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Challenges in Patrolling to Maximize Pristine Forest Area (Position Paper)

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Abstract

Illegal extraction of forest resources is fought, in many developing countries, by patrols through the forest that seek to deter such activity by decreasing its profitability. With limited resources for performing such patrols, a patrol strategy will seek to distribute the patrols throughout the forest, in space and time, in order to minimize the resulting amount of extraction that occurs or maximize the degree of forest protection, according to one of several potential metrics. We pose this problem as a Stackelberg game. We adopt and extend the simple, geometrically elegant model of (Albers 2010). First, we study optimal allocations of patrol density under generalizations of this model, relaxing several of its assumptions. Second, we pose the problem of generating actual schedules whose site visit frequencies are consistent with the analytically computed optimal patrol densities.

Introduction

Illegal extraction of fuelwood or other natural resources from forests is a problem confronted by officials in many developing countries, with only partial success (MacKinnon et al. 1986; Dixon and Sherman 1990; Clarke, Reed, and Shrestha 1993; Robinson 2008). To cite just two examples, Tanzania's Kibaha Ruvu North and South Forest Reserves are "under constant pressure from the illegal production of charcoal to supply markets in nearby Dar es Salaam,"[1] and illegal logging is reportedly "decimating" the rosewood of Cambodia's Central Cardamom Protected Forest (see Fig. 1). In many cases, forest land covers a large area, which the local people may freely visit. Rather than protecting the forest by denying extractors entry to it, therefore, protective measures take the form of patrols throughout the forest, seeking to observe and hence deter illegal extraction activity (Lober 1992; Sinclair and Arcese 1995). With limited resources for performing such patrols, a patrol strategy will seek to distribute the patrols throughout the forest, in space and time, in order to minimize the resulting amount of extraction that occurs or maximize the degree of forest protection, according to one of several potential metrics.

Figure 1: "A truck loaded with illegally cut rosewood passes through Russey Chrum Village...in the Central Cardamom Protected Forest." Photo from (Boyle Dec 21 2011).

Although in some cases patrols may catch would-be extractors as they are about to perform the extraction, and therefore will directly prevent extraction from occurring, we primarily focus on the extraction that the patrols *deter*. That is, the leader wishes to arrange the potential troublemaker's environment so as to render his choice of engaging in this behavior as expensive to him as possible.[2] More precisely,

[1] http://www.tfcg.org/ruvu.html

[2] We follow the convention of referring to leader as *she* and fol-

given the continuous nature of this setting, we wish *minimize* to the amount of extraction that will yield a positive net return in his cost-benefit analysis. (To cite two real-life examples of this phenomenon, when the New York City Police Department issued zero-tolerance policies on "squeegeeing" and subway fare-beating, arrests for these crimes reportedly went down rather than up (Kleiman and Kilmer 2009; Kleiman 2009).) Therefore we pose the problem as a Stackelberg game in which the policymaker or *leader* publicly chooses a (mixed) patrol strategy; in response, the extractor or *follower* then chooses whether or not to extract, or to what degree. The problem we study is of computing optimal leader strategies in such a game.

Economists have studied the relationship generally between enforcement policy for protecting natural resources and the resulting incentives for neighbors of the PA (Milliman 1986; Robinson 2008; Sanchirico and Wilen 2001). A number of models and problem formulations of forestry protection specifically have been proposed, including dynamic models (Robinson, Albers, and Williams 2008), forest shape modification to increase protection (Robinson, Albers, and Williams 2011), and combinations of forest protection with local economic activity such as bee-keeping (Albers and Robinson December 2011). Our point of departure in this paper is the simple, geometrically elegant forest protection model of (Albers 2010), in which there is a circular forest surrounded by villages (hence potential extractors); the task is to distribute the patrols' probability density across the region of interest; the objective is to minimize the distance by which the extractors will trespass into the forest and hence (since nearby villagers will extract as a function of this distance (Skonhoft and Solstad 1996; Albers and Grinspoon 1997; MacDonald, Adamowicz, and Luckert 1998; Hofer et al. 2000)) maximize the size of the resulting *pristine* forestland. We probe the probabilistic assumptions of this model and consider a number number of more realistic extensions to it. One example is permitting spatial variation in patrol density. As has been observed (Albers 2010), exogenous restrictions on patrol strategies, whether adopted for simplicity or to comply with legal restrictions, can degrade protection performance (MacKinnon et al. 1986; Hall and Rodgers 1992). We extend what is known analytically about the core model to these new settings and provide new results. We also pose the problem of computing actual patrol paths consistent with the desired densities.

The forest patrol problem we study here is an instance of the leader-follower Stackelberg game model, which has been the topic of much recent research and has been applied to a number of real-world security domains, including the Los Angeles International Airport (Paruchuri et al. 2008), the Federal Air Marshals Service (Tsai et al. 2009), and the Transportation Security Administration (Pita et al. 2011). See (Tambe 2011) for an overview.

The problem setting we address here differs from those considered in these previous works in several crucial ways. The biggest difference is that this setting is essentially continuous rather than discrete, both spatially and in terms of player actions. In the existing problems there are a finite number of discrete locations or segments to protect (e.g., modeled as nodes of a graph), whereas in the our setting ideally the entire forest area would be protected from extraction. As such, our primary focus is, at least initially, on the choice of distribution for patrol density over the two-dimensional forest region, i.e. a probability distribution from which to select patrols. (Of course, the continuous space can be discretized by overlaying a grid on it, but any choice of grid granularity will involve some level of approximation and error.) Second, the followers make choose a distance based on a cost-benefit analysis, considering both their expected returns and their labor costs based on distance.

lower as *he*.

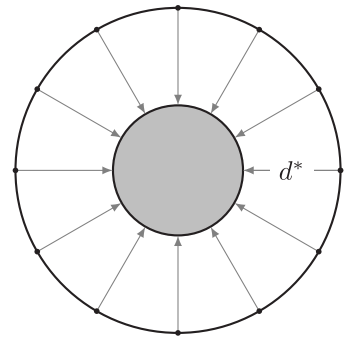

Figure 2: The forest, with the pristine area shaded.

The rest of the paper is organized as follows. After reviewing the model of (Albers 2010), including several proposed patrol density strategies, we will consider several extensions and generalizations to the model, including relaxing assumptions on both the problem setting and the permitted patrol strategies. Second, we consider the problem of computing actual patrol strategies consistent with the computed patrol densities, i.e., computing (sets of) walks within the region whose frequencies of visiting locations correspond (approximately) to those locations' patrol densities. We conclude with directions for ongoing and future work.

Core models

In this section we review and extend the model of (Albers 2010). The forest is a circular region of radius 1, with villagers uniformly distributed about its perimeter (see Fig. 2). A villager's action is to choose some distance d to walk on a line from the perimeter towards the forest center before returning his starting point, extracting on the return trip. Note that in this setting, due to symmetries and the fact that villagers' decisions are uncoordinated, the problem is essentially one-dimensional; we may assume that the extractor extracts only on the return trip from the forest. Villagers gain a benefit *if not caught* and incur a cost, based on a decreasing marginal benefit function $b(d)$ and an increasing marginal cost function $c(d)$. If caught, the villager's benefit is 0 (the extracted resources are confiscated) but the cost is unchanged (the extractor's traveled distance does not change; there is no positive punishment beyond the confiscation itself and being prevented from engaging in further

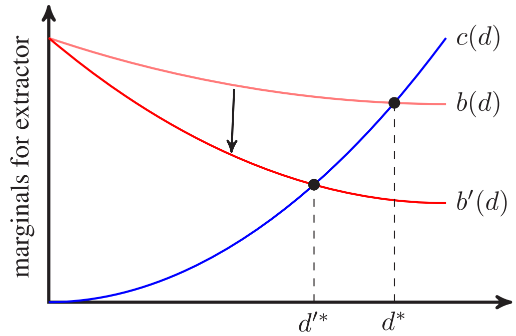

Figure 3: Shaping the extractor's cost-benefit analysis.

extraction while leaving the forest[3]). Thus a given patrol strategy will reduce the extractor's expected benefit for an incursion of distance d from $b(d)$ to some value $B'(d)$.

For a sufficiently fast-growing cost function relative to the benefit function, there will be a "natural core" of pristine forest even with no patrolling at all (Albers 2010); that is, the optimal value d^* will be less than 1, since the marginal cost of extraction will eventually outweigh the marginal benefit, corresponding to the point at which the curves $b(d)$ and $c(d)$ intersect (see Fig. 3). The overall result of choosing a given patrol strategy therefore is to transform the benefit curve $b(d)$ into a lower benefit curve $B'(d)$, thus reducing the extractor's optimal incursion distance (see see Fig. 3).

The leader has a budget E specifying (perhaps after application of a suitable normalization constant) a bound on the total detection probability mass that can be distributed across the region. The task is to choose an allocation in order to minimize the extractor's resulting optimal trespass distance d^*.

Detection probability models

Let ϕ be the detection probability chosen by the leader, constant over some subregion R of the forest. In the model of (Albers 2010) (a version of which we present in this paragraph, motivated slightly differently), the detection probability for a walk of distance d is equal to $d\phi$. This setting is best understood as one operating under a time model in which the patrol units move much less quickly than the extractors, and so patrols can be modeled as stationary from the extractor's point of view. We assume that an extractor is detected if he comes within some distance Δ of the patrol. Then indeed the probability of detection for an extraction path of length d (when there is a single patrol unit) will be proportional to ϕd, specifically $\phi d 2\Delta/|R|$, where $|R|$ indicates the area of R and the total area within distance Δ of the length-d walk is approximated as $d{\cdot}2\Delta$. Intuitively, the more steps the extractor takes undetected, the higher the probability he will be detected on the *next* step. (Here we assume the patrol unit is *not* visible to the extractor.) Suppose the available patrol budget determines the sensing range Δ; this is equivalent to it determining the detection probability ϕ.

Alternatively, we may consider settings in which Δ is constant and the budget can be spent on multiple patrol units. If there are some number of units u, then detection probability ϕ is the joint result of them together, i.e., $\phi = 1-(1-\phi_u)^u$, where ϕ_u is the detection probability due to each particular unit. Then the probability of capture from a length-d extraction path becomes $1-(1-\phi_u d 2\Delta/|R|)^u$.

An alternate time model is one in which the extractor moves much less quickly than the patrol units, and so from the extractor's point of view the patrol units are newly assigned random locations (with replacement) at each moment. If we approximate a walk of length d as consisting of $n = d/\Delta$ separate "trials", then the detection probability will be $1-(1-\phi)^n$, regardless of whether there is one patrol unit or many.

Patrol allocations

We describe three patrol allocation strategies have previously been considered:

- **Homogeneous:** Patrol density distributed uniformly over the entire region.
- **Boundary:** Patrol density distributed uniformly over a ring (of some small width w) at the forest boundary.
- **Ring:** Patrol density distributed uniformly over a *some* ring (again of width w) concentric with the forest.

It is observed in (Albers 2010) that boundary patrols will often be superior to homogenous patrols, since homogeneous patrols waste enforcement on the natural core. It is interesting to note that this need not always be the case. Consider the variable Δ setting, and let the budget be E; assume the homogenous-induced core radius is less than $1-d$, w is very small, and the trip length d satisfies $w < 1/2 < d \le 1$. With homogenous patrols, the detection probability will be simply $E/\pi \cdot d$. With boundary patrols, however, the detection probability will be $\frac{E}{\pi-\pi(1-w)^2} \cdot w = E/\pi \cdot \frac{w}{1-(1-w)^2}$, which approaches $\frac{E}{2\pi}$ as $w \to 0$. In this case, homogeneous patrols will actually outperform boundary patrols. Intuitively, this is because a patrol in the interior will "intersect" more trips from boundary to center than a patrol on the boundary will.

It would be interesting to classify the situations under which one patrol allocation is superior to another, for the different probability settings. The best ring strategy can only be better than boundary patrols, since the latter is a special case of the former.

Other extensions

A number of additional potential extensions suggest themselves.

- **Asymmetry:** The core problem setting is *highly* symmetrical; the symmetry assumptions could be relaxed by degrees. We could allow the weight of villager populations to vary around the forest perimeter, for example. More dramatically, we could allow other, noncircular forest shapes.

[3] Observe that since extraction occurs only on the return trip and given the nature of the punishment, we may restrict our attention to detection on the return trip.

- **Nonuniform importance:** Currently, all the forest area is equally important, both to the extractor and to the protector. Each of these assumptions could be relaxed, independently.
- **Continuity:** As discussed above, an essential feature of this problem setting is the continuity of space. Without subverting this, we could introduce obstacles to movement within the forest. With enough obstacles, however, the forest may become "sparse" enough to be representable by a graph.

Computing patrols

On whatever particular problem setting model is chosen above, once a patrol distribution is chosen, the ultimate task is to choose patrols in such a way that the frequencies with which they visit locations within the forest are consistent with the specified probability mass values of those locations. This algorithmic problem, which can be seen as sampling from a distribution or as a form of rounding, is the primary open problem to solve here.

Conclusion

In this position paper, we have presented a Stackelberg security game setting that differs significantly from those settings previously considered in the AI literature. In ongoing work, we plan to explore more realistic problem settings and tackle the problem of generating actual patrol schedules consistent with the optimal patrol probability density distributions.

Eventually, we aim to deploy the resulting patrol distributions and and schedules in real-world settings. In the past, one of us (H.J. A.) has worked with the forest managers and guards at Tanzania's aforementioned Kibaha Ruvu North and South Forest Reserves, which could provide one potential site for future research transition, as well as with the marine park managers of Mnazi Bay Ruvuma Estuary Marine Park. It may be possible to implement these models in the mangrove forests within that park, which exhibits a pattern typical among the forests prompting this work: the mangroves there are a source of wood and fuelwood/charcoal for local people but such use of them decreases the forest's ability to trap sediment, to clean water, and to provide a habitat to juvenile fish.

Acknowledgement

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