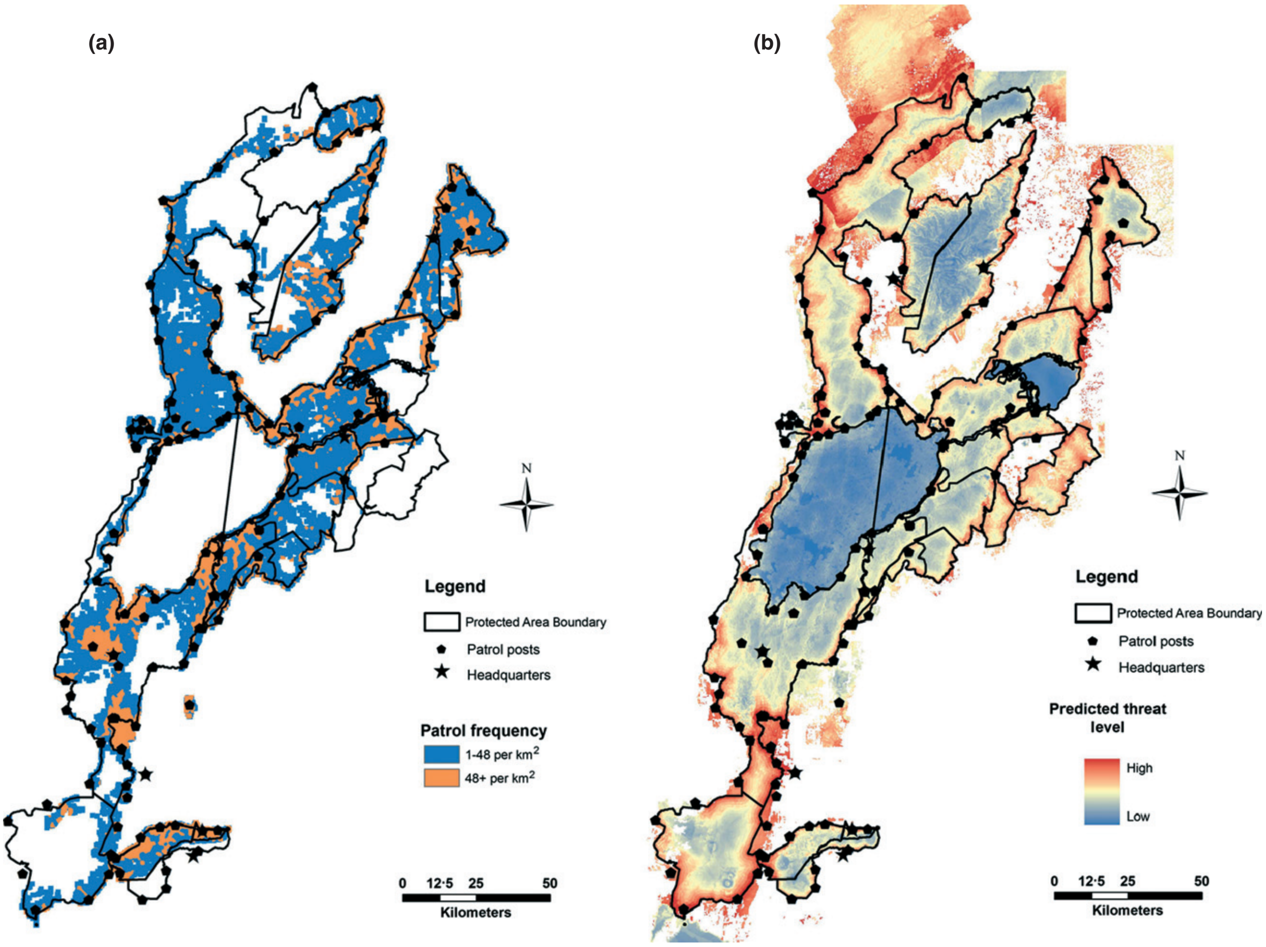

Fig. 2. (a) The intensity of patrol effort in relation to patrol posts. The relative abundance of GPS locations is plotted for each 1-km cell in the landscape and where more than 12 visits of 2 h per km^2 per year (48 position points) occur they are highlighted in orange. Unpatrolled areas are white. (b) The predicted threat intensity map from adding the models of the nine threats in the landscape.

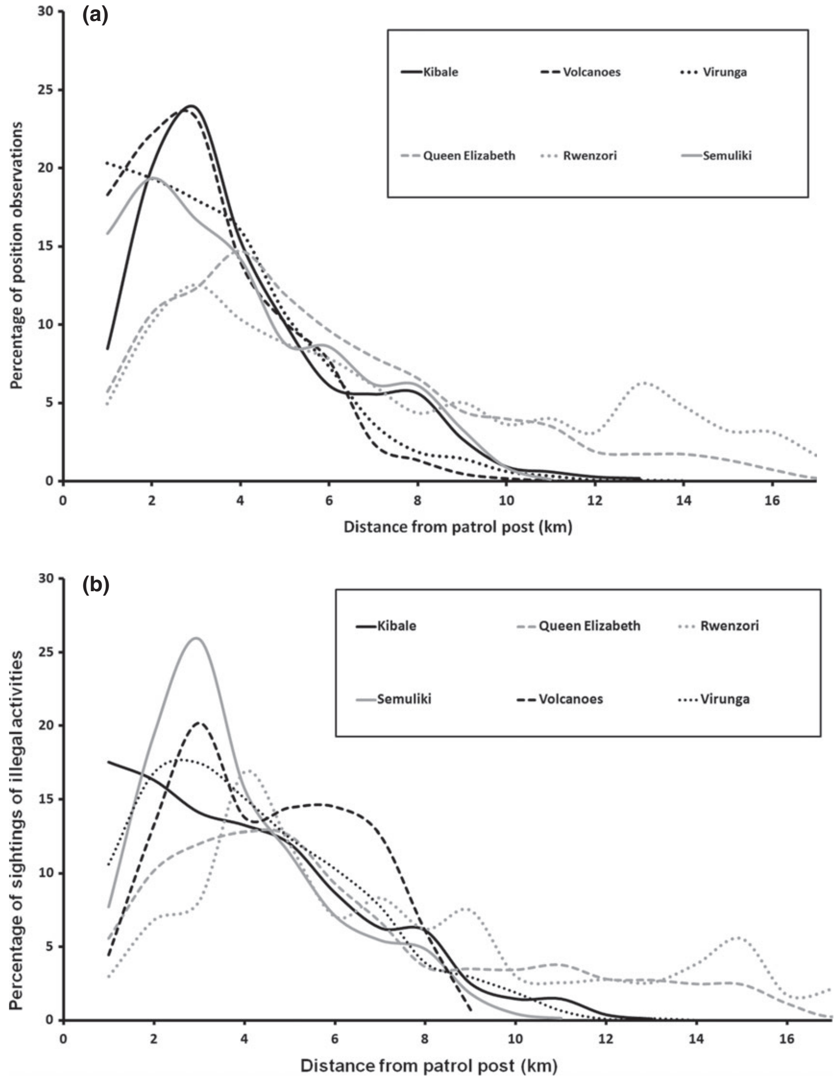

Fig. 3. (a) The percentage of position points (measure of patrol effort) with distance from patrol posts in each of the protected areas with ranger patrols. (b) The percentage of sightings of illegal activities with distance from patrol posts in the same parks. The three forest reserves in the landscape have very little patrolling because the National Forest Authority in Uganda does not have a permanent ranger force in its reserves. The two wildlife reserves are patrolled as part of Queen Elizabeth National Park's patrol effort.

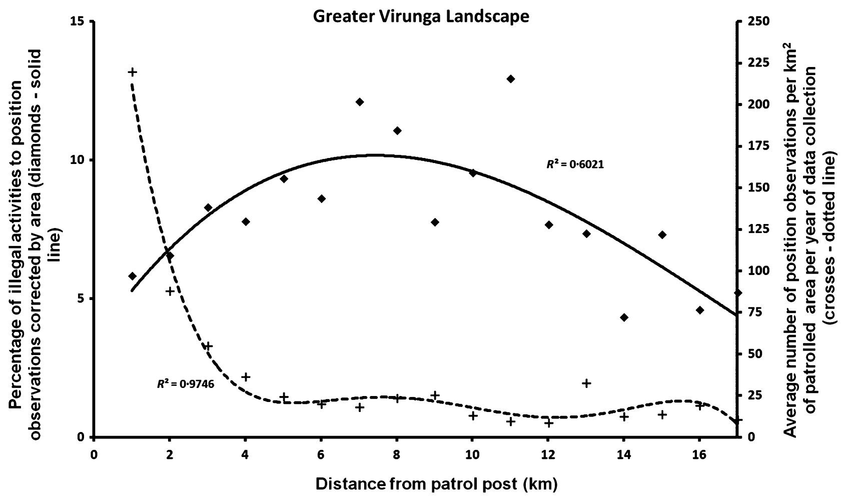

Fig. 4. The percentage of illegal activities per km^2 divided by patrol effort as measured by the number of position points for the landscape with polynomial trendline fitted to the data (bold curve – with equation and R^2 value). Also plotted is the patrol effort at different distances per km^2 per year of patrol data per patrol post (dotted line with power equation trendline and R^2 value).

LOCATION OF ILLEGAL ACTIVITIES IN RELATION TO PATROL POSTS

Sightings of illegal activities showed a similar pattern to the distribution of patrols, but were displaced further from the patrol posts (65% of illegal activities were sighted within 5 km and 38% within 3 km of the patrol posts; Fig. 3b). However, these patterns are somewhat confounded by the increase in area to be searched as distance from the patrol post increases. Correcting for this shows that there is an increase in illegal activities per unit area up to 8 km from patrol posts after which there is a decline (Fig. 4). Correcting patrol effort in the same way for the area change (Fig. 4) suggests that the patrols are effective at reducing illegal activity near the post, but that much illegal activity is not being deterred by patrols at greater distances. Beyond approximately 8 km, there is a marked reduction in illegal activity, most likely reflecting the relative remoteness of such areas but it may also be related to observer fatigue and a drop in detectability of illegal activity signs (Keane, Jones & Milner-Gulland 2011). Most funds used for patrolling per unit area of the landscape are expended within 3 km of a patrol post (Fig. 5). There is a need to allocate this budget more evenly so that patrols act as a more effective deterrence further away.

COMPARING COSTS OF PATROLLING USING REGULAR OR MOBILE PATROLS

The two cost layers produced for patrolling from current patrol post locations and costs of mobile patrols from park and subregional headquarters were used to calculate which patrol method was more cost-effective in the landscape. Patrols from existing ranger posts were more cost-effective and only a few areas were patrolled more cheaply by mobile patrols (Fig. 6). Given the greater emphasis being placed on mobile patrolling in some of these protected areas, this is an important finding.

Using the values in the cost layers, we estimated that to patrol all of the landscape effectively (a 2-h visit each month of the year) would cost \$5·8–9·1 million USD per year (Table 3). This is higher than the current budget for the landscape, which is approximately \$5·9 million but also includes costs of infrastructure, tourism and community conservation activities (Table 4). It is difficult to estimate the actual law enforcement costs at a site from these figures but it is likely to be 40–65% of the budget. We assessed the number of GPS locations of threats per summed probability score for the nine threats (Fig. 2b) and estimated that 77% of threat sightings occurred where the score was > 2·0. We therefore used this value as a threshold and estimated that it would cost \$3·3–5·3 million per year to patrol the landscape where this threshold was met (Table 3). This brings the costs down to a level that are probably within the current expenditures in the landscape (Table 4).

The results of the Marxan best-case scenario for ranger patrols from patrol posts and mobile patrolling select similar areas (see Appendix S3, Supporting Information). These maps show where patrolling should concentrate using the three methods (ranger patrols from patrol posts, mobile patrolling only or a combination of mobile and ranger patrols) to maximize the chances of deterring illegal activities that could affect the landscape species and the other biodiversity in this landscape. Patrolling the whole area of the Marxan best-case scenarios reduced patrol costs to \$2·2–3·5 million per year (Table 3), a significant reduction that would ensure that conservation targets were met at a cost that is well within current expenditure ranges. If patrol effort focused on areas where the modelled threat scores were > 2·0 within the best-case scenario, then costs could be reduced further to \$0·9–1·6 million (Table 3).

MOVING PATROL POSTS OR MOBILE PATROL BASES TO REDUCE COSTS

Another strategy for managers would be to consider moving some patrol posts or increasing the number of mobile patrol bases in the landscape to improve coverage and reduce costs. The method we used (Scenario 3 in methods) identified two sites for moved ranger patrol posts and two for mobile post headquarters (Fig. 7). Comparing the results, we can see that either the action of moving patrol posts or the establishment of two mobile

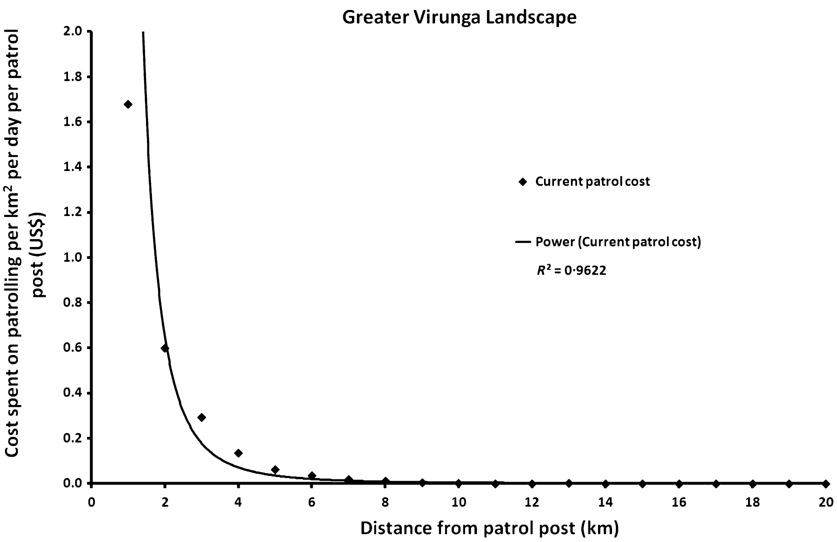

Fig. 5. Patrol funding expenditure per square kilometre per day in the Greater Virunga Landscape.

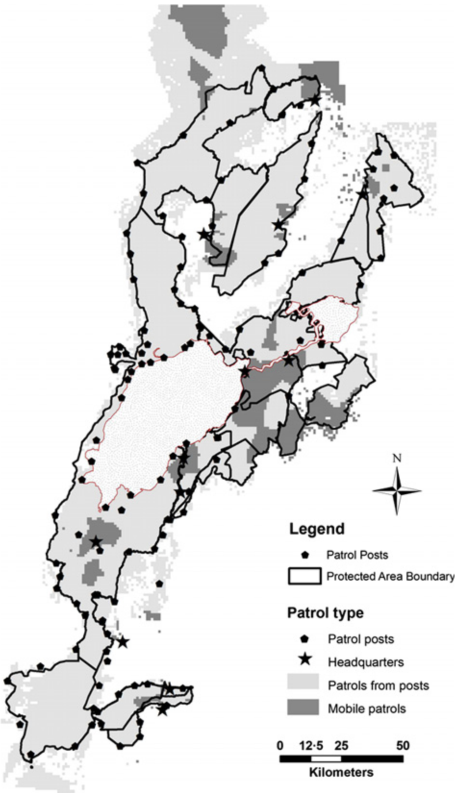

Fig. 6. Map showing the areas where it is most cost-effective to patrol from the existing patrol posts compared with those areas where it is more cost-effective to use mobile patrols.

substations did not significantly reduce the costs (Table 5). Increasing the mobile substations by two decreased the costs of patrolling in threatened areas by 13% and over the whole landscape by 10%. However, there was little impact on the Marxan best-case scenarios because these are selecting cells that conserve targets in the cheapest areas and reducing costs in expensive areas will not change the overall result greatly.

Table 4. Budget for management of each of the protected areas in the Greater Virunga Landscape in 2012. Costs per square kilometre of park and area to patrol for each law enforcement ranger are also calculated

Protected area	Area (km^2)	Annual Budget (US$)	Cost per km^2 ($US)	Km^2 per law enforcement ranger
Semuliki NP	220	92 504	421	11·00
Rwenzori Mountains NP	995	267 078	268	16·58
Queen Elizabeth Conservation Area	2040	757 617	371	22·17
Kibale NP	795	644 087	810	12·42
Mgahinga Gorilla NP	34	132 227	3889	1·89
Volcanoes NP	160	470 000	2938	4·32
Virunga NP	7844	3 500 000	446	28·01
Total	12 088	5 863 513		

Discussion

It is critical for landscapes in the tropics that the limited resources invested in patrolling are used in the most effective manner. This study shows that in the GVL patrol effort is inadequate both in its coverage of the landscape (only 22% being effectively patrolled as defined in this study) and in its allocation of resources available for patrolling (most patrol funding is spent within 3 km of a patrol post). While species numbers have been increasing in some parts of the landscape in Uganda, there has been a steady decline in large mammal numbers in Virunga Park in DRC (UWA & ICCN unpublished data). Therefore, management of patrol effort within the landscape must be reassessed and the available resources for patrolling should be targeted in a cost-efficient manner to maximize the impacts of patrolling on the conservation features identified for protection in the landscape.

Table 3. Costs of patrolling: (a) whole landscape effectively, (b) areas where threats are abundant in landscape, (c) area selected under the Marxan best-case scenario to minimize costs to protect conservation features and (d) areas where threats are abundant within the Marxan best-case scenario for conservation targets. The percentage of the total costs is given in brackets. The costs are given separately for Scenarios 1 and 2, using only patrol posts, using only mobile patrols and combining post and mobile patrols where cost-efficiency is maximized

Scenarios 1 and 2	(1a) Patrol post cost (US$)	(1b) Mobile Patrol cost (US$)	(2) Combined patrol post and mobile patrols (US$)
Patrolling whole landscape	6 152 170	9 139 850	5 892 120
Patrolling landscape where threats are abundant (77%)	3 505 020 (57%)	5 324 400 (58%)	3 334 030 (57%)
Focus on conservation features			
Patrolling Marxan best-case scenario	2 266 720 (37%)	3 463 280 (38%)	2 223 810 (38%)
Patrolling Marxan best-case scenario where threats are abundant (77%)	964 560 (16%)	1 653 600 (18%)	944 380 (16%)

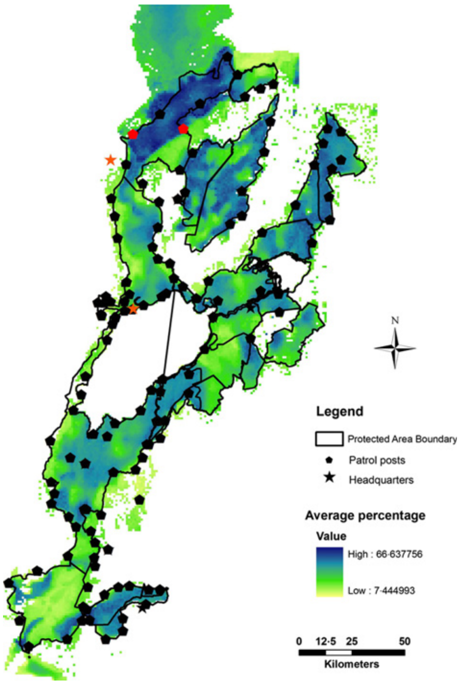

Fig. 7. Areas identified as important for focusing patrol effort based on their level of threats, their selection frequency by Marxan and their high cost of patrolling. The figure shows the sites with a combined high percentage value and areas that should be a focus of patrol effort and the locations of the two new patrol posts and now mobile substations (in red).

We have provided a method that can be used to solve the problem of where to optimally allocate patrol effort, using a modern conservation planning tool. By setting clear objectives for the patrol unit, costing out effort and having quantified targets, we have identified spatially explicit solutions for patrol areas that can deliver a better conservation outcome within the same price range as current operations. While in an ideal world the entire area in a landscape as rich and important as the GVL would be protected, it is clear from this analysis that the costs needed to achieve this are more than the currently available budget (Table 3). Our method shows that while protecting the whole landscape is not currently affordable, it is possible to target areas that would conserve viable populations of key species at minimum cost. If further resources can be raised, then our results indicate that they could be targeted at areas of high importance for conservation (selected frequently by Marxan). The method is dependent on good underlying data layers for species, habitat and illegal activity distributions. We present an approach using modelled species distributions and illegal activities using Maxent which is being critiqued as a method for species distribution modelling (Royle *et al.* 2012; Yackulic *et al.* 2013). We would recommend that future studies obtain data for these layers from a stratified random sampling approach rather than modelling from biased data and that an occupancy framework be considered to calculate the true probability of occurrence in each grid cell (e.g. Kéry, Gardner & Monnerat 2010; Comte & Grenouillet 2013), rather than using Maxent, as it can also incorporate detection probability (unlike Maxent or Maxlike). The study also shows that patrolling from fixed patrol posts for the most part is more cost-efficient than running mobile patrols, except in the Queen Elizabeth National Park where the road network in the park allows easy access by vehicle. While we based the calculations on the use of permanent roads or tracks and did not account for the ability of vehicles to move off track in savannas, the costs of running vehicles that go off track will increase per kilometre and therefore this may not reduce overall costs in the final assessment. More data on vehicle running costs are required to assess this. The better cost-effectiveness of the patrol posts is partly due to their large number in the landscape (125) and was based on data from 2000 to 2010. In 2009, the ranger force in Virunga Park was drastically reduced from about 600 staff to 220, which meant that there were not enough rangers to man every patrol post. Unfortunately, the data collection process established to monitor ranger patrolling was also stopped at this point also and we no longer have data on patrol coverage or patrol efficiency to determine the impact of these changes.

Improving the coverage and efficiency of patrolling from both mobile substations and patrol posts will require better monitoring of patrol effort and planned patrolling based on the results of this monitoring. Software now exists, such as MIST (Stokes 2010) and SMART (http://www.smart

Table 5. Costs of patrolling, targeting areas of importance and high cost and threat, by moving two patrol posts to the north of Virunga Park from the centre, and establishing two new mobile patrol substations in Virunga Park. The percentage of the original costs are given in brackets

Scenario 3	Costs of patrolling whole landscape ($US)	Costs of patrolling landscape where threats are abundant ($US)	Marxan best run cost ($US)
Move two patrol posts to new positions	6 105 250 (99%)	3 483 940 (99%)	2 215 130 (98%)
Establish two new mobile patrol substations	8 251 210 (90%)	4 644 950 (87%)	3 233 420 (93%)
Combine both actions	5 705 070 (97%)	3 183 120 (95%)	2 174 820 (98%)

conservationsoftware.org/), that can enable managers to monitor patrol coverage every month and adjust where patrols go in subsequent months to ensure effective coverage.

Poaching and other illegal activities are dynamic in nature and poachers might adjust where they operate depending on the level of deterrence. Our approach identifies where in the landscape deterrence should be in place such that all conservation targets are effectively protected. If this level of patrolling can be achieved, poachers might eventually be deterred from operating in the patrolled areas and could move to areas that are less important for conservation. Provided the distribution of conservation features does not radically change, such displacement of poaching should not present a management problem. However, we also explored matching patrolling to areas of high poacher threat, and in this scenario, changes in where poachers operate will lead to changes in levels of threats and the analysis will need to be updated dynamically. Thus, although targeting efforts in highly threatened areas may at first seem desirable and could be a cheaper option (Table 5), in the long run the repeated data collection and analyses required may mean that the costs outweigh the benefits of this approach. In ecosystems where some of the conservation features, such as landscape species, move over large distances, it will be necessary to make sure that corridor areas, where they move between sites, are selected also (by increasing the boundary length modifier in Marxan) so that all critical areas for viable populations are patrolled effectively.

Protected areas have been established across 10–12% of the world to address the global decline in biodiversity. Effective patrolling of these protected areas is critical for the conservation of key species even if protected areas are generally effective in abating habitat loss (Struhsaker, Struhsaker & Siex 2005). As protected areas become more accessible and isolated from natural habitat (Newmark 2008), the need to be more effective in law enforcement will only be increased. Using an analysis such as the one presented here can identify a more efficient mechanism for patrolling than the current situation and show that it can be carried out for similar or even reduced costs.

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Supporting Information

Additional Supporting Information may be found in the online version of this article.

Appendix S1. Selection of Landscape species.

Appendix S2. Method used to calculate cost surface for patrolling.

Appendix S3. Maps showing best-case scenario from Marxan outputs using ranger patrols, mobile patrols and a combination of both methods.