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Spatial and Temporal Modeling of Community Non-Timber Forest Extraction

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Abstract

This paper examines the interaction of spatial and dynamic aspects of resource extraction from forests by local people. Highly cyclical and varied across both space and time, the patterns of resource extraction resulting from the spatial-temporal model bear little resemblance to the patterns drawn from focusing either on spatial or temporal aspects of extraction, as is typical in both the modeling and empirical literature to date. Combining the spatial-temporal model with a measure of success in community forest management—the ability to avoid open-access resource degradation—characterizes the impact of incomplete property rights on patterns of resource extraction and stocks.

Key words: Spatial and temporal modeling; renewable resources; non-timber forest products; common property resources

1. Introduction

Extraction of products such as fuelwood and foods from community and government forests makes a significant contribution to rural people's welfare in many poor countries (Cavendish, 2000; Mahapatra, Albers, and Robinson, 2005; Bahuguna, 2000). Villagers make decisions about where, when, and how much to extract from forests based on resource quality, costs of extraction, and rules of access. Over time this extraction may cause degradation, which can in turn limit the forest's ability to provide environmental services, timber, and the extracted resources themselves. The interaction of spatial and temporal aspects of extraction decisions and the relationship between those decisions and the strength of local community resource management institutions (CRMI) determine the levels of rural welfare and forest resource stocks over time and space.

By analyzing a model that explicitly accounts for both spatial and temporal components of resource extraction—instead of focusing on one or the other—and incorporating the role of CRMIs, this paper predicts some previously unanticipated outcomes.[1] First, the spatial nature of extraction results in a dynamic extraction path that is cyclical—comprising multiple periods across which extraction quantities vary considerably—rather than smooth as predicted by purely dynamic non-spatial analysis. Second, the spatial pattern of extraction varies markedly across time—comprising patterns of high levels of extraction near the village in some periods and high levels of extraction away from the village in other periods—rather than the pattern of monotonically decreasing extraction over distance from the village predicted by purely spatial non-dynamic analysis. Third, management institutions that are not 100 percent effective can generate the bulk of both extraction value

[1] Some ecological models demonstrate variability across time and space, which implies that "understanding environmental change involves looking beyond natural-resource depletion and degradation in the aggregate" (Leach, Mearns, and Scoones; 1999; p. 226, para 3) and toward ecological and human processes across both space and time.

and resource stock size. Fourth, both the net present value of the extracted resource and the pattern of forest degradation are a function of the spatial distribution of the effectiveness of management institutions. Fifth, because the spatial pattern of the degree of effectiveness of management institutions interacts with the spatial aspects of extraction, a uniform distribution of management effort across locations is inefficient. Sixth, stock management policies such as "enriching" an area with certain species can have positive or adverse effects on stock sizes in other areas. Hence, this more integrated approach points to the pitfalls of focusing on a subset of the issues and identifies priorities for setting policy.

1.1 Literature

In taking an explicitly temporal and spatial approach to analyzing resource extraction, this paper brings together three typically separate strands of literature on forest degradation in poor countries: dynamic implications of resource extraction; spatial and distance dimensions of extraction; and the impact of community resource management institutions (CRMI) on extraction patterns and degradation. Because these three aspects of resource extraction interact in practice, the integrated model developed here provides useful insights for policy that are unlikely to come from any of the individual strands of research.

Research and policy have long incorporated a central characteristic of forests: they regenerate. The dynamic aspects of resource extraction involve balancing the level of extraction with the resource's growth rate to prevent excessive degradation, and have been widely addressed for many resources. For example, Clarke, Reed, and Shrestha (1993) and Bluffstone (1995) explore the time path of resource stocks in the setting of resource extraction in poor countries. Bluffstone (1995) pays particular attention to the role of the labor market in determining extraction paths.

Forest management policies are increasingly spatial; for example, governments typically create buffer zones for extraction between villages and parks to address the dual needs of rural people and resource protection (Wells and Brandon, 1992). Spatial aspects of resource extraction decisions matter because the configuration and quality of the resource stocks influence both villager welfare and the provision of ecosystem services, such as watershed protection, maintenance of biodiversity, or creation of recreation opportunities (Heltberg, 2001; Wu and Boggess, 1999; Albers, 1996; Shaefer, 1990; Diamond, 1975). These spatial aspects have been acknowledged, if not explicitly modeled, by various empirical studies that identify the distance to extraction sites as an important determinant of the labor time cost of extraction (Pattanayak, Sills, and Kramer, 2004; Kohlin and Parks, 2001; Amacher, Hyde, and Kanel, 1996). Kohlin and Parks (2001) develop a model of fuelwood extraction and an econometric analysis that demonstrates that "the collection decision depends on the relative returns from different sources of fuel … [and] that distance to the forest is a crucial factor" (p. 214). MacDonald, Adamowicz, and Luckert (2001) use a site choice model for fuelwood collection in which distance and trip difficulty contribute to costs of extraction and explore the impact of collection location on extraction and welfare. Heltberg (2001) uses a spatial measure—forest use penetration—to describe forest degradation. Robinson, Williams, and Albers (2002) use a household labor allocation model to demonstrate how access to markets alters the spatial profile of resource stocks in a forest. Yet even with these articles and the abundance of econometric evidence about the role of distance and time in extraction decisions, relatively little research exists that explicitly models the spatial aspects of forest resource extraction decisions.

A growing spatially explicit economic literature examines the issue of land use change in the tropics – particularly patterns of forest clearing (Chomitz and Gray, 1996; Nelson and Hellerstein, 1997). Much of that literature uses a von Thunen-style land rent model and econometric analysis to explain the location of deforestation. Only recently has that literature begun to include both location/spatial and temporal aspects of land use decisions (Vance and Geoghegan, 2002; Munroe, Southworth, and Tucker, 2002). Vance and Geoghegan (2002; p.317) argue that "de-coupling of spatial and temporal dimensions compromises the implementation of appropriate policy response" for deforestation. Sanchirico and Wilen (1999 and 2005) make a similar argument for the coupling of spatial and temporal dimensions for analysis of fisheries, because the fish can and do move, and not necessarily evenly across space and time. The model and analysis presented here for forests link the spatial and temporal dimensions through the relatively free but uneven movement of the human extractors.

Economic theory, emphasizing the role of dynamic externalities, predicts that, whether by an individual or community, sole ownership generates higher net present value and forest stocks than open access. As Hardin (1968) demonstrated, if a resource is open access, individual extractors do not fully incorporate the dynamic cost in terms of resource growth associated with current extraction and the resource is overexploited. In rural areas of poor countries, different property rights regimes are found, with differing levels of effectiveness. Many forests are subject to open access extraction even if, as commonly occurs, the government has the property right for that forest, because property rights are difficult and costly to enforce (Robinson, 2004; Larson and Bromley, 1990; White and Martin, 2002). Many forests—including many government forests—are managed as common property by village institutions (Heltberg, 2001; Ostrom, 1990); indeed, many NGOs and governments have policies to support or generate such institutions in order to raise welfare and resource stocks (Edmonds, 2002; Ligon and Narain, 1999). These institutions have had varying degrees of success. Some communities manage the resource in a manner that closely mimics the management strategy of a sole-owner, internalizing dynamic externalities, but others range across a continuum from open access to fully private (Schlager and Ostrom, 1992; McCarthy, Sadoulet, and de Janvry, 2001; Gibson, Lehouq, and Williams, 2002; Alix-Garcia, 2005). Further, partly in response to patterns of forest degradation and concern for the well-being of rural people, many countries have devolved resource management to the local level, giving rural communities defined rights to extraction from forests (Edmonds, 2002; Albers, Rozelle, and Guo, 1998).

From a modeling perspective, it is not clear that these improved but imperfect property rights should be represented as either the extreme of perfect rights nor the extreme of no rights whatsoever. Some intermediate range seems a better representation. Similarly, it is not clear that community resource management institutions are equally effective by space. A spatial-temporal model of property rights seems appropriate, in other words.

2. Model of extraction

This model of resource extraction incorporates three critical characteristics of rural resource extraction in poor countries: forest regrowth and trade-offs across time; spatial extraction decisions that incorporate distance costs; and the strength of community resource management institutions (CRMIs) over time. Three key equations characterize the model: a harvest function that links effort and resource stock levels to the amount extracted in a particular location; a cost function that is a function of the time spent extracting, the distanced traversed within the forest, and the amount of resource that is carried home; and a resource growth function that is the equation of motion linking periods. To solve the model, the community's objective function is defined, as is the nature of property rights. Equilibrium patterns of extraction over time and space are then determined as a function of the extent to which property rights are enforced over time. The model is discrete in time over a finite but effectively infinite number of periods and discrete in space over a finite area of land.[2]

2.1 Extraction function

Each period, *s*, the community's villagers enter the forest to extract a particular resource that is located in *N* discrete equidistant clusters perpendicular to the forest boundary (cluster *i*=1 is nearest to the village and cluster *i*=*N* located farthest into the forest). There is a nearby market where the resource can be bought and sold for a price p. The community chooses how much to harvest, $h_{i,s}$, each period s, in each cluster i, i = 1 through n_s, where n_s is the furthest cluster that the villager extracts from in period s. The individual cluster harvest, $h_{i,s}$, is a function of $w_{i,s}$, the time spent extracting in cluster i; $m_{i,s}$, the cluster's resource density at the start of the period; M the maximum carrying capacity of each cluster; and α, a parameter that represents, for example, the ease of harvesting per unit of effort. The harvest function exhibits the key characteristics of extraction, in particular diminishing returns to time spent extracting in any one particular cluster:

2 In practice, the resource could either be continuously distributed throughout the forest, such as grass or twigs, or located in discrete clusters, such as bamboo or mushrooms. Because villagers turn around at some location, even after just one period of extraction the distribution of the resource becomes discontinuous at that point, even if the resource distribution was initially continuous. The assumption of a continuously distributed resource therefore devolves very quickly into a discrete distribution. The choice of a continuous or discrete resource therefore does not change the problem fundamentally. Albers (1998) and Robinson et al. (1999) provide more detailed exploration of extraction behavior when the resource is evenly distributed for a one-period model.

$$h_{i,s} = m_{i,s}\left(1 - \frac{1}{1+\beta_{i,s} w_{i,s}}\right) \text{ where } \beta_{i,s} = \alpha \frac{m_{i,s}}{M} \quad (1)$$

2.2 Cost function

Extraction is costly, both in terms of the time spent extracting from each cluster, $w_{i,s}$, and the time taken to go from one cluster to another both going into and out of the forest. The time taken to traverse the forest between clusters of the resource is an increasing function of the amount of resource already harvested and being carried by the villager – that is, people slow down the greater the weight of the extracted resource, and hence they walk into the forest without a load and extract on the way out.[3] The total time spent in the forest in period *s* is written:

$$T_s = n_s v + \sum_{i=1}^{n_s} v\left(1 + \gamma H_{i,s}{}^{\theta}\right) + \sum_{i=1}^{n_s} w_{i,s} \text{ where } H_{i,s} = \sum_{i=i}^{n_s} h_i \quad (2)$$

The cost of this extraction is equal to cT_s, where c is the opportunity cost of labor per unit time.

The first term on the right hand side is the time it takes for a villager to go into the forest to the furthest cluster from which she will extract in that period, where v is the time it takes to walk between two adjacent clusters without a load. The second term is the time it takes to walk between clusters with a load on the way out of the forest, where $H_{i,s}$ is the cumulative harvest when the villager reaches cluster i, equal to $\sum_{i=i}^{n_s} h_i$, and the parameters γ

[3] Alternatively, the cost function could reflect an increasing opportunity cost of time over time (see, for example, Robinson et al, 2002). The functional form used in this paper is appropriate for a situation in which there is no uncertainty as to the location of the resource.

(γ>0) and θ (θ>1) determine how the weight of the load affects the villager – the larger γ the greater the sensitivity of traverse speed to the load carried, and the larger θ the more non linear the relationship between the load weight and speed of walking.[4] The third term is the total time spent extracting in each of the clusters 1 through n_s. Harvesting efficiency is not affected by how much the villager has already collected. The clusters are linked spatially through this cost function.

2.3 Equation of motion

The extracted product displays the typical characteristic of a renewable resource in that it regenerates according to a logistic growth function that provides the link – or equation of motion – across periods. The growth of the resource in plot *i* between the end of harvesting period s and the beginning of harvesting period *s+1*, $g_{i,s}$, is a function of the resource level and harvest in the previous period, the natural growth rate r of the resource, and the maximum carrying capacity, *M*:

$$g_{i,s} = m_{i,s+1} - (m_{i,s} - h_{i,s}) = r(m_{i,s} - h_{i,s})\left(1 - \frac{(m_{i,s} - h_{i,s})}{M}\right) \tag{3}$$

According to Equation 3, the regrowth in any one plot is solely a function of the biomass in that plot. There is no spatial dispersal of the biomass, as in the application to "patchy" fisheries by Sanchirico and Wilen (1999 and 2005). The model of resource extraction presented here is the antithesis of the bioeconomic situation emphasized by

[4] Once a model recognizes that distance itself imposes a cost, without some non-linearity in the cost function, the extractor would not turn around until she reached the end of the forest. Further, whether a discrete or continuous space model is used, the spatial aspect of the model also means that the cost function must take account of both the time it takes to traverse the forest and the time it takes to extract from each cluster.

Sanchirico and Wilen, in that the spatial connections come solely through human extraction, especially through the linear arrangement of the plots. Moreover, the human extractors are forward looking, which matters in all situations except for the extreme of open access with no pre-commitment of harvesting effort. Because most actual situations, whether in forests or in the sea, involve some pre-commitment, some incomplete property rights, and some biological dispersal, the two models complement each other.

3. Equilibrium transition path and steady-state patterns of extraction

The community resource management institution, acting as a social planner, allocates temporal extraction rights to a large number of identical villagers, residing adjacent to an area of forest, so as to maximize the net present value of net returns to extraction, V.[5] The choice variables are the quantities extracted from each cluster each period, $h_{i,s}$, and therefore how far into the forest villagers go each period. The discount rate is written ρ, where $\beta = 1/(1+\rho)$, and the net returns in period s are written R_s. The community's optimization equation, assuming an opportunity cost of time c can therefore be written:

$$Max[V] = \max \sum_{s=1}^{S} (\beta\phi_i)^{s-1} R_s$$

$$= \max_{w_{i,s}, n_s} \sum_{s=1}^{s} (\beta\phi_i)^{s-1} \left[p(H_s) \sum_{i=1}^{n} h_{i,s}(w_{i,s}, m_{i,s}) - cT_s(w_{i,s}, n_s) \right] \quad (4)$$

Subject to Equations 1,2, and 3.

5 Although in practice, in some cases, individuals are permitted to live within a government forest, this paper assumes that the government successfully excludes people from dwelling in the forest. Hence people live adjacent to, and not within, the forest. Such an approach emphasizes how distance from a villager's home to an extractable resource influences the pattern of extraction. In addition, the assumption that villagers reside outside the forest is especially pertinent if *de facto* buffer zones within a forest or protected area are recognized (for example: Hall and Rodgers, 1992).

To solve the model for the amount extracted in each cluster in each period, the property rights regime – that is the institutional setting – must be specified. ϕ_i is a parameter that augments the discount rate, and is introduced to represent the community resource management institution's effectiveness in managing the resource over time in a particular cluster ($0 \leq \phi_i \leq 1$). ϕ_i=1 represents fully effective CRMI and hence optimal extraction that results from fully considering the future in current decisions. ϕ_i=0 represents a complete breakdown of the CRMI or open access, modeled as equivalent to period-by-period myopic extraction in which the extractors fail to consider the future in current extraction decisions.[6] Hence, a parametric reduction of ϕ_i represents weakening of the effectiveness of the CRMI. ϕ_i can also be interpreted as the confidence that the community has over whether it will have extraction rights in the next period – that is, uncertainty of property rights, the level of cooperation among villagers, or the level of activity by "outsiders" who ignore the management institution's rules. Perhaps next period the villagers will lose rights to harvest from a particular cluster in the forest, or perhaps from that period future rights will weaken. Perhaps next period rights will strengthen, and if they strengthen in one cluster, they may weaken on another. Hence, the proper solution of the full stochastic dynamic programming problem will be equivalent to some current discount on the certain future, namely ϕ_i. What degree and pattern of future uncertainty corresponds to the certain ϕ_i need not be a concern from the modeling perspective. Further, whereas most existing models consider either perfect property rights or no property rights, the single parameter ϕ_i is a simple way to represent in addition the range in between.

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[6] Alix-Garcia (2004) uses a similar parameter to denote the "different qualities of collective action, ranging from a social planner […] to a tragedy of the commons situation." (page 12, paragraph 2) Similarly, Ligon and Narain (1999) depict the degree to which a group can design institutions and enforce rules for controlling fuelwood collection from government land. This paper's model structure implies that ϕ depicts the ability to internalize the time-based externality associated with extracting a growing resource.

From both a mathematical perspective and a behavioral effect, ϕ_i is similar to a tax on capital. ϕ_i less than 1, that is, incomplete property rights, favors more current exploitation of the resource rather than saving it for later exploitation. As does a tax on capital, the influence of poor property rights compounds over many periods. That is, from the perspective of the decisions in the current period, ϕ_i less than 1 distorts the tradeoff between current exploitation and savings but the value of any savings is further depressed by the distortion next period between exploitation then and further savings, and so on into the future.

Conceptually this dynamic optimization problem can be solved by writing the discrete time Bellman equation, in which the returns to extraction are decomposed into the returns to extraction in the current period and the returns to extraction in all future periods, then formulating the Euler equations, which provide the first order conditions for the villager's equilibrium behavior. However, because of the complexity of temporal-spatial models, even using the simplest of equations, analytical solutions would not be satisfactory for describing the equilibrium. The use of calibration and numerical simulations to solve the above system of equations confirmed that, though the model equations are relatively simple individually, they combine to produce a complex non-linear system in which the equilibrium is multi-period and cyclical, the number of periods in the equilibrium being endogenous to the model parameterization and calibration. Euler conditions cannot provide a sense of such an equilibrium. Nor can Euler conditions give any clues as to the transition to the steady state and whether the transition is important.

The Euler conditions, even in the abstract, can, however, give insights into how the model can be solved. Even though the community's optimization involves many periods – s could even be infinity – in practice the optimization requires a sequence of two-period comparisons. The selection of the optimal amount to harvest involves the comparison of harvesting in the current period versus saving the resource for the next period, at which time there is a similar decision. Given an appropriate function to represent the value of the resource bequeathed to the next period, the optimization reduces to the amounts to harvest in a single period, which is a much easier problem for the community (and indeed for the analyst). The problem is not simplistic, nonetheless. The discreteness of the clusters and the fixed costs to traveling the intervening distances between clusters together create complications such that numerical methods are required to solve the model.

For solving dynamic problems numerically, the common technique is the backwards induction at the heart of dynamic programming. Some value function is presumed for some distant period s, and the numerical algorithm works backwards through period s-1, s-2 to period 2, to period 1, the initial period. Earlier periods thus take into account later periods. For certainty models, the sequence can proceed in the other direction, from the present to the future, provided some function represents the future.[7] If that function proves to imply itself, the dynamic path has been determined (by the analyst). That function can be updated through broader iterations, until the solution stabilizes.[8] That function exists even when ϕ=0, because there is some value to savings even when the community does not consider that value.

For solving spatial problems numerically, the common technique is creation of a conjectured social planner maximizing supposed social surplus. The solution to that

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7 What matters in practice is the marginal value function, not the value function. The numerical method used in this analysis deduces the marginal value function by considering what 0.1 more unit would be worth to the next period, cluster by cluster by cluster. The marginal value function is the numerical technique developed for dynamic spatial problems in Williams and Wright (1991), Chapters 9 and 10.

8 In the present application, fifteen of these broader iterations were used, as well as ninety periods. Those choices seem to have little affect on the solutions, given that the longest cycle found for the parameters used appeared to be twelve periods, but there could be longer cycles not uncovered. The fixed costs influence the computations in many ways.

maximization problem will have first order conditions, ones equivalent to no arbitrage opportunities existing in equilibrium. Those first order conditions, which will typically be discontinuous and numerically unstable, are not easy to solve simultaneously. In the setting at hand, the numerical technique can be further refined, taking advantage of the arrangement of clusters along a line. The numerical technique computes in sequence the net gains from extraction by distance, including no distance at all, selecting the highest value rather than looking for a particular marginal condition.

To solve the model, an initial resource profile is stipulated, a transition phase from the starting conditions to the equilibrium is included, and an equilibrium is postulated which comprises q periods. Explicit functional forms are chosen, and the model solved numerically. Without costs to travel between clusters, the solution is easy to find numerically, being a simple rate of harvesting that repeats period after period (that rate differing to the extent the future is considered). With fixed costs of travel, the steady state cycles. Experimentation with different calibrations revealed that the equilibrium is highly sensitive, particularly in terms of the number of periods that constitute the steady-state long-run equilibrium. The results that are shown should therefore be considered illustrative of different features of the model. Indeed, the very sensitivity of the model to the calibration is an interesting result in itself.

4. Spatial and temporal patterns of extraction, stock size, and net present value

4.1. Spatially constant institutional effectiveness (ϕ constant across clusters)

Case 1:Perfectly Effective Community Resource Management Institution (ϕ=1)

When ϕ=1 for all clusters, $p_s = \overline{p}$, and the forest is initially pristine ($m_{i,1} = M$ for all *i*), the per-period extraction and the remaining resource in both the transition path and equilibrium for the five clusters closest to the village are as shown in Figure 1.[9] The characteristics of both the transition phase and equilibrium are very different from those that would be predicted by a non-spatial unconstrained dynamic optimization model. The transition path, rather than being a single period (such as is found in Clarke, Reed, and Shrestha, 1993), comprises ten periods, five with unique positive levels of extraction alternating with five of zero extraction.[10] The equilibrium is indeed cyclical, with extraction varying over space and time. It comprises a repeating pattern of twelve periods, again with no extraction in alternate periods.[11] In any particular period of the equilibrium, marginal net returns to extraction are equal across those clusters where extraction occurs.[12] Across periods, because villagers have fully effective spatial and temporal property rights, they

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9 For the chosen calibration (α=0.9, γ=0.03, θ=1.7, v=1.0, ρ=0.1, c=4.0, p=7.0, r=0.7)villagers never enter more than the first five clusters, hence there is no need to show more than five clusters in the figures.

10 This model has not specified the time period represented by each period. Indeed, the relationship between extraction and regeneration will depend on how often the product is harvested relative to its natural growth rate. For example, a small amount of fuelwood typically is harvested daily or weekly and constant but gradual regeneration occurs. Fish are often harvested seasonally, with regeneration of the stocks occurring annually. The transition periods to a steady state could therefore be weeks, years, or decades, depending on the specific resource.

11 Zero extraction in alternate periods occurs in part because the villager must travel some distance even to reach the cluster closest to the village. In addition, this model views communities as being able to make tradeoffs across time without per-period subsistence constraints.

12 Marginal net returns are not equal across all clusters because of the transactions costs of moving from one cluster to another, and the consequent zero extraction in some clusters.

choose between harvesting in the current period and permitting the resource to regenerate in anticipation of future payoffs. That is, villagers choose between extracting (taking a "dividend"), and allowing the resource to regenerate further ("asset growth"). Hence, where extraction occurs, the marginal benefits across time are also equal. Not surprisingly, as is found in non-spatial models, harvesting rents remain at the end of the period because the community is able to enforce its management rules over space and time and ensure that no cheating by villagers or outsiders occurs while the resource regenerates.

The further the cluster is from the village, the more costly it is to reach it, and hence the more cost effective it is to let the resource regenerate for several periods. Once the cluster's resource has regenerated, extraction merits incurring the relatively high transportation cost. More distant clusters are therefore harvested less frequently but more intensively per extraction period. For example, for the given calibration, in periods 1, 5, and 9 of the equilibrium, extraction occurs in the first four clusters, in period 3, in the first three clusters, and in periods 7 and 11, in just the first two clusters. Further, because it is costly to move from cluster to cluster in the forest, the cost of distance "protects" clusters 5 onwards from extraction and hence degradation, both in the transition phase and in the equilibrium cycle (hence the figures only show clusters one through five).

The decision to extract in distant clusters is influenced by the resource densities in clusters close to the village. Intuitively, if the clusters closer to the village are completely degraded, transportation costs are incurred reaching the distant clusters but no revenue can be generated en route back home. In comparison, if the villager can also extract while returning from the distant clusters, then the effective cost of reaching the distant clusters is reduced.

Case 2: Completely ineffective community management (ϕ=0)

At the other extreme, if CRMI breaks down completely (ϕ=0), the transition is also ten periods but the equilibrium is a six-period cycle, again with extraction only occurring in alternate periods.[13] In equilibrium, villagers extract from clusters 1 through 4 in periods 1 and 3, and from clusters 1 through 3 in period 5 of the equilibrium cycle (Figure 2).

Unlike the full property rights case above, villagers enter cluster 5 in the second period of the transition phase, but do not enter this cluster in the equilibrium cycle. That is, cluster 5 is degraded during the transition phase, yet is "protected" for all future periods from extraction in later periods by a combination of distance and degradation in near clusters, even when the resource in cluster 5 is fully regenerated. This finding – that a cluster further into the forest can be degraded when the near-village clusters are less degraded, but protected when more degradation occurs in the near-village clusters – suggests that efforts to enhance a buffer zone, for example to benefit local residents, might have the unanticipated effect of encouraging villagers further into the forest (into cluster 5 in the model) when community management is less effective, but not with more effective management. An analysis only of the equilibrium would not reveal this extraction behavior because it only occurs during transition. Although in this model the extracted resource is renewable and so eventually regenerates fully in cluster 5, it is quite possible in cases with other resource regeneration functions—such as those that contain thresholds—that, during the transition phase, villagers could cause irreversible damage to other resources that are located in cluster 5. This finding suggests that additional protection of inner, more pristine areas of forest might be required when the outer areas are less degraded.

[13] That the transition phase is the same length as for effective community management is simply coincidence.

Figure 3 provides summary comparisons of the equilibrium cycles for effective and ineffective community management. The difference in average stock sizes reflects the typical anticipated differences between open access and efficient management. In equilibrium the average amount harvested from each cluster is similar, however, the average stock size remaining under fully effective management is much greater than under ineffective management, because less extraction occurs during the transition phase. Effective community resource management therefore results in more extraction, higher net profits, and greater remaining resource than in the ineffective resource management institution case. These results are not surprising.

Perhaps less intuitive is that the two extreme cases of institutional effectiveness differ significantly in the time path of extraction. When the CRMI is fully effective (ϕ=1), the resource profile varies considerably over time, consistent with "sophisticated" extraction. Villagers choose to specialize, focusing their extraction each period on fewer clusters and permitting clusters to recover for several periods without extraction. Although the maximum stock—the highest stock size attained over the equilibrium cycle—increases with distance from the village, the minimum stock size—the lowest stock size observed over the equilibrium cycle—does not follow a linear pattern with distance from the village, being greatest in clusters one and four with clusters 2 and 3 experiencing the most degradation.

In contrast, when a CRMI is ineffective (ϕ=0), villagers tend to extract relatively evenly from each cluster across time, resulting in smoother spatial profile of extraction and remaining resource stock. As for the ϕ=0 case, the distance cost generates a spatial pattern of resource stocks in which the maximum stock increases with distance from the village. However, in contrast, the minimum stock also increases monotonically with distance from the village.

Parametric variation of management effectiveness

Many research papers and policy discussions call for the improvement of community resource management institutions both to improve welfare and to avoid the "tragedy of the commons" of eroding resource stocks and values. For example, McCarthy, Sadoulet, and de Janvry (2001; p.308) argue that "the quality of cooperation will improve with policy interventions that help reduce the variable costs of cooperation". In this section, parametric variation of ϕ demonstrates that many of the benefits of well-functioning resource management institutions can be attained at levels of effectiveness that are somewhat lower than would be expected from a linear interpolation between the extremes of effectiveness, open access and perfectly efficient.

As is typical and to be expected, villager welfare decreases as ϕ becomes smaller. This decline in net present value indicates the degree of costliness of the "tragedy of the commons" at different levels of CRMI effectiveness. That is, the more effective is the CRMI in avoiding inter-temporal open access, the greater the returns to resource extraction. However, the relationship between ϕ and welfare is non-linear. For example, for the given calibration, the fully ineffective CRMI generates 64 percent of the village welfare benefits of the perfectly effective CRMI, and to receive 95 percent of the effective institution's NPV, the institution need only have an effectiveness of ϕ=0.72. The model therefore suggests that NGOs, villages, and governments that seek to improve rural welfare by supporting CRMI can achieve much of their goal without perfectly effective institutions.[14]

[14] For example, a village may include a group of extractors who are not willing to cooperate with CRMI rules or may face difficulties in excluding some outsiders. These results show that the cooperating villagers may be able to create a strong enough CRMI to achieve significant improvements even without full agreement from, or enforcement against, non-cooperators.

Similarly, because governments care about the resource stock size, they may support programs that establish access rights and management institutions, thereby increasing ϕ.[15] Again, the government may be able to achieve most of the resource stock goals with a less than perfect CRMI. For example, to achieve 95 percent of that stock size goal, the management institution must have an effectiveness of ϕ=0.83. Further, if the government wants to focus on protecting clusters further from the village, recognizing perhaps a *de facto* buffer zone closer to the village, the management effectiveness can be low. For example, if the government wants to prevent any degradation in cluster 5 even in the transition periods, it need only support a management institution with an effectiveness of ϕ=0.15.

4.2. Spatial variation in the effectiveness of community resource management institutions (ϕ variable across clusters)

In many situations, a community resource management institution may function reasonably well but not perfectly (Schlager and Ostrom, 1992). For example, the institution might be successful at inducing cooperation among villagers but less successful at preventing all extraction by outsiders (Heltberg, 2001). Equally, the institution may be more effective closer to the village where extraction behavior is easier to monitor, and less effective further from the village where "defections" are harder to detect. Alternatively, a village may not have an effective CRMI for forests near the village but non-local government may establish and enforce effective management rules elsewhere, for example in a buffer zone between the village and a government-protected area. This section therefore explores the spatial pattern of effectiveness of CRMIs on the net present value of resource

[15] McCarthy, Sadoulet, and de Janvry (2001) develop a model of costly cooperation amongst common pool resource users. If those costs are not covered by an external policy, program, or project and are instead born by the CRMI participants, the fixed and variable costs of CRMI management can make the optimal level of management lower than that resulting from the sole-owner's optimization.

extraction and the resource stock density. The same calibration is used as for the base simulations.

To demonstrate the impact of varying spatial CRMI effectiveness across the forest resource, the specific effectiveness in each cluster is varied whilst the average effectiveness across clusters is kept constant. For example, if the CRMI is perfectly effective (ϕ=1) in the three clusters closest to the villagers, and completely ineffective (ϕ=0) in clusters 4 and 5, the average effectiveness of ϕ is 0.6 over the five clusters. But, the NPV generated with this spatial pattern is equivalent to all clusters 1 through 5 having a CRMI effectiveness of 0.85. Conversely, if the CRMI is completely ineffective in clusters 1 and 2, and perfectly effective in clusters 3 through 5, also implying an average effectiveness of ϕ=0.6, the NPV corresponds to a CRMI effectiveness in all parcels of only 0.45. These findings suggest that, for example, a community with limited funds should concentrate its management efforts closer to the village. In part, these results are driven by the earlier finding that in the steady state villagers do not extract from cluster 5 regardless of the degree of effectiveness of community resource management institution. Hence varying institutional effectiveness in cluster 5 does not affect the equilibrium. Distance alone protects the resource in cluster 5 from degradation without potentially expensive property rights enforcement there.

From a forest manager's perspective, focusing management efforts on particular clusters can also generate greater overall stock levels than if the effort is even across clusters. For example, in the first example above, where institutional effort is concentrated in the three clusters closest to the village, the maximum stock size (other than in cluster 5) is 9.498 (in cluster 4) and the minimum stock size is 5.381 (in cluster 1). In the second example, where institutional effort is concentrated further from the village, stocks are lower – the maximum is 9.048 (in cluster 4) and the minimum 4.041 (in cluster 1).

Consider a third example, proposed in Albers (1998), which suggests that a more effective approach to managing forest resources might be to permit a *de facto* buffer zone in the outer peripheries of the forest – where villagers are more inclined to extract and it is particularly costly to prevent that extraction, concentrate institutional effort on the center clusters (2, 3, and 4) which can be protected from excessive extraction relatively cost effectively because distance from the village provides some additional protection, and allow distance alone to protect inner cluster 5. With such an institutional arrangement, the maximum stock size is 9.865 (in cluster 4)—higher than in any other configuration of CRMI effectiveness considered here including $\phi=1$ in all clusters—and the minimum stock is 3.96 (in cluster 1)—lower than in all other configurations of CRMI effectiveness including $\phi=0$ in all clusters.

In general, if the CRMI enforces extraction restrictions evenly across all clusters, for whatever reason, they will typically do so at a cost in terms of net present value, stock sizes, or wasted enforcement. In general, to generate the higher stocks and benefits associated with spatially focusing CRMI effectiveness, that focus must not include the clusters farthest from the village. This result stems from the fact that distance is costly for villagers and so creates natural limits on extraction from far-off clusters, even with open access. Without appropriate institutions to internalize the dynamic externality and the over-extraction it induces, the relatively lower cost of extracting in nearby clusters encourages more over-extraction there.

The framework developed here does not specify a decision maker's preferences nor a cost of CRMI effectiveness, which would permit further exploration of the optimal allocation of CRMI support funds.[16] Yet even without that step, this framework

[16] The perspective of a social planner who makes tradeoffs between rural welfare and resource stocks with costs of enforcing property rights and management institution rules is the subject of current research through further model development and through empirical exploration of

demonstrates the complexity of the tradeoffs involved between generating NPV, maintaining high stock sizes, and establishing minimum stock sizes. In addition, the management of one cluster is partially determined by the management of other clusters; the spatial costs and the spatial distribution of CRMI effectiveness play a major role in the patterns of resource extraction over time and over space.

Alternative spatial configurations of CRMI effectiveness raise other interesting issues. For example, if the property rights are configured ϕ=1.0, 0.5, 0.0, 0.5, 1.0 for clusters 1 through 5, the minimum stock observed in cluster 1 is greater than if ϕ=1.0 for all 5 clusters because extraction is displaced to cluster 3, where extraction is open access. Despite this displacement, cluster 3's minimum and maximum stock sizes are higher than if ϕ=0 for all 5 clusters. That is, when CRMI effectiveness varies spatially, extraction can be displaced to the clusters with lower access restrictions but the combination of distance costs and CRMI in each cluster determines the impact of that displacement.

5. Discussion

This paper develops a framework for examining the interaction between the spatial and intertemporal aspects of resource extraction and between these extraction patterns and the effectiveness of community resource management institutions (CRMI). The results inform a discussion about the importance of the level and location of CRMI activities for protecting resources from open access degradation and the lower stock and rural welfare that typically result from such over-extraction.

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enforcement and extraction patterns. That line of research addresses the issues of costly property rights and requires careful characterization of the spatial and temporal features of those cost functions.

First, the spatial-temporal analysis demonstrates that when the location of the resource implies a distance cost to extraction, which many empirical studies find to be important, the spatial pattern of extraction varies period by period, leading to a multi-period and cyclical steady state. Temporal variation in the spatial pattern of extraction is high across all levels and patterns of CRMI effectiveness. That variation includes periods in which no extraction occurs in any cluster of the resource while that resource regenerates. This temporal variation in the spatial pattern of extraction suggests that analyses and policies that are based on a single year of observation of extraction behavior may misjudge the situation and lead to inappropriate policy statements. For example, a government seeking to establish a buffer zone could underestimate the enforcement needs and the impact on welfare if they base their siting and sizing decision on observation of extraction patterns during a year in which distant clusters are left to regenerate.

Second, this analysis demonstrates that the bulk of the losses associated with "the tragedy of the commons" can be avoided with CRMIs that are significantly less effective than the benchmark of a sole owner/manager. Much of the discussion of CRMIs in the economics literature focuses on whether institutions can effectively manage resources and, if so, what characterizes successful CRMIs. Although not representative of a particular setting, the parameter analyses here demonstrate that even if CRMIs are not successful in inducing full cooperation of villagers or in completely deterring extraction by outsiders, partial effectiveness can generate large welfare and stock size rewards. This result suggests that policies to foster CRMIs to a moderate level of effectiveness may be more important than attempting to generate more and more effective CRMIs. In addition, the analysis here suggests that as CRMIs become more effective in a forest, forest stocks will be higher, as expected, but the spatial and temporal pattern of extraction and stocks may also change markedly.

Third, the cost associated with distance to the extraction site or cluster affords more distant clusters some measure of protection from excess extraction and degradation. Even in forests where a CRMI is completely ineffective and open access occurs, extractors allow resources in far-off clusters to regenerate to a relatively high stock size before extracting there in order to extract enough to cover the fixed cost of distance. Because the distance cost encourages resource regeneration, CRMI effectiveness matters less in those clusters; the stock size and net present value of distant clusters do not increase dramatically with increases in the CRMI effectiveness. The spatial-temporal-CRMI effectiveness framework shows that the location of CRMI effectiveness contributes at least as much to the protection of resources from over-extraction as the average level of the effectiveness of CRMI across space. This result suggests that policy makers, CRMIs, and NGOs can use the spatial cost information in siting parks and extraction zones and in allocating typically scarce budget resources to enforcement of access restrictions; resource stocks and net present values are higher when CRMI effectiveness focuses on clusters closest to the village.

This paper brings together three related but not integrated lines of research. The large literature on common property, open access, and the role of CRMIs in resource management in developing countries rarely addresses temporal or spatial characteristics of the managed resources. Similarly, the growing econometric literature on forest resource extraction typically determines that distance generates a cost to extractors but rarely examines the interaction of the spatial decision with the property rights regime. This paper demonstrates that these lines of research have much to learn from each other in the pursuit of spatially and temporally efficient resource management.

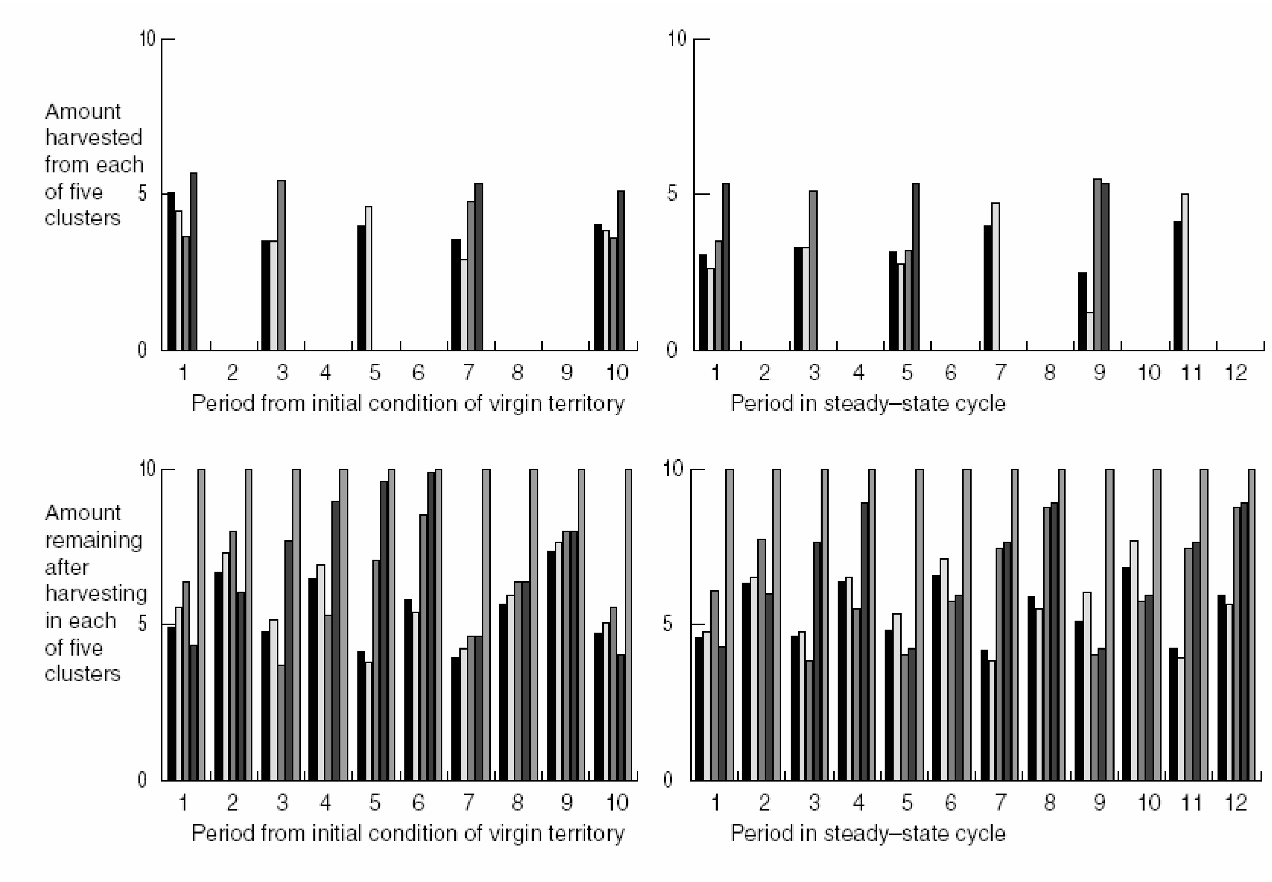

Fig. 1. Spatial-temporal extraction patterns and resulting resource densities in the forest when ϕ=1 for all clusters

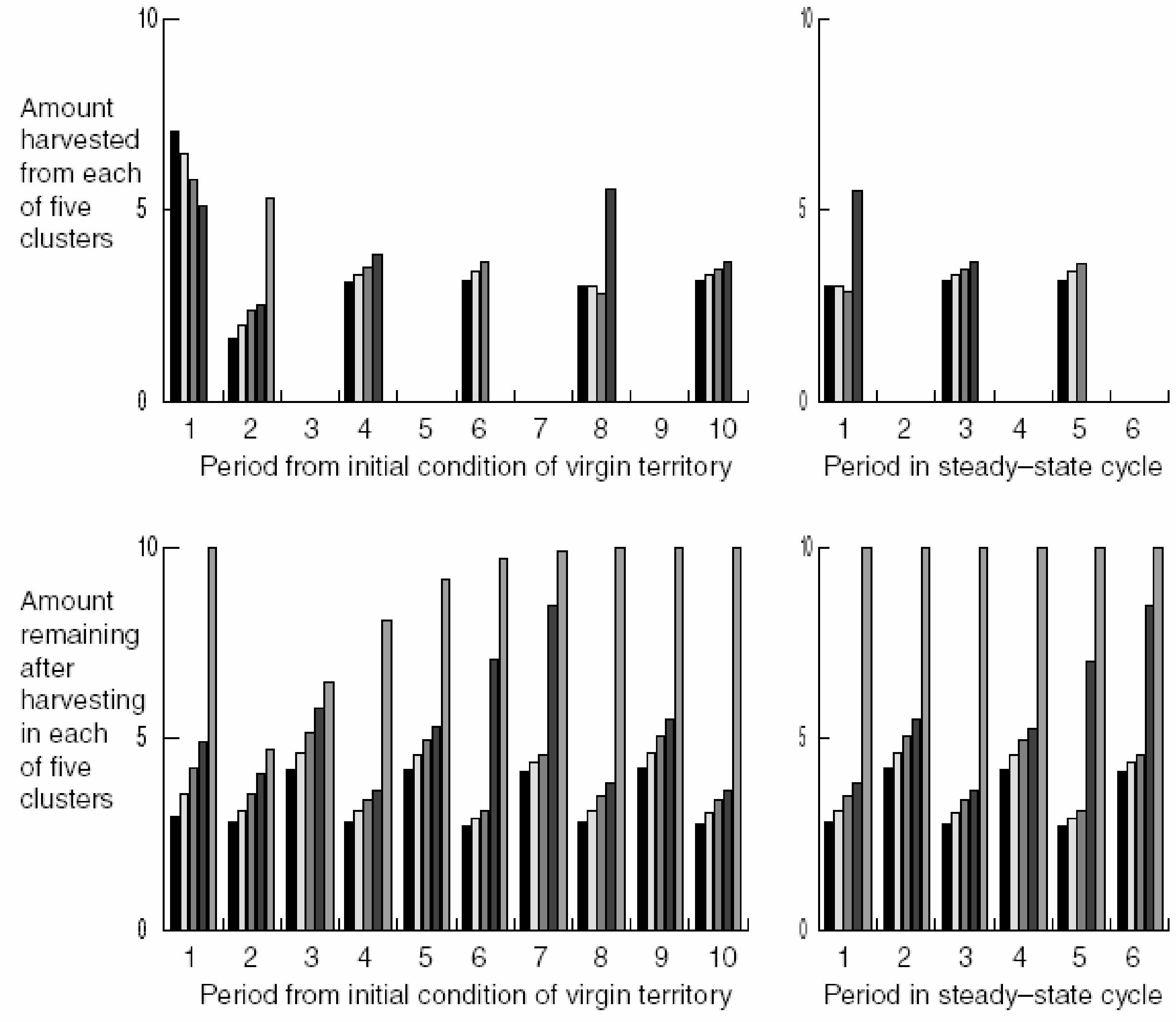

Fig. 2. Spatial-temporal extraction patterns and resulting resource densities in the forest when ϕ=0 for all clusters

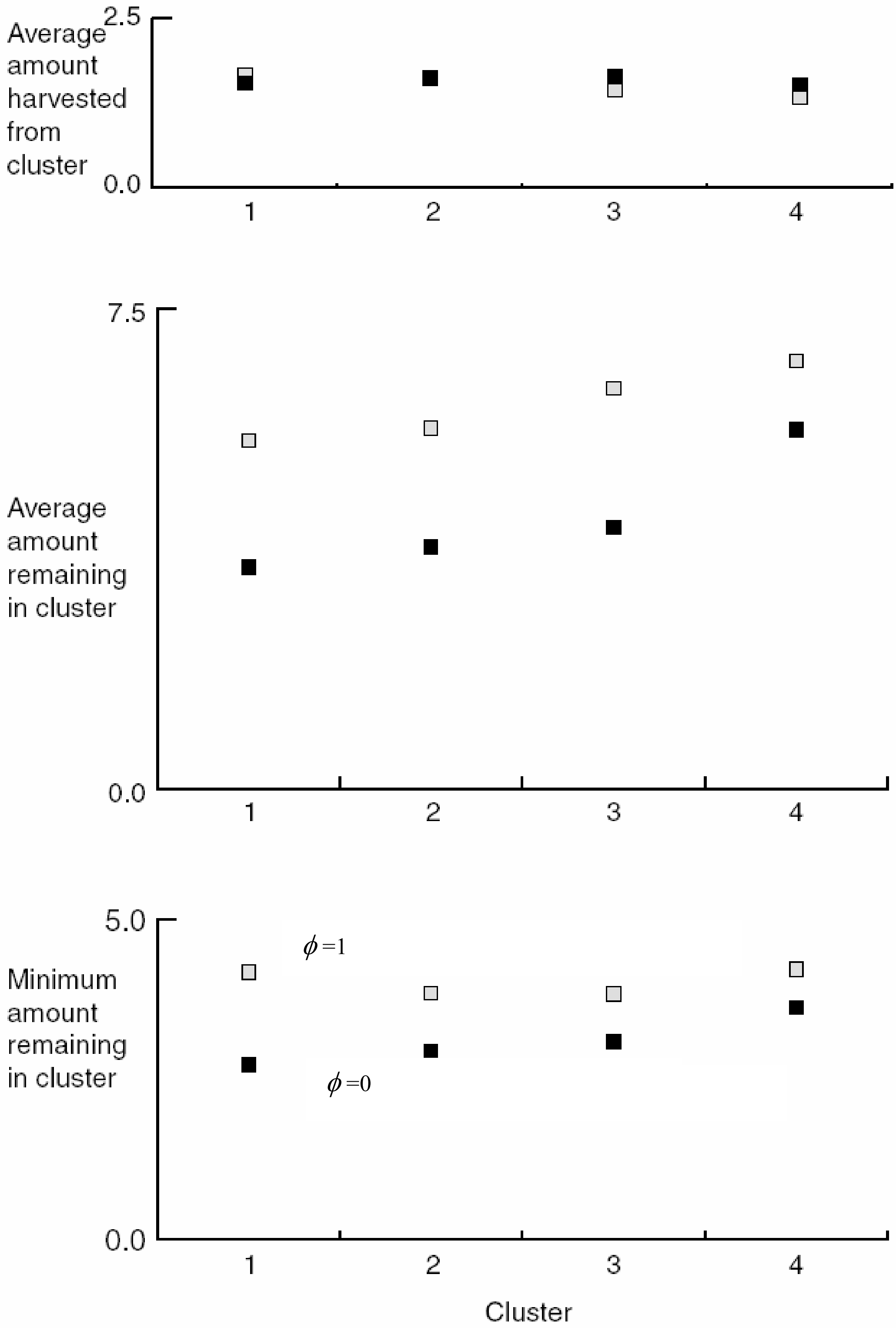

Fig. 3. summary comparisons of the equilibrium cycles for effective (ϕ=1) and ineffective (ϕ=0) community management

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