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A Computational Model of Nomads

Mobility and Sustainability of African Pastoralists

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Abstract

Nomadic pastoralists inhabit a large area of arid and semi-arid lands (ASALs). This paper offers a simple computational model of pastoral mobility, which is the key component explaining their survival in otherwise inhospitable ASALs. Employing an agent-based modeling (ABM) approach, the model explicitly simulates complex movement patterns of pastoralists over a landscape which shows the typical unpredictable dynamics of African dryland ecology. The model's behavior is assessed against the rich evidence from the prior empirical literature on African pastoralism. The paper also reports on several sets of 'policy experiments' which evaluate the effect of rangeland interventions on mobility and livelihoods of pastoralists. These endeavors will pave the way for empirically richer as well as more policy-relevant analyses of African pastoralism.

1. Introduction

A large part of the Earth's land surface belongs to arid and semi-arid lands (ASALs). In ASALs, with their typical low and unpredictable rainfall, the availability of natural resources (e.g., vegetation, water) is spatially patchy and temporally variable. Nomadic pastoralists inhabit such a harsh environment. In Africa alone, where ASALs occupy about 40% of the land surface, there are an estimated 268 million of people who more or less rely on a pastoral livelihood (AU 2010). The key for their survival in inhospitable ASALs is mobility: nomadic pastoralists constantly move around extensive space with their livestock (camels, cattle, goats, sheep), and exploit spatially and temporally variable resources through grazing of the livestock.

The pastoral mobility is a direct product of the long-time adaptation of pastoralists to the vagaries of ASALs. In recent years, however, this adaptive capability has been significantly challenged. Among various risks and threats that are facing pastoralists, the most serious one is an

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increasingly intense trend of land competition and deprivation with its direct impingement on pastoral resource access and use (Boone 2014; Lund 2008). In Africa, for example, processes as different as state territorial control, agricultural development, wildlife conservation and oil drilling have been converging to bring about a significant level of displacement of pastoral communities (Galaty 2013). The consequences can be quite serious; from bloody armed conflicts over increasingly scarce resources to starvation of millions of people with a single stroke of drought (e.g., East Africa Drought in 2011-2012).

Against these backdrops, this paper offers a simple computational model of pastoral mobility which can be an effective tool for understanding the sustainability of pastoralism in ASALs. Employing the agent-based modeling (ABM) approach, the model explicitly simulates complex movement patterns of pastoralists over a landscape which shows the typical 'non-equilibrium' dynamics of African dryland ecology (Behnke et al. 1993; Ellis and Swift 1988; Oba et al. 2000). Here, the model's behavior is assessed against the rich accumulation of observations and insights found in the preceding literature on African pastoralism. Extensive simulations show that the model actually captures some of the prominent aspects of pastoral mobility, including, among others, the remarkable adaptability this mobility can bring to pastoralists. The paper also reports on several sets of 'policy experiments' concerning land access of pastoralists: simulations which evaluate the effect of various rangeland interventions (e.g., group ranching, land expropriation) on mobility and livelihoods of pastoralists. These endeavors will pave the way for empirically richer as well as more policy-relevant analysis of African pastoralism.

2. Literature

The literature on pastoralism has a long history, and consists of a wide array of academic works in fields as diverse as anthropology, geography, ecology, agriculture, and economics (see Dyson-Hudson and Dyson-Hudson 1980; Homewood 2008; Scoones et al. 2013 for review). The mobility has always been a focus in this literature, especially among anthropologists (e.g., Baxter 1972; Evans-Pritchard 1940), but its importance for pastoralism in ASALs had not easily been recognized in a wider community of researchers and practitioners, at least until the late 1980s. Several decades of outright failures of rangeland interventions in African drylands such as group ranching and settlement schemes, which seriously limited pastoral movements, finally brought this recognition (Niamir-Fuller 1999; Oba et al. 2000; Sandford 1983; Scoones 1994; Scoones and Graham 1994). A new generation of range ecologists, who faced the uncertain and unstable nature—non-equilibrium dynamics—of the dryland ecology, strongly pushed this trend by providing solid theoretical rationales for pastoral mobility (Behnke et al. 1993; Ellis and Swift 1988; Mace 1991; Oba et al. 2003).

With the growing appreciation of pastoral mobility, efforts for data collection on this aspect of pastoralism have been accelerating. From daily herding around a temporary camping site to seasonal movements between ecological zones, pastoralists move on several different spatial and temporal scales. These movements have long been the object of detailed description among anthropologists and geographers (e.g., Bassett 1986; Niamir-Fuller 1999; Sato 1980; Stenning 1957). Along with these studies, there is now a growing body of research which extensively utilizes advanced technologies such as satellite imagery and GPS for tracking movements of pastoralists and their livestock (Butt 2010; Degteva and Nellemann 2013; Ermon et al. 2015; Moritz et al. 2010; Pickup and Chewings 1988; Sulieman and Ahmed 2013).

Despite the growing appreciation of mobility and the increasing volume of data, however, the progress in the literature has been seriously constrained in one important respect: there are few theoretical models which explicitly deal with pastoral mobility (see Dyson-Hudson and Smith 1978; Ermon et al. 2015 for relevant works). There is a distinct lack of behavioral models of pastoralists which can generate coherent explanations and understanding to various empirical observations and insights obtained in the literature. This is especially true about movements of relatively large spatio-temporal scales such as seasonal transhumance (see Coppolillo 2000; 2001 for a formal model of daily herding and grazing): exactly the type of movements which can be most directly affected by the recent intensification of land competition and deprivation.

One possible reason for this theoretical paucity is a substantial amount of complexity involved in pastoral mobility. Pastoralists 'track' unpredictably changing landscapes in pursuit of grazing resources for their livestock (Sandford 1983). In this process, pastoralists also interact with each other as well as with other neighbors (e.g., farmers, traders, state agents, etc.) by mutually raiding, negotiating, trading, sharing and/or avoiding. Each movement made by each group of herders is a product of these strong spatial interactions. Hence, a modeling exercise can easily become too complex to enable a meaningful understanding of the subject at hand, as some of the preceding simulation models of pastoralists illustrate (Boone 2005; Boone and BurnSilver 2002; Thornton et al. 2006). ABM, which is employed in the model described below, makes this complexity methodologically manageable.

3. Model[2]

The model presented here consists of two parts: a spatial environment (hereafter called *Env*) and mutually interacting pastoral agents (*Nomads*). *Env* is a two dimensional grid space representing a certain tract of ASALs. It has a heterogenous spatial distribution of grazing resources, which dynamically changes according to some stochastic rule. Rather than pursuing too much realism at this stage, *Env* here reflects somewhat stylized but still realistic settings borrowed from 'West

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[2] The model is coded in Python 2.7.5 extended with other widely-used modules including NumPy 1.9.0, SciPy 0.14.0 and Matplotlib 1.4.0. The model's implementation partially depends on a Python-based simulator developed by Sayama(2013). The source code will soon become downloadable from the author's webpage (http://researchmap.jp/takuto_sakamoto/?lang=english).

African Nomads Game (WANG),' one of the classical gaming materials for geography education provided by Rice(1975)[3].

Specifically, *Env* provides a single type of grazing resources for *Nomad* agents, whose availability variously changes due to two types of events: *Drought* and *Tsetse*. *Drought* represents different levels of rainfall shortage in the dry season, while *Tsetse* represents a varying degree of spread of tsetse flies—the primary vectors of trypanosomes which can cause serious human as well as livestock diseases—in the rainy season. The occurrence of each of these events is both temporally and spatially controlled in the way depicted in Figure 1. If the timing as well as the location are right for an event to occur, its actual realization and effect are determined according to the fixed probability distributions described in Table 1. In the absence of any of these events, the same amount of resources (normalized to 1.0) is available anywhere other than the settlement sites (land class 3), which are assumed to offer nothing to *Nomads*. Overall, this spatio-temporal behavior of *Env* capture the characteristic West African ecological dynamics, which sharply vary along the north-south direction (from Sahelian to Sudanian to Guinean ecological zones), in a minimum and somewhat exaggerated fashion.

Nomad agents, each of which represents a group of herders, move around in this variable, uncertain environment. They seek grazing resources for their livestock, whose existence is implicitly assumed in the model. For this purpose, each *Nomad* plans a route of monthly movements over a year (*Route*), and carries out this plan by visiting particular locations on *Env* in the designated order. At some intervals of years, *Nomads* adaptively updates its *Route* in response to the amount of the resources actually obtained from *Env* as well as the information on nearby resource availability occasionally collected during the course of its movement. Figure 2 depicts the basic flow of each *Nomad*'s behavior.

When a *Nomad* renews its own *Route*, it considers the specified number of alternative yearly paths along with the existing one that the agent has followed thus far. These alternatives are random combinations of the sites which the agent already visited or scouted. The agent assesses each path by computing its 'potential': lower potential implies more favorable assessment, thus higher probability for the path to be adopted as the next *Route*. The potential is a linear combination of the (negative) expected availability of grazing resources and some costs incurred during the agent's movement along the path. The former is directly derived from the agent's 'knowledge' about surrounding landscape conditions, which has been obtained through its grazing and scouting behavior. The latter is calculated in a quite simple way. For each pair of adjacent sites along the given path, if the distance between the two sites exceeds a certain mobility

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[3] There are several notable differences between the model offered here and West African Nomads Game. Particularly, the former only implicitly assumes the existence of livestock, while in the latter the number of cattle is itself a major state variable. The former also omits another significant type of interactions found in the latter (as well as in reality): livestock trading at urban markets. These omitted dimensions can be fruitfully recovered in the future in order to make the model empirically more relevant.

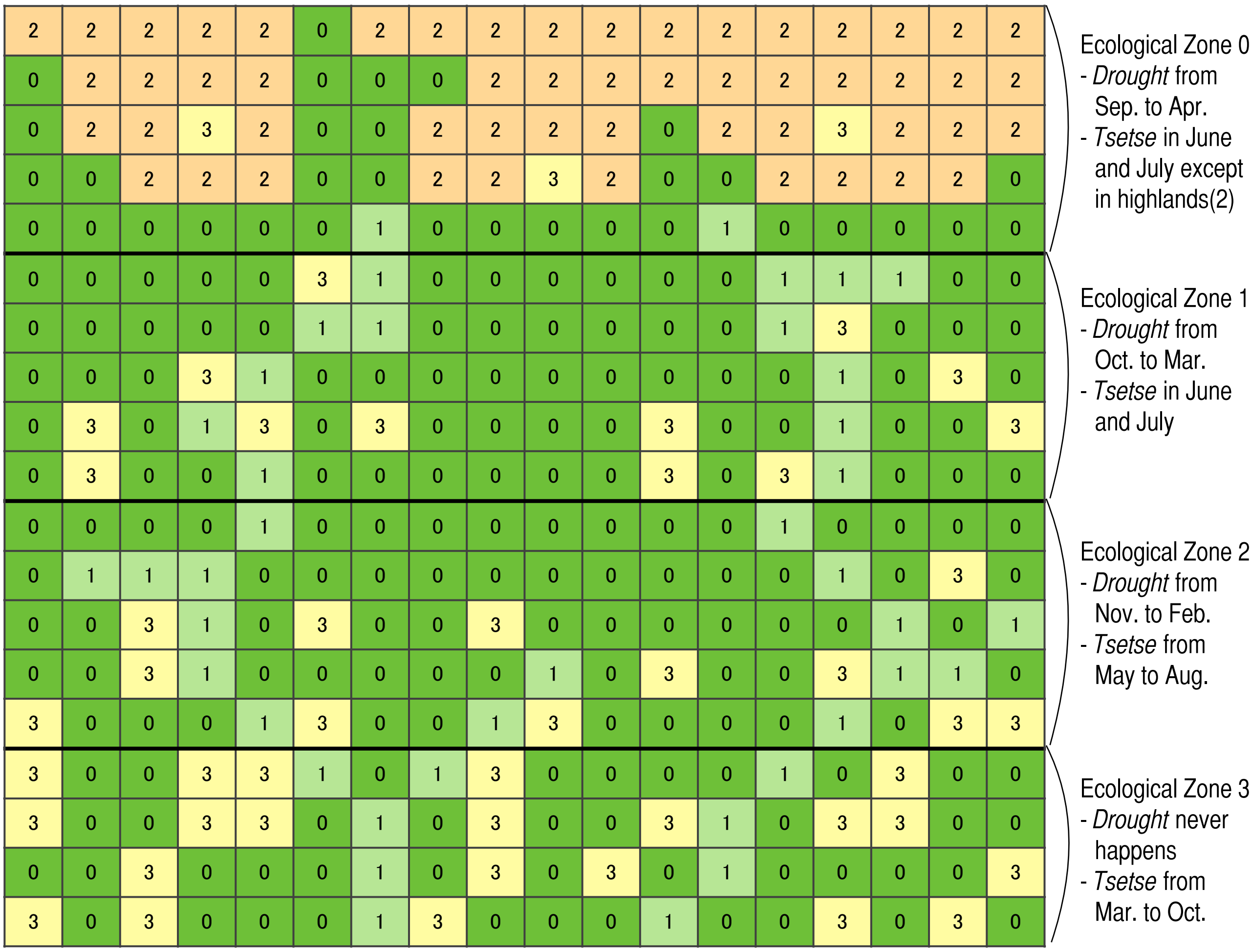

Figure 1 *Env* Landscape Configuration and Event Occurrence

land classes: 0 grassland 1 riverine grassland 2 highland 3 settlement or town

Table 1 Effects and Frequencies of Drought and Tsetse Events

Drought	Effect (reduction in resource availability)	Prob.
major	-50% (riverine areas(1)) -100% (otherwise)	4/36
moderate	-50%(except riverine areas(1))	23/36
no drought	no effect	9/36

Tsetse	Effect (reduction in resource availability)	Prob.
major	-100%	4/36
moderate	-50%	18/36
minor	-25%	7/36
no tsetse	no effect	7/36

threshold, the agent suffers a huge 'penalty.' The overall movement costs of the path is defined as a sum of these penalties. Hence, a physically unrealistic *Route*, whatever benefits it brings about, tends to be discouraged. Finally, the stochastic selection of a new *Route* occurs based on the potential values of the alternatives thus calculated.

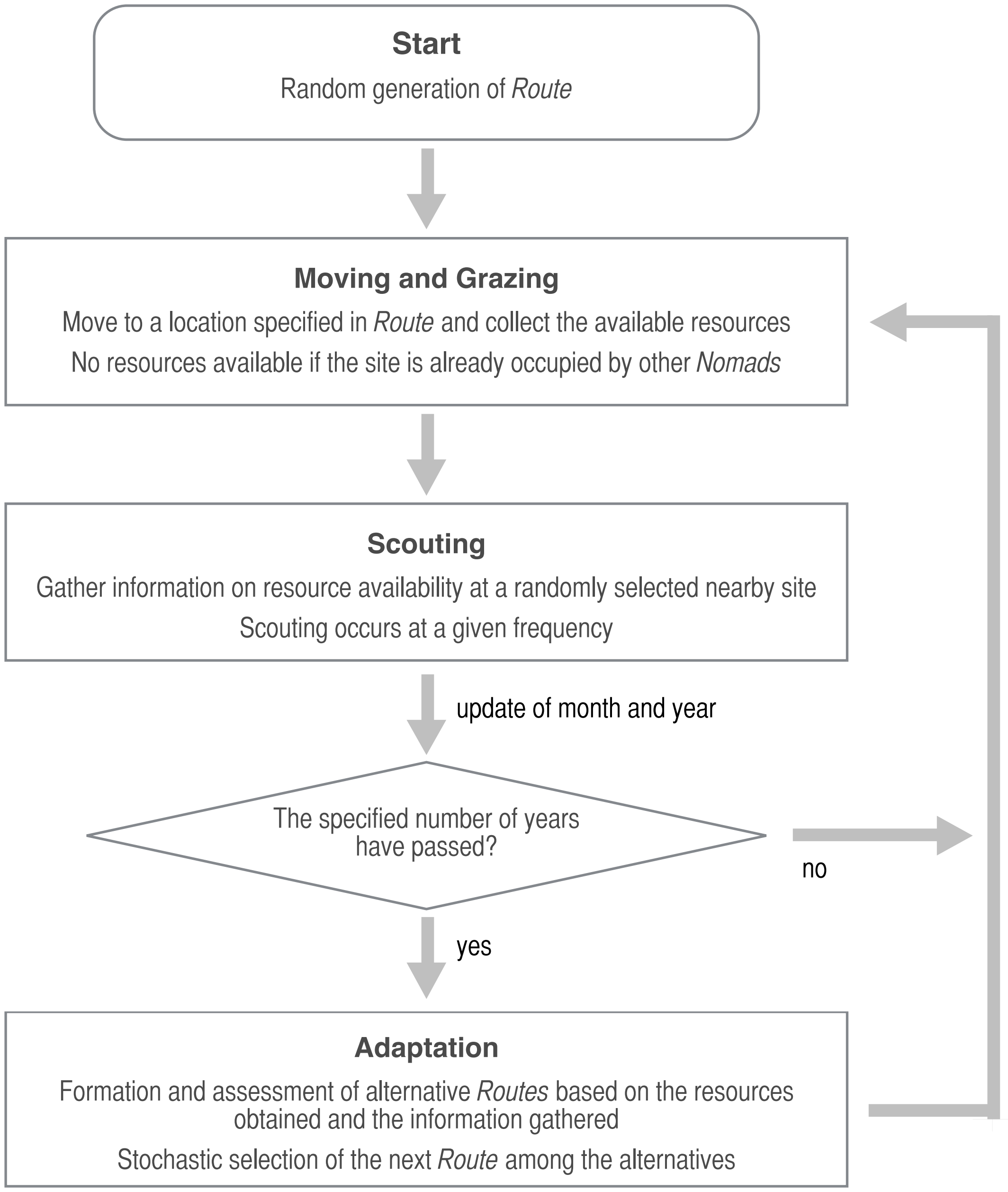

Figure 2 Behavioral Rule of a *Nomad* agent

At present, interactions between *Nomads* happen only when two or more agents stay at the same site in the same month. Then the randomly selected 'first comer' takes all of the available resources, effectively dislodging the other agents. Moreover, following the original formulation of WANG, whenever a site is grazed by a *Nomad*, it becomes 'degraded', and the grazing resources there remain unavailable for the next three months. These rather exaggerated forms of interactions, along with other aspects of the model described above, hugely simplify the diverse and complex nature of pastoral livelihoods. Still, this minimal combination of simplified actions and interactions can capture some of the essential empirical properties of pastoral mobility.

Table 2 The Common Parameters and Their Values

Intervals of Route Update (years)	10
Move Range (per month)	5
Scouting Frequency (per month)	0.1
Scouting Range (from the camping site)	5
Number of Alternative *Routes* Considered (incl. current *Route*)	100
Penalty to Movement beyond Move Range	10
Range of Stochastic Noise Applied during the Update	[0.00001, 0.01]

4. Simulations

This section reports on preliminary results which were obtained through running the model with several different settings. Reflecting the interests posited at the beginning of this paper, the simulation outputs discussed here are spatial movement patterns (as represented by *Route*s) that *Nomad* agents evolve over time as well as conditions of resource access among the agents that these patters bring about. Unless otherwise mentioned, the following simulations were conducted with the parameter values given in Table 2.

One Nomad Model

Given the structure of the model, the simplest possible setting is a scenario in which a single *Nomad* is moving freely over the *Env*: the land access is completely open to this agent without any competitor hindering its land use. Nothing other than its own physical limit (represented by mobility threshold *Move Range* in Table 2) constrains its movement. This is an utterly unrealistic situation but still offers a useful starting point because the observed dynamics there, as will be made clear, have a certain level of robustness against manipulation of different model variables and parameters.

Figure 3 displays a snapshot of the model's typical behavior in such a scenario. It plots successive locations of monthly 'camping sites' specified in the *Nomad*'s *Route* with each circled number denoting the corresponding staying month. Starting from an initial *Route* which consists of randomly chosen sites, the model has evolved a rather clear pattern of north-south transhumant movement across different ecological zones. Specifically, the *Nomad* avoids tsetse flies by staying around highland areas in the north during the rainy season, while it flees impending droughts into more humid southern areas as the dry season progresses. These features are quite consistent with widely recorded movement patterns of Fulani herdsmen in West Africa (Bassett 1986; Stenning 1957; Turner 1999).

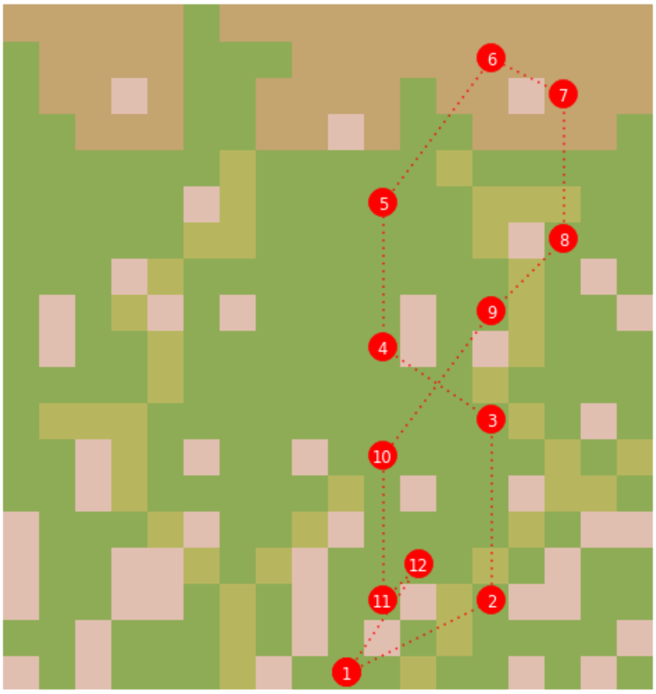

Figure 3 A Snapshot of a Simulation Run

One *Nomad* case; taken after 5000 updates of *Route*

Although this particular snapshot in Figure 3 was taken after 5000 times of *Route* updating, it does not generally take long to see the first emergence of such a pattern of movement. Most of the time, the 'relaxation' occurs fairly quickly, several hundreds of updates at most. Thereafter, the overall pattern of the north-south transhumance basically remains there, although the exact locations of composite sites constantly change and even an abrupt alteration of *Route* can occasionally happen due to the stochastic elements incorporated in the model. Moreover, this dynamically stable pattern of movement is consistently observed across different simulation runs seeded with different series of random numbers. In fact, quantitatively speaking (in statistical tests not reported here), the model's behavior in these different runs are indistinguishable from each other as to various aggregate indicators (e.g., time-average of obtained resources and average distance of monthly movement).

Two graphs in Figure 4 capture the model's dynamics in the one-*Nomad* scenario from a different angle. The top graph depicts the time series of a mean amount of resources obtained during a period between two consecutive updates of *Route*, denoted here as 'Generation', which, given the 10-year update intervals specified in Table 2, amounts to 120 months. The graph suggests that, while suffering occasional fluctuation of resource availability, the *Nomad* managed to access a relatively large amount of grazing resources by tacking the changing environment along the north-south path. This becomes even clearer when the same samples are binned and rearranged as a histogram as in the bottom graph in Figure 4 (the samples obtained from the first 1000 generations

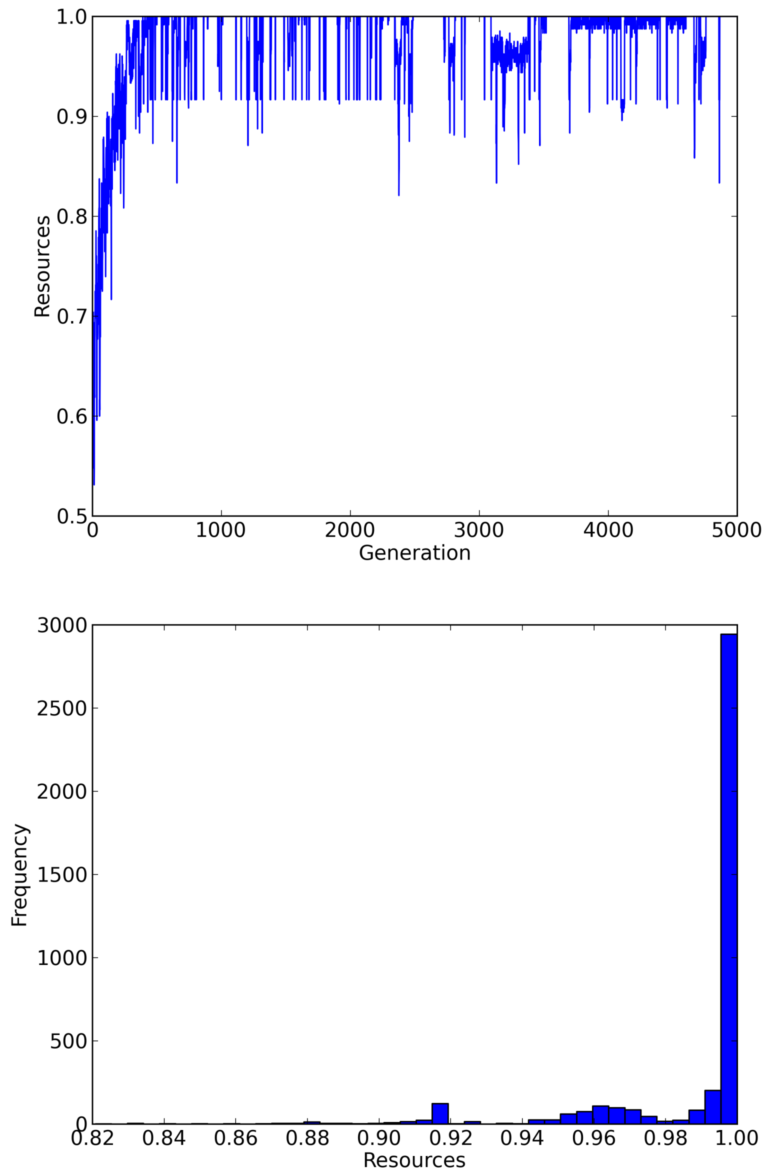

Figure 4 Time-Series and Distribution of Mean Grazed Resources

top: time-series during 5000 updating; bottom: frequency distribution (first 1000 samples omitted)

are removed because of the generally unsettled nature of adaptation process in the early part of a simulation run). At a frequency almost as high as the third quarter, the *Nomad* was able to access the maximum amount of resources available (1.0) during all the months in a generation, avoiding any misfortune that *Drought* and *Tsetse* can pose to it.

Additional simulations, summarized in Figure 5, confirm that the high performance of the mobile agent reported above is a direct product of its constant adaptation to the variability and uncertainty of the surrounding landscapes. The graph illustrates the frequency distribution of the time-means of resources obtained by 5000 different unadaptive agents. A *Route* of each agent here was randomly generated, only constrained by the mobility limit of 5.0. The mean (averaged over 5000 agents) of this distribution is 0.601 (std. dev.: 0.100), while that of the previous one in Figure 4 is

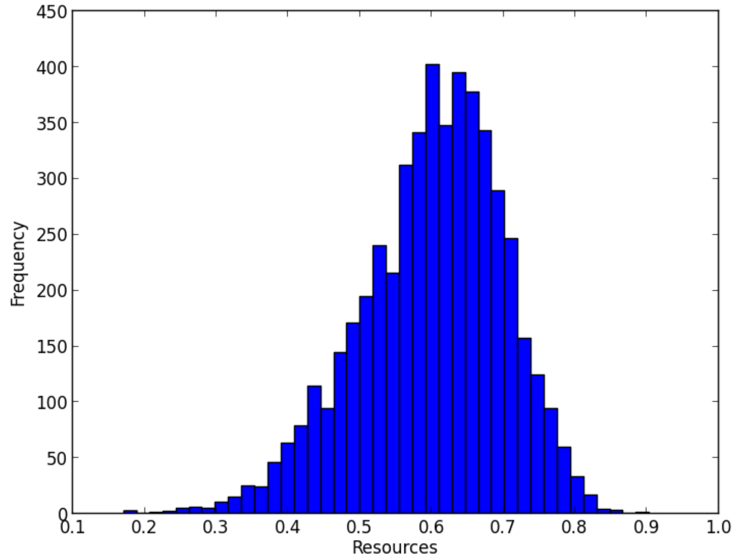

Figure 5 Distribution of Performance of Randomly Moving Agents

Histogram of mean resources grazed during 120 months by randomly generated 5000 *Nomads*

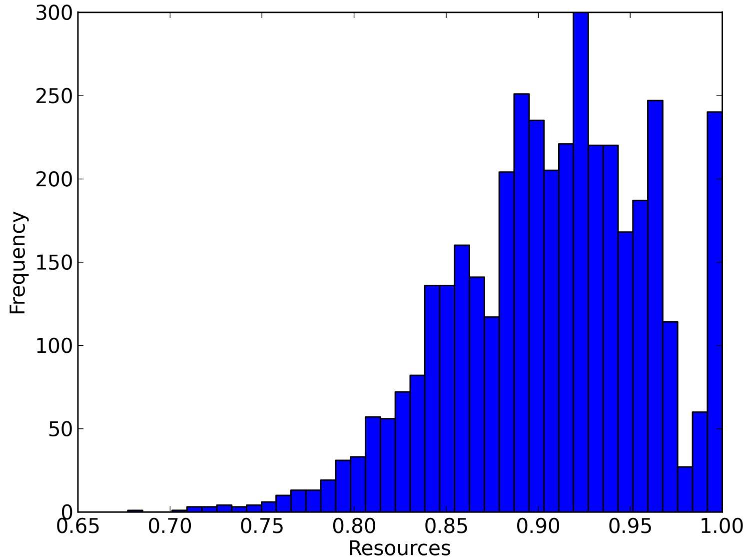

Figure 6 Distribution of Mean Resources in the Case of No Knowledge Inheritance

The same as the run described in bottom graph in Figure 4 except the knowledge inheritance rule

0.989 (std. dev.: 0.024). Without any need to perform a statistical test, it can be safely said that the movement pattern that the *Nomad* evolved brought about marked improvement in its performance in living in ASALs.

This overall conclusion provides strong theoretical support for the ‘mobility paradigm’ which has been developing for the past several decades (Niamir-Fuller 1999). At the same time, however, something more than mere mobility is involved here. Figure 6 summarizes the results from yet another set of simulations. This time, the *Nomad* adapts its *Route* constantly as it did before, but the knowledge about the surrounding landscapes, which the agent has gained while moving and scouting, is never inherited nor accumulated beyond one generation (120 months). In other words, the *Nomad* now has to choose its next *Route* solely based on the information that it has gathered after the previous update event. As the figure illustrates, this change causes a noticeable downturn in its performance with the resources access becoming both more limited (sample mean: 0.907) and more unreliable (std. dev.: 0.053). This result implies that extensive ecological knowledge and its inheritance constitute a major component of the pastoral adaptability, again corroborating the wide array of empirical observations found in the literature (Oba and Kaitira 2006; Sato 1980; Schareika 2003; Sulieman and Ahmed. 2013).

Introducing Interactions among Nomads

Departing from the single-agent setting, this sub-section examines possible effects of introducing multiple agents into *Env*. Given the exclusive nature of local interactions assumed in the model, increasing the number of *Nomad*s generally implies increasing the pressure of land competition. This alteration of settings adds new dimensions to the overall behavior of the model.

Figure 7 shows snapshots of two different simulation runs: one with two agents and the other with ten. The familiar pattern of north-south transhumance is still visible in both panels: the tendency for a *Nomad* to adaptively develop this pattern is highly persistent. On the other hand, a certain degree of disruption of the pattern can also be seen in the bottom panel. Without going deep into the quantitative details, this disruption manifests itself in (1) a decreasing range of movement especially along the north-south direction and (2) a decreasing degree of synchronization among moving directions of different agents. These aspects become even more pronounced as the number of *Nomads* increases still further.

The disrupted mobility has significant welfare implications. As Figure 8 illustrates, the overall level of resource access, as measured by the mean amount of resources which are averaged over both time and agents, steadily declines as *Nomads* begin to suffer from increasingly packed landscapes. Using the case of a single agent as a baseline, for example, two-independent-sample t-test locates the start of noticeable deterioration in the resource access at the 4-*Nomad* case (t-value: 3.00; p-value < 0.01)[4].

Moreover, this overall decline has a serious distributional aspect: a widening gap among *Nomads* as to the resource access. This can be clearly seen in Figure 9, which illustrates how levels of resource access enjoyed by several classes of *Nomads* change as the total population increases. Obviously, the 'minimum' *Nomad*, who performs most poorly in terms of the resource gained in

[4] Since samples gathered in each run of the model constitute a time-series, not randomly sampled measurements, t-test can not easily be performed. Here, along with other similar tests reported below, t-values were computed from a set of measurements which were sampled at sufficiently long intervals. This interval was set to be 100 generations, which ensured a sufficiently low level of serial correlation.

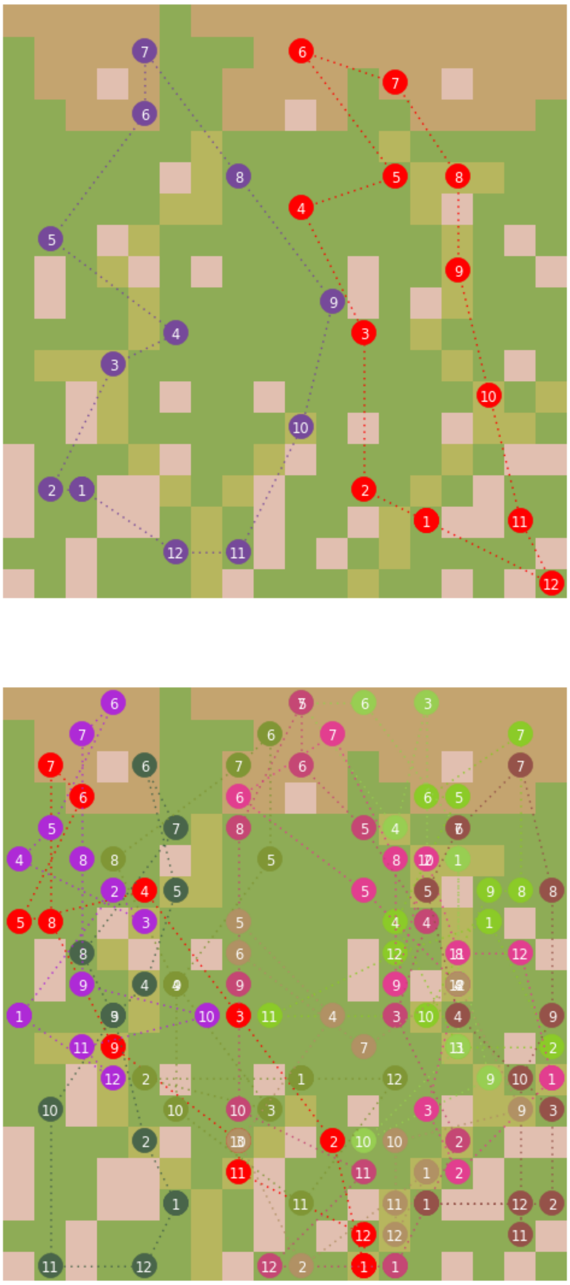

Figure 7 Snapshots of Simulation Runs

top: two-*Nomad* case after 4500 updates bottom: ten-*Nomad* case after 5000 updates

each generation, suffers the most from the increasing pressure of land shortage; whereas the ‘maximum’ *Nomad*, who performs the best, has managed to contain possible loss to a certain minimum. The widening inequality among *Nomads* is also reflected on the stead rise in the standard deviation of obtained resources among all the agents.

Lastly, Figure 10 displays yet another consequence that the increased interactions can bring about. Here, the model’s behavior in each level of population is summarized by using the *monthly* standard deviation of resources obtained by a *Nomad* over a year, which is then averaged over

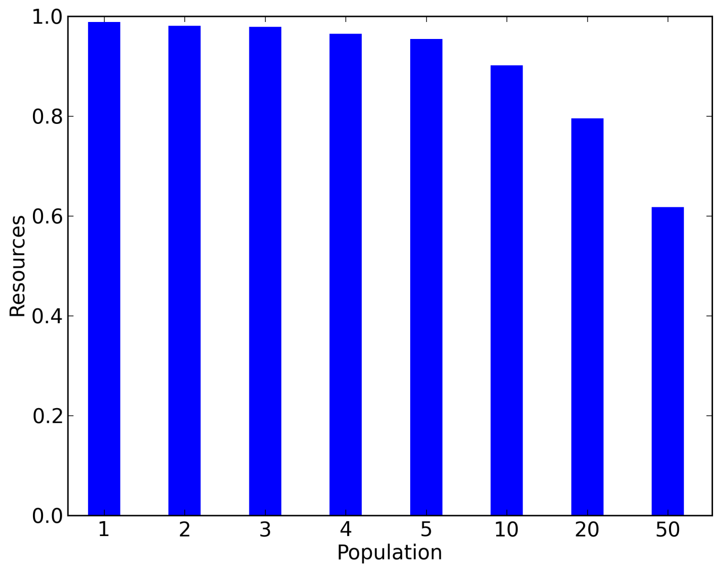

Figure 8 Comparison of Mean Grazed Resources among Different Population Settings

Data obtained during 5000 *Route* updates in each case; first 1000 samples omitted

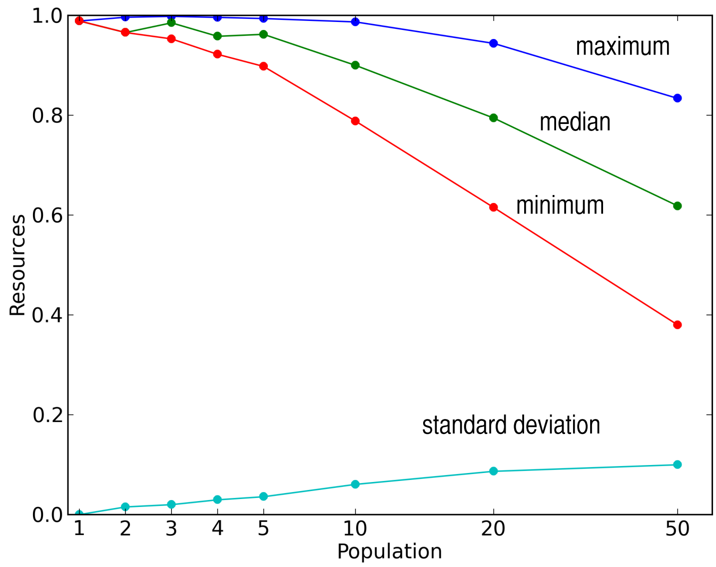

Figure 9 Comparison of Resource Statistics among Different Population Settings

Computed from the same set of data used in Figure 8

time and agents. This indicator, denoting the fluctuation of resource availability over time, can usefully be considered as the overall vulnerability of *Nomads* to the vagaries of *Env*. As the figure tells, increasing the population tends to amplify this vulnerability.

These analyses rather clearly suggest that a heightened level of land competition among a significant number of *Nomads,* through the disruption of their mobility, can lead to overall deterioration in the resource access, widening inequality of this access among the agents, and increased vulnerability of the agents to the unpredictability of drylands. Needless to say, these

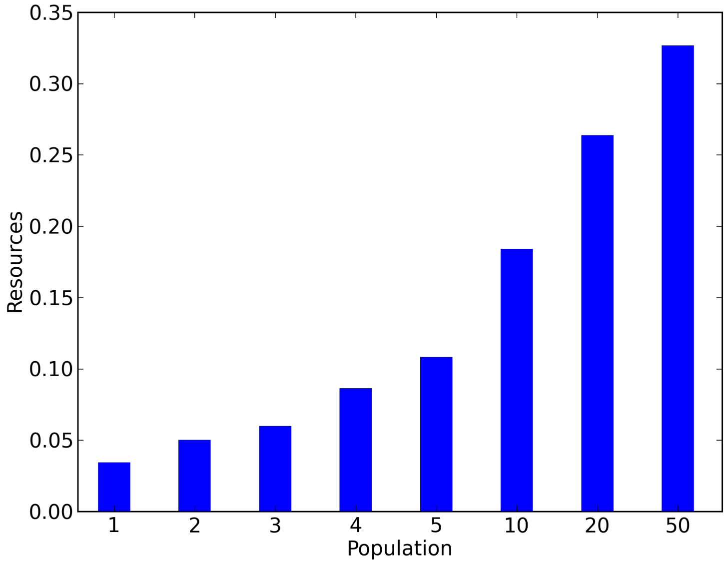

Figure 10 Comparison of Resource Fluctuations among Different Population Settings

Monthly standard deviations of obtained resources; computed from the same set of data used in Figure 8

negative effects depend on various specifications of the model, including the somewhat crude assumption—'first-come, first-served'—about agent interactions. This assumption is not always true. Rather, the nature of relationships among pastoralist groups is mostly reciprocal, and often highly complex (e.g., Spencer 1973). Still, the unfavorable prospects described above can not easily be disregarded because they certainly capture the widely documented aspects of pastoral societies in the current world. In fact, poverty, inequality and vulnerability, along with various other sources of risk, have frequently been associated with reduced means of pastoral livelihoods such as the disrupted mobility (Catley and Aklilu 2013; Fratkin and Roth 2004; McPeak et al. 2012; Opiyo et al. 2014; Toth 2015).

Manipulating Institutional Settings

Given these negative prospects, the next logical step might be seeking ways for ameliorating or avoiding them. While various 'levers' for affecting the model's dynamics are conceivable, an obvious option is finding a proper institutional setting which induces agent interactions towards a more desirable direction. In the context of African pastoralism, institutional matters have most often been discussed with regard to land ownership and land use in ASALs (Lane and Moorehead 1994; Moritz et al. 2013; Musembi and Kameri-Mbote 2013; Niamir-Fuller 1999). As the first step towards a more comprehensive treatment of this subject, some of the standard (and often controversial) rangeland interventions are examined in the simulated drylands.

Two broad types of rangeland interventions are considered: land division and land expropriation. So far, the land access in *Env* has been governed by something similar to a universal 'open access' institution: any *Nomad* can legitimately access and use resources anywhere. The land division changes this situation by dividing the land and assigning each tract to a particular *Nomad* or a particular group of *Nomads* for its exclusive use. This is a somewhat crude notion because, depending on a specific context, the resulting form of land tenure can become either private ownership or group ownership like a group ranch. The land expropriation, on the other hand, takes some portion of the land away from *Nomads* altogether for a totally different land use. Again, depending on a specific context, it can become 'nationalization', 'agricultural encroachment', 'land grabbing', and so on.

Specifically, the following four variants of land division are introduced to the model: (1) 2-by-2 equal division of the *Env* (denoted as '2*2'), (2) 3-by-3 equal division ('3*3'), (3) 5-by-5 equal division ('5*5'), and (4) division of the land into 4 areas along the north-south direction ('1*4'). Each *Nomad* is then associated with one of the areas curved out so that the resulting agent distribution becomes as even as possible. A *Nomad* cannot gain any resources outside its own assigned area. Except these artificial treatments, simulation was conducted just as before.

Figure 11 shows some of the results obtained when ten *Nomads* interact. Both one-way ANOVA (F-value: 236.07 in the case of mean resources, which implies an almost infinitesimal p-value) and non-parametric Kruskal-Wallis H-test (H-statistics: 168.18) strongly indicate that the difference in land division has a significant impact on resource availability to *Nomads*. Particularly, in the most sweeping '5*5' case, the resource access conspicuously worsens. Moreover, the inequality of the access among the agents seems to be heightened, although a 2-sample t-test on the standard deviation against the control case (without any form of land division) could not establish this assertion at stringent levels of significance (t-value: 2.52; p-value < 0.05). In contrast, in the case of '1*4' division, which still allows the *Nomads* to exploit a certain degree of ecological variability along the north-south direction, these negative effects are not so pronounced. Rather, in several indicators, this case is statistically indistinguishable from the control case. All these results suggest that the rangeland regime which disregards the underlying ecological dynamics can have serious consequences for pastoralists, the point made by scholars like Scoones (1995; 1999).

Regarding the land expropriation, simulations were conducted with the following five variants as treatments: (1) random confiscation of 30% of the entire space (342 sites), excluding the settlement areas ('Random'); (2) expropriation of all of the 40 sites belonging to riverine grasslands (land class: 1) ('River'); (3) expropriation of all of the 72 sites belonging to the most humid ecological zone 3 ('Zone3'); (4) expropriation of all of the 56 sites belonging to highlands (land class: 2) ('High'); (5) the same as (4) except that the highlands become open to *Nomads* in two months (June and July) in the rainy season ('High-'). In the expropriated sites, a *Nomad* cannot gain any.resources.

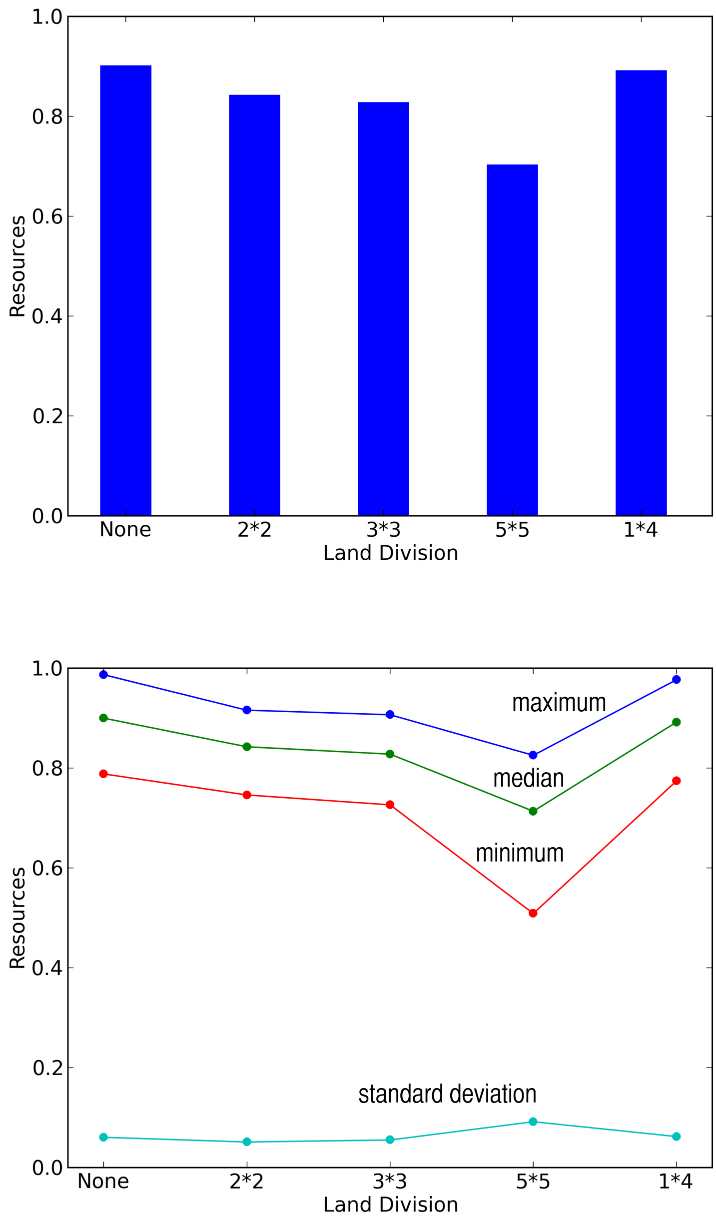

Figure 11 Comparison of Different Land Division Treatments

10 Nomads case; top: mean grazed resources bottom: other resource statistics

Some of the results in the 10-*Nomad* setting appear in Figure 12. Again, one-way ANOVA (F-value: 88.05 for mean resources) and Kruskal-Wallis H-test (H-statistics: 143.48) strongly confirm the overall effects of the difference in land expropriation on various indicators of resource access. As the figure illustrates, different measures of land expropriation generally reduce the availability of resources to *Nomads*, but the specific impact can vary considerably depending on which type of land is actually affected. For example, compared with the control case (without any land expropriation), the 'Zone3' treatment leads to the most marked reduction in the average amount of resources available (t-value: -12.79, which implies a near-infinitesimal p-value). On the other hand, regarding the inequality of access as measured by a standard deviation of resources, 'River' can cause the most undesirable consequence (t-value: 3.83; p-value < 0.001). Lastly, the sharp

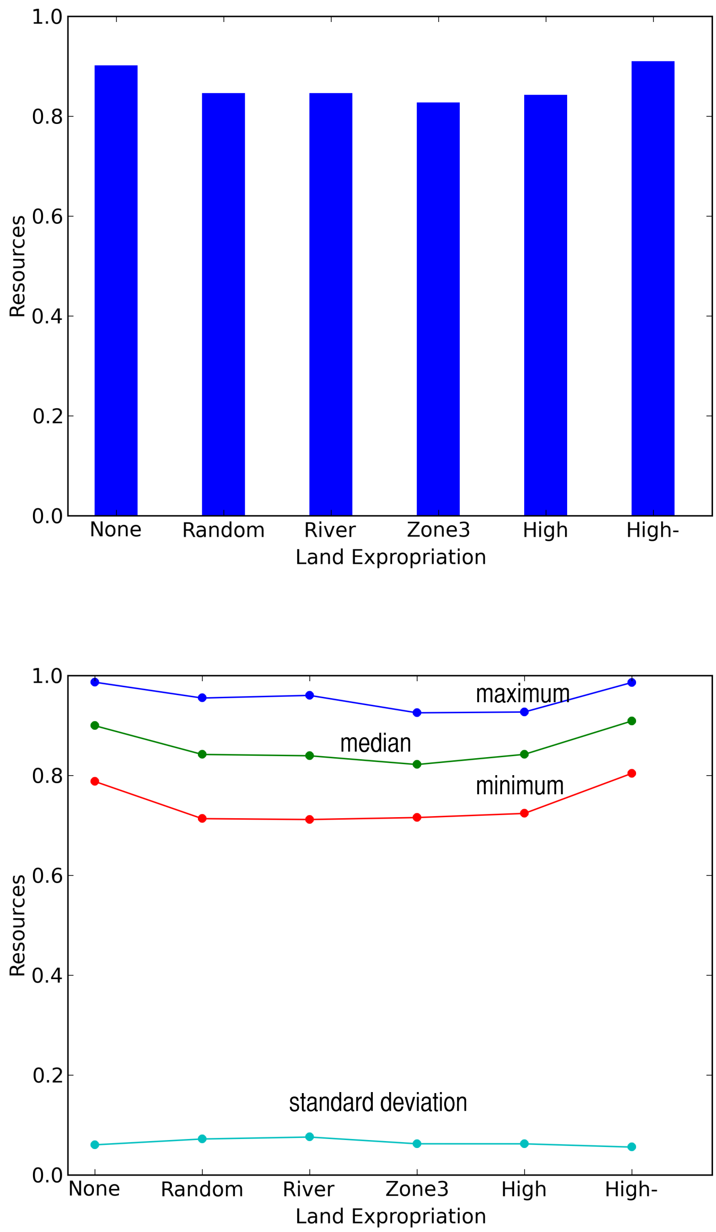

Figure 12 Comparison of Different Land Expropriation Treatments

10 Nomads case; top: mean grazed resources bottom: other resource statistics

contrast between'High' and 'High-' treatments (t-value: 3.83; p-value < 0.001) reveals the critical importance of the temporal dimension of access for a viable rangeland regime.

5. Conclusion

This paper presents an agent-based model of pastoralist movement which purports to advance theoretical understanding of this crucial component of dryland pastoralism. The model has simple structure and simple behavioral rules, often wildly simplifying intricate and complex aspects of pastoral livelihood. Yet it still retains some essential elements of actual pastoralist behavior such as the adaptive adjustment of a movement pattern and the information gathering on local rangeland conditions.

Applied to somewhat stylized ASAL settings imported from WANG gaming material, this model was able to generate a rich array of dynamics and patterns, many of which were quite consistent with empirical observations and insights found in the preceding literature. These include the emergence of a specific transhumant route; the adaptive advantage of pastoral mobility; the importance of ecological knowledge and its inheritance; the disruption of mobility under the condition of heightened population pressure; and its mostly negative consequences on the welfare of pastoral people. While these associations remain qualitative and sketchy at this stage, they indicate the promising potential of this model for a more rigorous fit with the reality.

Moreover, the model was shown to be fruitfully deployed for more practical, policy-oriented purposes. Manipulating institutional settings as to land access and use, some of the standard alternatives of rangeland intervention were introduced to the model, and their effects were examined. Although many of these alternatives such as land subdivision have been harshly criticized and sometimes totally discredited in the past literature, the complicated nature of the results shown above suggests a need for more careful, nuanced evaluations of different policy and institutional options. While being still crude and rudimentary, the model has a potential for becoming a useful policy tool as well.

In order to fully realize these potentials, at least two major challenges have to be met. One is an obvious need for an empirically more sound model. As was already mentioned, there is a substantial body of empirical observations and descriptions about pastoral movement patterns, against which the model's behavior can be rigorously checked. There is also a growing body of spatially as well as temporally fine-grained data on dryland conditions, especially those derived from satellite imagery (Booth and Tueller 2003; Egeru 2014; Ruelland et al. 2010; Tueller 1989). By fully employing these spatio-temporal data, the still abstract and stylized aspects of the model (e.g., time evolution of resource distribution in *Env*) can fruitfully be replaced with more data-driven dynamics.

The other challenge is a need for a formally more flexible model. Given the huge practical challenges that are facing pastoralists, especially those related with the land access, the need for a better policy and a better institution cannot be overemphasized. However, possible policy options and institutional choices are not limited to those examined above. In contrast to land division and land expropriation, both of which are formal and territorial in nature, there are a wide array of more local, less formal and more flexible institutions which pastoral and other communities have developed for managing access to their common resources. Incorporating these into the model is needed, but it is quite a challenge because they are themselves products of decentralized and reciprocal interactions among pastoralists and other people over a long period of time (Behnke 1999; Scoones 1999). A substantial expansion of the model might be necessary in the future.

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