Location Choice for Natural Resource Extraction with Multiple Non-Cooperative Extractors: A Spatial Nash Equilibrium Model and Solution Method

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Abstract The distribution and extraction of many renewable resources in open access settings reflects the uncoordinated spatial extraction decisions of multiple extractors, especially in lower-income countries with limited property rights. Such extraction settings can be found for timber, non-timber forest products, fish, and wildlife. Yet most economic analyses of extraction decisions, and the resulting spatial patterns of resource use, rely on simplifying assumptions that do not reflect the full spatial decisions of extractors in response to the resource distribution and other extractors' actions. This paper presents a model and solution method that finds spatial Nash equilibria that result from many extractors making uncoordinated decisions about the pattern and number of locations they extract from, and the amount of extraction, in a patchy resource environment. Using variations of the solution method, multiple equilibria with different characteristics are found and analyzed for varying distances between patches. The different model assumptions generally suggest small differences in resource profiles, but much greater differences in the number of extractors found in each patch and the extraction paths used. The solution method obviates the need for outcome-impacting assumptions such as single extraction locations, representative agents, and unmodeled location assignment institutions, and investigates the effects of using these.

Keywords Natural resource extraction • Spatial equilibrium • Optimal pathways • Resource patterns

JEL codes: C63, C72, O13, Q56, Q57, Q22, Q23

1 Introduction

Spatial patterns of resource stocks and extraction affect the production of ecosystem services and economic outcomes. In *de facto* open access settings such as those often found in forests and fisheries in lower-income countries, these patterns derive from the uncoordinated actions of multiple resource extractors. When those resources grow in a patchy environment, extractors make decisions about the number and specific set of patches from which to extract and the level of extraction intensity in each patch. In making these decisions, extractors consider the travel costs of accessing different patches and their opportunity costs of time, the resource stock in each patch, and the extraction decisions of other extractors. These observations suggest that understanding resource patterns and resource use therefore requires modeling how individual extractor spatial decisions aggregate across all extractors in the landscape.

Yet despite the prevalence of uncoordinated spatial resource extraction, many models make simplifying assumptions about extractors' spatial decisions or about the interactions of extractors. As examples, many models assume a representative agent; or that all extractors allocate their labor the same way across patches and wage labor; or constrain extractors to extract in only one patch, or along one ray (Robinson et al., 2002, 2008; Lopez-Feldman and Wilen, 2008; Albers, 2010; Behringer and Upmann, 2014). Such assumptions, while reasonable for some resources and behaviors, cannot accommodate situations in which extractors pass through a landscape, have the opportunity to extract in several places along their chosen path, and where different extractors choose different paths.

The objective of this paper is therefore to develop a more flexible model that accommodates these more complex extractor choices and interactions, to provide greater insights into resource extraction, and to explore the implications of various assumptions that constrain extraction choices. We develop a mechanistic model and solution method that determines the spatial Nash equilibrium resulting from a group of extractors with the same utility function and labor endowment, that face the same landscape, yet who make individual decisions over pathways through the patchy resource, extraction locations, and intensity of extraction at each location. As such, our paper has similarities with sorting models such as Bayer and Timmins' (2005) and Timmins and Murdock's (2007) spatial Nash bargaining game.

The exploration of our model's results reveals the role of distances between patches in determining the heterogeneity across extractors in equilibrium. By using variations of the solution method, we find and characterize multiple equilibria. Our paper demonstrates how an agent based model, within a spatially explicit landscape, provides new insights in comparison to previous models, particularly with respect to variation in extractor choices of extraction pathways, the existence of multiple equilibria, and spatial patterns of resource stocks.

The next section develops the spatial extraction model. The third section describes the general computational solution method and variations of it that solves for the equilibrium and possible multiple equilibria. The fourth section depicts and discusses the results of the model for several different distance settings, and compares the resulting equilibria with constrained extraction location choices. Section five concludes.

2 Model

Our model considers equilibrium resource extraction decisions over both locations and quantities for a group of extractors with identical labor endowments and preferences, who face labor allocation trade offs across distance time costs, extraction, and a non-resource extraction labor option, such as wage labor.

2.1 Spatial Setting

The spatial setting contains one village (or port) located at a distance from a patchy resource landscape. This landscape comprises six resource patches arranged in a two by three grid, with three resource patches at increasing distance from the village along each of two "rays" (Figure 1). Each patch's location is described (r,y) by its ray, r = 1,2, and its placement at increasing distance from the village on that ray, y =1,2,3. No travel can occur diagonally between rays.

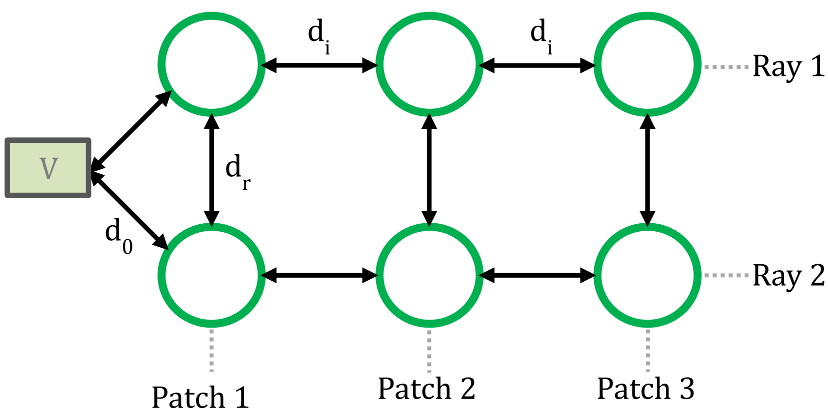

Figure 1: Spatial landscape showing village, resource patches, distances between patches, and permissible pathways

2.2 Individual extractor's optimal decision

Each individual, *i*, of *V* extractors seeks to maximize their individual net returns, W_i, by allocating their labor endowment L_i across extraction labor in each patch (r,y), l_{iry}; wage labor l_{iw}; and distance travel costs which depend on the path taken through the patchy landscape. The extracted resource is sold at an exogenous price, *p;* and wage labor receives a wage, *w,* which is a function of the total wage labor supply of all extractors. An extractor's labor allocation choices define that extractor's optimal set of patches from which to extract, the pathway for that extraction, and the optimal amount to extract from each patch visited. Each extractor makes these choices independently while considering the resource stock in each patch and recognizing that all other extractors face the same decisions. We write an individual extractor's optimization as follows:

$$\max_{L_i}[W_i(L_i)] = \max_{(l_{i,ry}, l_{i,w})}\left[p \sum_{r,y} h_{i,r,y}(l_{i,r,y}) + w_i(l_{i,w})\right] \quad (1)$$

s.t.

$$L_i = \left(\sum_{r,y} l_{i,r,y}\right) + l_{i,w} + l_{iD}$$

$$H_{r,y} = qR_{r,y}\left(\sum_{j=1}^{V} l_{j,r,y}\right)^{\gamma};\ \gamma < 1$$

$$h_{i,r,y} = \frac{l_{i,r,y}}{\sum_{j=1}^{V} l_{j,r,y}} H_{r,y}$$

$$w_i(l) = w \cdot \frac{l_{i,w}}{\sum_{j=1}^{V} l_{j,w}} \cdot \left(\sum_{j=1}^{V} l_{j,w}\right)^{\beta}\ where\ \beta < 1$$

In Equation 1, $h_{i,r,y}$ is the amount of the renewable resource extracted by extractor *i,* through the allocation of labor $l_{i,r,y}$ in a particular patch (r,y). The total amount harvested in any patch, $H_{r,y}$, follows a modified Schaefer-type function that allows for diminishing returns to total labor effort extracting from a particular patch (Zhang and Smith, 2011) where q measures an extractability (or catchability) coefficient and $R_{r,y}$ is the resource stock of patch y in ray r at the start of a time period. Thus within a particular time period, the total resource extraction in patch (r,y), $H_{r,y}$, is a function of the extraction decisions of all the extractors choosing to extract from that patch. With extractors considering each other's extraction decisions, the model's solution comprises individually optimal labor allocation decisions within a spatial Nash equilibrium. Between periods, the resource in each patch partially regenerates after harvest, $\Delta R_{r,y}$, according to a logistic growth function:

$$\Delta R_{r,y} = r \cdot \left(R_{r,y} - H_{r,y}\right) \cdot \left(1 - \frac{R_{r,y} - H_{r,y}}{K_{r,y}}\right) \quad (2)$$

$$R'_{r,y} = R_{r,y} - H_{r,y} + \Delta R_{r,y}$$

In Equation 2, r is the natural growth rate, $K_{r,y}$ is the patch carrying capacity and $R'_{r,y}$ is the resource stock after the regrowth. This paper considers the long run socio-ecological steady state (after sufficient time periods such that $R'_{r,y} \approx R_{r,y}$) and the corresponding spatial Nash equilibrium of extraction decisions.

3 Solution Method

The solution method is set up as an agent based model (Bonabeau 2002, Farmer and Foley 2009, An 2012) and the results are therefore the emergent outcomes from the interactions of the agents' (here extractors) actions. It finds the non-cooperative Nash equilibria for different landscapes, specifically the distance between patches, when there are no constraints over extractors' choices of pathways and extraction patterns. Our approach differs from those approaches that use equilibrium conditions directly in the solution method (for example, Robinson et al., 2008), thus relying on tacit assumptions such as all individuals make identical decisions. In contrast, our solution method, based on an iterative process of sequential series of plans, finds equilibria in which extractors identical in labor endowments and preferences can make different decisions that maximize their individual returns to labor.

The solution method is numerical and thus we introduce discreteness into the labor allocation choice, with the level of resolution reflecting the need for a manageable number of computations. Specifically, extraction in a patch, $l_{i,r,y}$, or wage labor, $l_{i,w}$, is allowed in multiples of 0.05 of an extractor's available labor time, after time spent travelling has been accounted for. Each extractor can visit any number of patches with the constraint that travel time cannot be greater than her total labor endowment. The travel time reflects the shortest travel time costs between patches from which the extractor extracts, assuming diagonal paths are not permitted.

3.1 General solution method

We assume period-by-period (myopic) optimization by the extractors. The non-cooperative solution method searches iteratively for spatial patterns of individual labor allocations that maximize each individual extractor's returns to their total labor, given the actions of all other individuals. The process is as follows:

1. All extractors are assigned an initial labor allocation across resource patches and wage labor.
2. Extractors are then given an order in which they state their plan.
3. One at a time, each extractor i=1… V, sequentially states their plan to reallocate their labor across patches and wage labor. All extractors know distances to, and current state of, each resource patch, the price of the NTFP, returns to wage labor, and the most recent plans of the other extractors. The extractor calculates her returns to labor in the different patches and to wage labor for all plausible labor allocation alternatives, and chooses the one that would yield the maximum return to her labor. If multiple equally valued alternatives exist, the first one encountered is chosen.
4. When all extractors have stated their plan, the process in step 3 is repeated until no extractor wishes to change her chosen labor allocation. Thus extractor by extractor updates their plan iteratively, until each has found a labor allocation from which she does not wish to deviate, given the stated labor allocations plans of the other extractors. A spatial Nash equilibrium has then been found and extractors act on these final plans at the same time.
5. The period then ends and partial regrowth of the resource follows.
6. Steps 1-5 are repeated until the resource stocks and the labor allocations show a stable repeating pattern, at which point the long-run steady state for the myopic single period non-cooperative equilibrium has been reached, and the simulation ends.

The algorithm is easily adjusted to explore more restrictive non-cooperative equilibria by imposing conditions such as extractors only being able to extract from one patch; extractors only being able to extract from one ray; or all extractors choosing the same extraction pattern, to mimic a representative agent assumption.

3.2 Modeling framework to search for multiple equilibria

Four aspects of the solution method are varied to explore the impact of different starting positions and algorithmic steps on the Nash Equilibrium. We first address three extremes of initial labor allocation assignments (Step 1 above): all extractors allocate all their labor to wage labor; all extractors allocate their labor equally across each patch and wage labor; and each extractor is given a randomly assigned extraction pattern. Second we explore the impact of the connection between extraction time periods: specifically whether the equilibrium extraction patterns from the previous period are used as a starting point for the time period that follows; or alternatively if the starting points in each of the time periods are assigned according to one of the three principles described above. Third, we explore the impact of the order in which extractors state their plans, which can either be the same each iteration, or randomized. Fourth, we repeat the above three variations for different levels of initial resource stocks.

Undertaking this sensitivity study for the solution method revealed the occurrence of multiple Nash equilibria which are more prevalent when patches are closer together, and less prevalent at greater distances. When patches are sufficiently far apart there is one unique Nash Equilibrium for each set of distances.

4 Results and Discussion

Although all extractors are identical with respect to endowment and objective function, heterogeneity is introduced through the implementation of the solution method with respect to extractors' initial plans and order of updating. Solutions to the model demonstrate that important differences among extractors exist with respect to the paths extractors take through the resource landscape; the patches they extract from; and whether or not they choose to extract in only one of the patches on their chosen path, rather than multiple. Further, some individuals do not extract at all, but only engage in wage labor. In choosing their sets and pathways of extraction, in equilibrium extractors fall into three general types: patch "specializers" who extract from only one patch; "multipatch" extractors who extract from two or three patches along one ray; and "multiray" extractors who extract from patches in both rays.[1] Which and how many types of extractors are found in equilibrium is endogenous to the model parameterization. Finally, depending on the distances between patches, the four different variations of the solution method can lead to multiple equilibria for the same sets of distances.

4.1 Effect of distance on equilibrium patterns

We demonstrate the impact of distance for three different specific distances between patches. We set all orthogonal distances between patches and the distance

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[1] To these type names a subscript is added to signal which patches the individual extracts from. For example Multiray$_{12,12}$ denotes an individual that extracts in patch 1 and 2 of both rays.

between the village and the first patch equal: $d_0 = d_i = d_r = d$.

"Intermediate" distance d=0.05

With intermediate distances between patches we find multiple Nash equilibria that comprise many different types of extractors. For example, in one of the multiple equilibria for the intermediate distance d=0.05, we find multipatch, multiray, and specializer extractors. Four different extractor types extract from the four patches closest to the village: Specializer$_1$ extractors who collect only from the closest patch in either Ray 1 or Ray 2; Multipatch$_{12}$ extractors who collect from the two closest patches in one of the rays; and Multiray$_{12,12}$ extractors who collect from the closest two patches in both rays, thus spreading their effort across four resource patches each period in equilibrium. Two further types extract from the more distant patches, Multipatch$_{23}$ and Multiray$_{23,23}$. This illustrates the considerable heterogeneity in extractors' spatial extraction decisions, as they locate across the landscape to take full advantage of the available rents. In a second Intermediate d=0.05 equilibrium we find a different set of extractor types: Multipatch$_{12}$, Multiray$_{12,12}$, Multiray$_{1,1}$, Multiray$_{3,3}$, and Specializer$_1$ extractors. Figure 2 illustrates two additional equilibria for d=0.05. In the first, each individual "distance specializes", extracting from patches in both rays at the same distance from the village. In the second individuals "ray specialize", extracting from one or multiple patches in one ray. Studying the various multiple Nash equilibria that we find for this distance, out of the total of 18 extractors, the number doing only wage labor varies from 1 to 3; the number of extractors only going to one ray varies from 2 to 15; and the number of extractors focusing on only one distance away from the village varies from 5 to 16.

Type	# of villagers	Ray	Patch 1	Patch 2	Patch 3	Travel time	Wage labor	Returns to individual
Wage only	2	1				0%	100%	0.82
		2						
$MR_{3,3}$	5	1			33%	35%	0%	0.87
		2			33%			
$MR_{2,2}$	5	1		38%		25%	0%	0.88
		2		38%				
$MR_{1,1}$	4	1	43%			15%	0%	0.83
		2	43%					
S_1	1	1	52%			10%	32%	0.83
		2						
S_1	1	1				10%	32%	0.83
		2	52%					

Type	# of villagers	Ray	Patch 1	Patch 2	Patch 3	Travel time	Wage labor	Returns to individual
Wage only	1	1				0%	100%	0.85
		2						
MP_{23}	3	1				30%	0%	0.90
		2		18%	53%			
MP_{12}	3	1				20%	0%	0.84
		2	28%	52%				
S_1	1	1				15%	36%	0.84
		2	54%					
MP_{23}	4	1		25%	46%	10%	0%	0.82
		2						
MP_{12}	2	1	28%	52%		10%	0%	0.84
		2						
$MR_{1,1}$	2	1	38%			10%	0%	0.83
		2	47%					
S_1	2	1	50%			10%	41%	0.83
		2						

Figure 2: Extractor types and labor choices for two Nash equilibria for the "Intermediate" distance (d=0.05) scenario. Dark shaded patches represent the furthest patch where an extractor extracts from; medium shaded are intermediate patches the extractor extracts from; and light grey shaded patches with a diagonal pattern are those that the extractor passes through without extracting.

"Large" distance: d=0.15

In contrast, when distance costs are sufficiently large, for each distance there is one unique spatial Nash equilibrium in which each individual either extracts from just one patch or only engages in wage labor. For *d*=0.15, there are 13 "specializers" while five individuals only engage in wage labor (Figure 3).[2]

Type	# of villagers	Ray		Patch 1		Patch 2		Patch 3	Travel time	Wage labor	Returns to individual
Wage only	5	1							0%	100%	0.72
		2									
S_3	1	1						10%	90%	0%	1.10
		2									
S_2	3	1				40%			60%	0%	0.71
		2									
S_1	3	1		70%					30%	0%	0.74
		2									
S_3	1	1							90%	0%	1.10
		2						10%			
S_2	2	1							60%	0%	0.93
		2				40%					
S_1	3	1							30%	0%	0.74
		2		70%							

Figure 3: Extractor types and labor choices for the unique Nash equilibrium for "Large" distance scenario

"Small" distance: d=0.005

When patches are almost contiguous, *d*=0.005, the distance costs of moving between patches is very low, producing a landscape close to a zero-dimension patchy resource landscape. Many Nash Equilibria can be found in which most or all extractors extract from every patch ($\text{Multiray}_{123,123}$), with varying levels of labor allocated to each patch (Fig 4)[3].

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[2] At even greater distances, patches eventually become protected by distance alone. No villager enters these patches because all their labor would be used up to reach the patch.

[3] At the extreme, for zero distance costs and no discreteness in labor allocation choices, an infinite number of Nash equilibria exist. Because our algorithm introduces discreteness in labor allocation for the model solution to be tractable, there is a large rather than infinite number of equilibria.

Type	# of villagers	Ray	Patch 1	Patch 2	Patch 3	Travel time	Wage labor	Returns to individual
$MR_{123,123}$	14	1	13%	14%	18%	3.5%	7%	0.85
		2	13%	14%	18%			
$MR_{12,12}$	3	1	76%	20%		2.5%	24%	0.85
		2	16%	20%				
$MR_{1,1}$	1	1	25%			1.5%	49%	0.85
		2	25%					

Figure 4: Extractor types and labor choices for an example Nash equilibrium for ”Small” distance scenario.

4.2 Discussion of the equilibrium patterns of extractor choices

A number of clear regularities emerge from our model simulations. First, when patches are close together, individual extractors spread their resource collection across patches and rays, resulting in a large number of extractors in each patch, particularly in the closest patches. When patches are further apart, we find more instances of different types of specialization, some extract at only distance, some in only one ray, and some in only one patch. At larger distances, all villagers are patch specializers. Second, we find multiple equilibria when the patches are closer together; whereas for larger distances we find a unique Nash equilibrium for each distance. Third, as we parametrically increase distance between the patches, we stop finding multiray extractors at relatively small distances, such as for an intermediate parameterization with d=0.075, whilst we continue to find multipatch extractors (i.e. ray specializers) for larger distances.

The interplay of distance costs moving from one resource patch to another, the spatial inter-connectedness of patches (such that individuals extracting from more distant patches must pass through the closer patches), and diminishing returns to total labor extracting in a particular patch, together drive these complex patterns of equilibrium extraction. Individually, extractors face trade-offs between spending time travelling to more distant patches, and spending more time extracting from patches they must pass through to reach these distant patches. These choices are more pronounced when patches are further apart. Individuals only extracting from nearer patches cannot do better incurring the greater distance time costs to extract in the more distant patches, whilst villagers extracting from these more distant patches cannot do better by allocating any labor to extraction in the nearer patches. Thus in large distance equilibria we find a unique Nash equilibrium with all villagers specializing, implying that some extractors pass through nearby patches without any extraction on their way to more distant patches; and resource stocks greater and marginal returns to labor higher the more distant the patch from the village.

When multiple equilibria exist for a given distance d, at least some individuals must extract from more than one patch (i.e. at least some extractors are not patch specializers). Some of these equilibria differ in the set of extractor types that are found. For example, for our solution method, we find that initially assigning all extractors' labor to only wage labor results in equilibria which more frequently have extractors specializing at only one distance into the resource landscape (see Figure 2a). In contrast, when the initial spatial pattern of labor allocation is assigned by randomization, the solution method generally produces equilibria dominated by ray specializers (see Figure 2b). Other multiple equilibria comprise the same set of extractor types but differ in how extractors split their labor across the same set of patches. These multiple equilibria occur when the average returns to labor for wage and extraction in different patches are equal, implying distances between patches do not drive wedges between the marginal returns to labor in these different patches. Further, the total labor extracting in each patch is the same for all equilibria.

Finally, there is a natural asymmetry between moving within a ray, and moving across rays, with the cutoff distance for finding multiray extractors smaller than for finding multipatch extractors. By moving laterally extractors have access to an additional patch in the alternate ray at a distance time cost that is half of that of moving to the next patch along the same ray, but this patch is more accessible to individuals only extracting within that alternate ray. This kind of tradeoff underpins the occurrence of the two different types of multiple equilibria in which "ray specialization" or "depth specialization" is more frequent among the extractors.

4.3 Constrained extraction

We contrast the long-run equilibrium patterns of resource extraction explored above with equilibria reached if we make various modeling assumptions that restrict the choices extractors can make over the path they take through the landscape and the number of patches that they can extract from.

One patch restriction

First we consider the implications of constraining individuals to extract from one patch (similarly López-Feldman and Wilen, 2008, restrict extractors to one location). This restriction only affects extractors in lower distance settings (including our intermediate and small distance examples), because in high distance cost settings, unconstrained extractors are all patch specializers. We find a unique spatial Nash Equilibrium for each distance. For our intermediate distance we find fewer extractors on average in each patch, with those extracting from patch 3 obtaining returns to their labor almost 20% greater than for the unconstrained individuals who extract from patch 3, but those extracting from closer patches obtaining lower returns (Figure 5a). The constrained small distance setting produces an equilibrium with 3 extractors in each of the six patches. This is in distinct contrast to the unconstrained model where all 18 individuals extract from the closest patches, and returns to labor are lower. Because one-patch constrained extractors do not have the option to cover their distance costs by extracting in multiple patches along a pathway, for smaller distances, the one-patch constraint in general leads to fewer extractors extracting more from more distant patches, and higher equilibrium levels of resource stocks in nearby patches (Figure 6). Thus the one-patch constraint mischaracterizes both the extractor behavior and the pattern of resource stocks in any setting with low to moderate distance costs.

Type	# of villagers	Ray		Patch 1		Patch 2		Patch 3	Travel time	Wage labor	Returns to individual
S_3	3	1						76%	3%	21%	0.91
S_2	3	1				77%			2%	21%	0.91
S_1	3	1		76%					1%	23%	0.92
S_3	3	2						76%	3%	21%	0.91
S_2	3	2				77%			2%	21%	0.91
S_1	3	2		76%					1%	23%	0.92

Type	# of villagers	Ray		Patch 1		Patch 2		Patch 3	Travel time	Wage labor	Returns to individual
S_3	2	1						70%	30%	0%	1.06
S_2	3	1				72%			20%	8%	0.81
S_1	4	1		58%					10%	32%	0.81
S_3	2	2						70%	30%	0%	1.06
S_2	3	2				72%			20%	8%	0.81
S_1	4	2		58%					10%	32%	0.81

Figure 5. Extractor types and labor choices for an example Nash equilibrium for (a) “intermediate” and (b) “small” distance scenarios, with one-patch extraction constraint

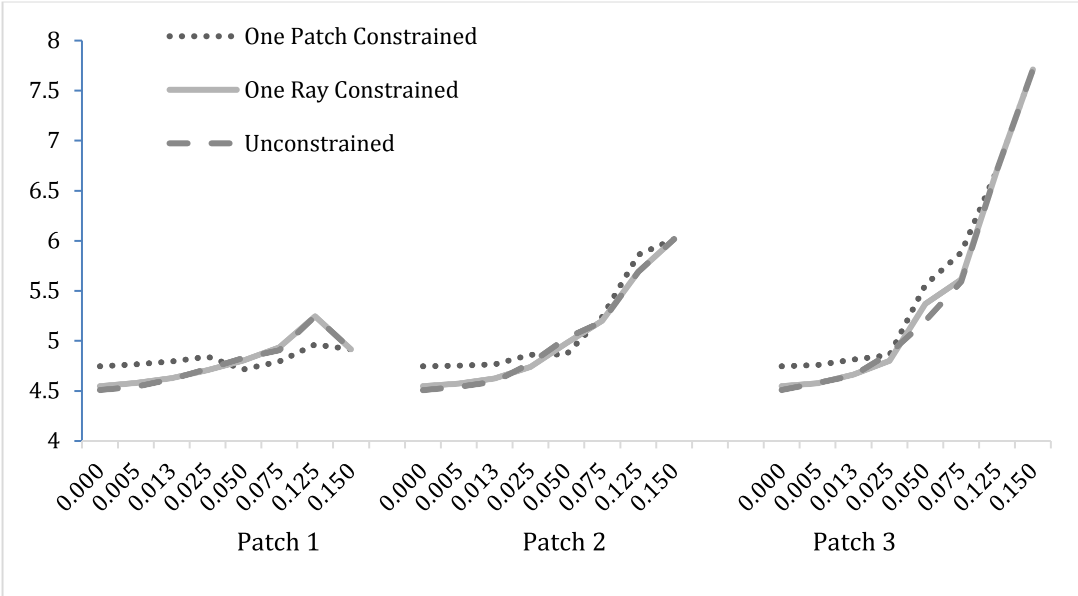

Figure 6: Impact of constraints on villager choices on average resource stocks

One ray restriction

Similar to the one patch restriction, a one ray restriction only affects the equilibrium for smaller distances for which at least some unconstrained extractors would choose to extract from more than one ray (including our intermediate and small distance examples above). Many studies, implicitly or explicitly, assume extraction along a line from a village (for example Albers and Robinson, 2011). With our model we still find multiple equilibria in which some extractors are multipatch extractors, and others specialisers. However, by construction there are no multiray extractors. Such modelling choices change the spatial patterns of resource extractors, but have minimal impact on the spatial resource stock profile for the studied landscape geometries.

Representative extractor

Noailly et al. (2003: 184) write that "agents can exhibit heterogeneous characteristics, interactions between which often lead to 'emergent' patterns that cannot be easily predicted at the population level by using representative agent models". Our findings support this. In this model setup, we constrain all extractors to follow the same pathway through the landscape and make the same labor choices over extraction. We find that for both small and intermediate distances, extractors enter all six patches, behaving as identical $\text{Multiray}_{123,123}$ extractors.

For the small distance d=0.005, compared with the unconstrained case, assuming a representative agent leads to considerably lower extraction per patch and per extractor, and consequently equilibrium stock levels and wage labor are higher. This difference in extraction labor occurs because the representative agent simulates implicitly a rudimentary form of cooperation among identically behaving extractors. For our large distance case, the representative agent allocates all labor to wage labor, in distinct contrast to the unconstrained model.

There are some distances for which the long run equilibrium is cyclical. For example, for d=0.135, the long run equilibrium comprises a repeating cycle where the representative extractor extracts as a $\text{Multiray}_{12,12}$ extractor for two time periods, and then every third period they only do wage labor. This cyclical equilibrium is characterized by alternating intense and zero extraction over space and over time. Such "pulsing" is found in the fishing literature (Sluczanowski 1984; Nøstbakken 2006; Maroto et al. 2009), in situations where moving between resource patches is costly, or when there is uncertainty, or, as is the case here where there is a representative agent (as is also the case for Robinson et al. 2008).

5. Conclusion

The model and solution method developed here permit exploration of the patterns of resource extraction and resource stocks that derive from the interactions of multiple extractors' spatial labor allocation decisions in a patchy resource setting. Unconstrained villagers that face the same landscape, with the same utility function and the same labor endowment, choose very different sets of patches from which to extract, with these choices highly sensitive to the distances between resource patches. Our mechanistic agent based model clearly demonstrates that simplifying assumptions such as representative agents and single-patch extraction can misrepresent the extraction patterns across the spatial setting and cannot reveal complex extraction pathways or heterogeneity in choices from identical extractors respectively. A representative agent assumption is most likely to misrepresent when distances between patches are larger, and underestimate total extraction and thus degradation. A single patch extraction assumption is most likely to misrepresent when distances between patches are smaller.

The different model assumptions generally suggest small differences in resource profile and overall stocks, but much greater differences in the number of extractors found in each patch. The unconstrained model typically finds many more individuals extracting in each patch. This has implications for conflict between extractors, and for species that are not extracted or hunted, but are sensitive to human presence. Differences are also found in the returns to individuals, which are more similar in the unconstrained model.

By providing a more general model of spatial resource extraction, our model and solution method provide a more appropriate starting point to explore the impact of moving from non-cooperative to cooperative extraction regime; or the impact of introducing spatial zoning and access restrictions to protect specific areas from resource extraction and degradation. This paper highlights implications for conflict, equity, and natural resource management in general.

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