Land Use Patterns in Central Asia. Step 1: The Musical Chairs Model

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Herding and farming coexisted in Central Asia for several thousand years as main options of pre-industrial economic production. The relationship between people practicing different variants of these modes of subsistence is known to have been dynamic. Among the many possible explanations, we explore this dynamic by modeling mechanisms that connect aggregate decisions to land use patterns.

Within the framework of the SimulPast project, we show here the results from step 1 of our modeling program: the Musical Chairs Model. This abstract Agent-Based model describes a mechanism of competition for land use between farming and herding. The aim is the exploration of how mobility, intensity and interdependence of activities can influence land use pattern. After performing a set of experiments within the framework of this model, we compare the implications of each condition for the corroboration of specific land use patterns. Some historical and archaeological implications are also discussed. We suggest that the overall extension of farming in oases can be explained by the competition for land use between farming and herding, assuming that it develops with little or no interference of climatic, geographical and historical contingencies.

1. Introduction

In Central Asia the main variants of pre-industrial economic productions (from nomadic pastoralism to irrigated agriculture) coexisted for several thousand years. This coexistence is well expressed by the term “oasis”, which implicitly refers not only to an irrigated heartland but also to the surrounding steppe landscape. However, within oases, the relation between the different economic activities is known to have been unstable, with plentiful examples of conflict at different geographical scales (Hildinger 2001) and most places having seen shifting patterns of land use right up to the early 20th century (Luong 2004; Chuluun and Ojima 2002; Sabol 1995).

Most historians and archaeologists specialized in Central Asia assume that pastoralism is an exogenous factor, implying that these oases are merely the result of water management practices (Stride et al. 2009). This is because archaeologists working on the irrigated heartlands in Central Asia have a vast amount of data available, whereas archaeologists working on the surrounding pastoral populations have to infer mostly (but often exclusively) from funerary evidence in the form of monumental tombs (*kurgans*). The daily life of herders is thus rarely traceable because of the dearth of permanent structures and nonperishable materials (Cribb 2004) —especially in the heartland of major oases— and therefore scholars are unlikely to consider the complex interactions between farming and herding land uses as a key factor in the existence of the oasis.

From the perspective of behavioral ecology, oases can be seen as the result of niche construction processes (Laland et al. 2000), whereby human groups transform the environment and modify the ecosystem to engineer specific land uses, which in turn will benefit their own survival. As a result of such transformations, the two main human niches, agricultural and pastoral, appear clearly differentiated in the landscape, with large scale irrigation networks, which provide water for agriculture and urban communities, and vast steppe areas, seasonally used as pastures (Fig. 1).

How does the border between farmland and pasture emerge around Central Asian oases and how does it change over time? Several models of interaction between agriculture and pastoralism have been proposed in literature, combining archaeological data with ethnographic and anthropological sources from different parts of the world (Adas 2001; Khazanov 1994; Kradin 2002). Some proposals have been formalized using Agent-Based Modeling, a technique extensively used in Biology —particularly in Ecology— and the Social Sciences, including Archaeology (Costopoulos and Lake 2010; Matthews et al. 2007). Nonetheless, most Agent-Based models representing interaction between agriculture and pastoralism are set on African case studies (Bah et al. 2006; Hailegiorgis et al. 2010; Skoggard and Kennedy 2013; Kuznar and Sedlmeyer 2005, 2008), while for arid Eurasia models are focused either on agriculture (Christiansen and Altaweel 2005) or pastoralism (Rogers et al. 2012). Here we propose a modeling program that revisits some of the theoretical aspects approached by these models, intending to contribute to the building of new theories on the interaction between agriculture and pastoralism and its role in Central Asia oasis land use patterns.

We use computer simulation to test a set of alternative narratives for Central Asian land use patterns and to evaluate their coherence and consistency from a bottom-up perspective. This experience aims at supporting theory building by enabling us to take into account variables and mechanisms that are hard to detect archaeologically, but which could have played a fundamental role in setting the extend of farmlands in an oasis. Archaeology deals with limited evidence and markers, whereas computer simulation offers the opportunity of dealing with the underlying variables and processes, thus helping to reconsider the significance of archaeological evidence and to formulate new field research strategies. We consider this approach experimental for it relies on the controlled manipulation of variables to test hypotheses, not with real settings, but with virtual ones. This paper presents the first results of our experiments modeling a simple set of interactions as co-evolutionary mechanisms, between farming (sedentary agriculture), herding (mobile livestock breeding) and the land covers associated with them (farmland and pasture) . The main aim is to explore the evolutionary processes of Central Asian oases, considered as ecosystems where sedentary agriculture and mobile livestock breeding interact to produce specific land use patterns.

2. Materials and methods

2.1 Modeling in stages

There are likely to be several possible —and not mutually exclusive— explanations for the emergence of the different land use patterns involving the interaction of farming and herding. To try and understand them, we have followed a growing complexity approach in order to avoid replicating the studied problem, without gaining new insights into the mechanisms involved: a) first we establish a reduced set of assumptions, defining a competitive situation, b) we consider a single mechanism —expressed as behavioral rules— that solves this situation, c) then we explore this mechanism for different conditions (which is the subject of this article), and d) we test it in more realistic scenarios by gradually introducing other interacting aspects (as social institutions, geographical settings, climate, etc.). Ultimately, our goal is to evaluate the significance of this interaction in terms of its explanatory power for oasis construction.

The current stage development sets a general (apt to generalization) and abstract (not empirically inspired) mechanism of competition for land use between herding and farming. We assume land units are dominated by either farming or herding, so that the remainder land uses are locally less extended or absent. The territory in question is the portion of land which could be effectively used as either pasture or farmland during a given (competitive) season (Fig. 1). Although at this point we assume that there is no change in environmental and technological constraints, the extension of this area may fluctuate or even change drastically when considering real cases. We further assume that land use demands of both farming and herding increase in time, due to demographic and/or economic growth, so all land available in the territory is assigned to one of these. A direct consequence of these assumptions is that competition between the two land uses will take place, once there are no unassigned land units.

We suggest that a mechanism of small-scale and unplanned adjustments regarding land use assignment is the most basic response to this competitive situation. Expanding farming activities could overcome the predominance of herding in a land use unit, thus switching it to be predominantly farmland. Conversely, the pressure to expand seasonal pastures may entail the transformation of farmlands into pastures. Such adjustments may be produced by unilateral and potentially conflictive actions (i.e. transgressions) between fully independent farmers and herders. However, it is also possible that more complex processes are involved and dependencies between farming and herding land uses cause one to curb itself in favor of the other. For instance, if families engaged in farming are also practicing transhumance, the expansion and reduction of land uses may be the outcome of management at household and community levels.

The Musical Chairs model is a proposal —inspired by the homonymous game— of how this mechanism works. This model mainly addresses the interplay of this type of competition with the *intensity*, *mobility* and *interdependency* of people and resources involved in farming and herding. At this stage, we have chosen not to model any form of institutionalized interaction, such as the exchange of goods or political mediation.

2.2 The Musical Chairs model

2.2.1 Concept

The Musical Chairs model consists of two populations competing for positions in a limited area. Its name comes from the children's game, in which players move around a group of chairs accompanied by music. The difficulty of this game is that, each time the music starts, one chair is removed and so one player, unable to sit in the next turn, is bound to leave the game. Despite similarities, our model differs from the game in four essential aspects:

1. Players in our model belong not to one, but to two different classes and they cannot take chairs from players of their own class.
2. The players of one class stay seated when music is playing, while those of the other can force them out once music stops.
3. Instead of having fewer chairs every turn, the pressure is determined by new players constantly entering the game. Consequently the game never ends.
4. Players can choose to leave the game if conditions are deemed unfavorable for them to stay.

While the chairs of our model represent land units, players are potential (when standing) or effective (when sitting) land use states of these. Thus, when a player successfully occupies a chair, it means that a land unit will adopt the properties of a particular land use variant, including its class (i.e. farming or herding). Land use changes whenever a player takes a free chair or steals one previously occupied by another.

In our model, we assume that such changes are influenced by four conditions (Fig. 2):

a) *Extension*. How many chairs remain untaken by players of the same kind, or what opportunities there are to further extending a given type of land use. The more extended a class of land use is, the less likely it will be extended. This will remain the only relevant factor until there is no vacant chair available.

b) *Intensity*. How strong are the players disputing a chair, or how many people and resources are involved in the competing variants of land use. The more intense is a variant, the more likely it will stay.

c) *Integration*. How many associates do players have within their own class, or how many people and resources involved in land use variants are also dependent on other variants of the same type. The more integrated a class of land use variants is, the more likely it will be extended.

d) *Independence*. How well players value those of the other class, or how many people and resources involved in land use variants are also involved in or dependent on variants of the other type. The more independent a land use variant is, the more likely it will stay and compete.

Finally, the two classes of players behave according to different rules. Players representing variants of herding land use are obliged to stand and move each time music is playing (i.e. herds need to leave seasonally), while those corresponding to farming land use are able to stay in their chairs. While the music plays (i.e. when herds are elsewhere), new players, representing the increasing demand of farming land use, may take chairs previously used by players representing herding land use. Once music stops (i.e. herds arrive), all players representing the variants of herding land use, both old and new, must find a free chair in order to keep playing. At this point, if all chairs end up taken, each player still standing may try to displace a player of the other class, posing a dilemma to be solved by the game: which variant of land use, farming or herding, will take place and which one will disappear.

2.2.2 Design

The model represents the dynamics of land use in and around oasis, specifically the area that can be used either to settle farms or to graze herds. For the sake of simplicity, this area is modeled as a quantity of land units, regardless of spatial distribution. Agents are the land use variants to be associated with land units and they are differentiated by their class (*farming*, *herding*), their *intensity* and their *independence*. The two latter are treated as agents' fixed traits and are initialized as random numbers. *Independence* is a value between 0 and 1, while *intensity* ranges between 0 and an arbitrary maximum. The maximum for *intensity* is class-specific and the difference between classes is defined as the parameter *herding relative maximum intensity* (e.g. if its value is 5, then herding is able to achieve five times more intensity than farming). *Integration* is explored as population-level parameters, which define the proportion of agents of the same class that are connected to a single agent. The time step for the whole system consists of a cycle of four steps (Fig. 3).

Step 1 and 2: *farming and herding expansion*

In the procedures regulating the expansion of each land use, typical growth dynamics (intrinsic and extrinsic growths) are performed over the two populations of agents, which are subsequently modulated by the land use opportunities at a particular time (fit-to-maximum and density-dependent exclusions). Agents generated out of intrinsic growth are copies of those currently present, while extrinsic growth is modeled as the creation of agents with randomized parameters. Farming expansion is yet constrained by another specific operation, the volition-opportunity exclusion: new farming agents will only stay if they are sufficiently independent from herding or the number of land units used by herding agents is sufficiently small.

Step 3: *update land use*

Once growth is calculated, the *update land use* procedure will assign the values of the two land use alternatives, *farming* and *herding*. The amount of farmland at the start of the competitive season will be proportional to the number of farming agents present in the territory, whilst the land available for herding agents is limited to the remainder area.

Step 4: *check competition*

The *check competition* procedure is the one actually accounting for events during the competitive season. In it, the resolution of single competitions between herding and farming agents (*resolve competition*) is performed repeatedly, either until all area required by herding agents are taken, or herding agents themselves are reduced to match the available land.

In the *resolve competition* procedure, one herding agent and one farming agent are randomly-chosen to be the ones driven into competition (the *unlucky*). Specific helpers are also randomly-chosen among each class of agents, accordingly to the respective degree of *integration*. The overall *intensity* of each party is summed up and compared (*ratio of intensities*, where 1 represents the maximum score for herding). The incentives that the *unlucky* herding agent have to pull back its land use (*incentives for relinquish*) is then quantified, as a function of the *ratio of intensities* and the current land use pattern. This value is then compared to its degree of *independence*. Depending on this comparison, the *unlucky* herding agent will either be excluded from the simulation or press for the use of a randomly-chosen land unit, currently occupied by a farming agent. If the latter is the case, the situation will be accounted as a *dilemma event* and the *ratio of intensities* will serve as a probability of the herding land use variant being extended over farmlands. Moreover, if herding is finally extended, the *unlucky* herding agent will be able to stay and displace the *unlucky* farming agent, accounting as an *oasis degression event*. Any agent without an assigned land use unit at the end of this cycle is removed from the simulation.

Implementation and simulation of the Musical Chairs model were done using Netlogo (Wilensky 1999). An extended description of the model, following the ODD protocol (Grimm et al. 2006), is available in Appendix 1.

2.3 Experimental setting

Experimentation in the Musical Chairs model was focused on 1) identifying the conditions in which different land use patterns emerge through competition, and 2) in which conditions selection of the agent's traits, intensity and independence, occurs.

For these purposes, we designed a set of predefined experiments (Table 1), in which several specific conditions regarding the parameter space were explored in regular intervals within a realistic range of values (112 parametric settings, 10 repetitions each, 1120 runs in total). Plots containing data of predefined experiments use the following abbreviation: *ext* stands for both *farming and herding extrinsic growth rates*; *integ* stands for both *farming and herding integration*. Also, a single randomized experiment with 2500 runs was undertaken, exploring a broader range of parametric settings in a stochastic manner. All experiments were executed in a world with 2000 land units, a midpoint between unnecessary computational costs and unrealistic path-dependency due to low resolution. Variables were measured once simulations reached 600 time steps, a sufficient number for equilibrium to be achieved.

3. Results

3.1 Initial extensions

We explored different scenarios of initial conditions to detect possible dependencies on the scale of the initial extensions of the two land uses and the unbalance between them. Sensitivity to both of these variations was only detected in one scenario: with integration levels at maximum (*integ* = 1), no extrinsic growth (*ext* = 0) and herding maximum intensity doubling the one of farming (*herding relative maximum intensity* = 2). Under these conditions, while settings with unbalanced initial extensions are more favorable for the initially most extent class of land use, balanced extensions of greater scale will favor farming land use (Fig. 4). All other scenarios returned no systematic variance related to initial extensions and randomized experimentation (Table 2) clearly indicates that these parameters have no statistical value for explaining the diversity of outcomes.

3.2 Land use patterns

Regarding the use of land, the final states of all performed simulations were either equilibrium or quasi-equilibrium, i.e. the land use pattern either did not change or had small fluctuations. Since all final states are saturated —i.e. land is completely used either for farming or herding—, land use pattern can be assessed by simply accounting for the proportion of farming land units or the percentage of farming.

Classes of land use patterns

Three classes of oases emerge, qualitatively distinguished by their trend in land use patterns (Fig. 5, Table 2):

- *Big oases*. We classified as big oases those states where nearly all land units are predominantly used for farming. It is generally achieved when farming land use variants are the most intense and integrated.
- *Small oases*. We classified as small oases those states where nearly all land units are predominantly used for herding. It is generally achieved when herding land use variants are the most intense and integrated.
- *Intermediate oases*. We classified as intermediate oases those states where farming and herding activities use equivalent proportions of land during the competitive season. It is achieved only when conditions are fairly balanced between farming and herding and both experience extrinsic growth.

No pure solution

Because the *density-dependent exclusion* is applied for both populations, their simultaneous presence is extremely likely. Whatever the conditions, settings dominated by one land use always present some marginal area used by the other (i.e. the percentage of farming is never equal to 0 or 100).

Model's good predictability

Strongly path-dependent equilibria —those whose development is very sensitive to initial conditions and stochasticity— occurs only in a single predefined experiment, when there is no extrinsic growth (*ext* = 0), integration levels are at maximum (*integ* = 1) and the herding maximum intensity is exactly two times higher than the one of farming (*herding relative maximum intensity* = 2). Consequently, all other equilibria presented here are fairly predicted by the conditions expressed by the parameters, especially by *herding relative maximum intensity*.

Maximum intensity

There is a strong negative correlation between the percentage of farming and *herding relative maximum intensity*, returning a clear range of variation within which land use pattern will be different depending on this parameter (i.e. extremely low and high values of the latter correspond with big and small oases, Fig. 6). The parameter *herding relative maximum intensity* strongly conditions the outcome of *dilemma events* and, thus, the rate in which farmland is successfully converted into pastures (*oasis degression events*).

Integration and extrinsic growth

There is no linear effect of balanced *integration* levels and *extrinsic growth* rates on the land use pattern, within the conditions explored in the predefined experiments. However, unbalanced integration levels, as explored in the randomized experiment, return oases in which the most cohesive land use tends to be the most dominant; e.g. in Table 2, big oases have a higher mean of integration for farming than for herding.

More significantly, these parameters strongly interact with *herding relative maximum intensity*, by modifying its impact on the land use pattern at equilibrium (Fig. 6). Whenever there is absolute *integration* (*integ* = 1), the variation of *herding relative maximum intensity* presents a narrow threshold around 2, separating the conditions in which big oases (*herding relative maximum* *intensity* < 2) and small oases (*herding relative maximum intensity* > 2) are likely to exist, and so rendering intermediate oases extremely unlikely.

In turn, contrasting with the effect of *integration*, the increase of *extrinsic growth* rates widens the aforementioned threshold range and, consequently, makes intermediate oases more likely within the conditions explored; e.g. again in Table 2, the greater means for both *extrinsic growth* rates correspond to the cluster of intermediate oases. *Extrinsic growth* also boosts the effect of *herding relative maximum intensity* on the land use pattern at equilibrium, so the latter can be accurately predicted by considering this parameter, even if they represent intermediate oases; in Fig.6, note the narrower variability of data within each condition of *herding relative maximum intensity* when *extrinsic growth* is present (*ext* = 0.25).

Bias in land use assignment

The Musical Chairs model returns an asymmetric dynamic between farming and herding land uses, in which the former is clearly favored. Although experimentation used an unbiased sampling of values for the explored parameters, big oases are the most probable equilibrium, contrasting with a much lower frequency of small oases. When *herding relative maximum intensity* equals 1 —a condition that is supposedly neutral— settings generally have more farming than herding land units; hence, when the levels of *intensity* are balanced, the sole dynamic of competition is shown to favor farming land use.

As the behavior of herding agents is the only one sensitive to the *ratio of intensities* (Fig. 2), the scenarios with evenly distributed intensities (*herding relative maximum intensity* ~ 1) and high *integration* of both land uses (*integ* = 1) facilitate farming land use. A good estimation of the presence of herding activities –and thus their land demands— cannot exist without information on the intensities involved, and this information is not available when herds are not around. This limitation end up restraining less the expansion of farming land use, and utterly unbalances the *ratio of intensities* against herding.

Furthermore, according to this model, competition for the use of land mostly returns equilibria dominated by either one or other land use, and intermediate situations are relatively unlikely (e.g. see the bimodal distribution of the percentage of farming in the randomized experiment, Fig. 5). In predefined experiments, they only occur when there is no integration among land units (*integ* = 0) and herding maximum intensity is approximately between the same and the double of the one of farming (1 ≤ *herding relative maximum intensity* ≤ 2).

3.3 Stability

The number of *dilemma events* occurring in a time step represents the amount of attempts made to change one land use unit from farming to herding. On the other hand, the number of *oasis degression events* is the number of those attempts that actually succeed. Together they are indicators of both potential and actual rates of change in land use assignment, and therefore may be understood as measures of the instability of a given land use pattern (i.e. the greater they are, the less stable).

Experiments (Fig. 7, also Table 2) show that the number of *dilemma events* is higher whenever the outcome is most unpredictable (*herding relative maximum intensity* ~ 1). However, it features its lowest values in equilibria in which either farming can be much more intense than herding or farmlands are too scarce and marginal to be considered for grazing (e.g. when *herding relative maximum intensity* is extremely low and high, respectively). Generally, according to this model, big oases should be more *conservative* (i.e. with fewer land use changes) than small oases, although the least stable oases are by far the intermediate ones, with the highest frequency of both *dilemma* and *oasis degression events*.

If there is *integration* among land units, the occurrence of both *dilemma* and *oasis degression events* is drastically lower. *Integration* increases the certainty of the outcome of a *dilemma event* by defining more clearly the dominance of a land use, and so discourages any change against it. In turn, *extrinsic growth* rates have a strong positive effect on the frequency of *dilemma* and *oasis degression events* (note the difference in the scale of *dilemma events* between *ext* = 0 and *ext* = 0.25). Because all potential variants of land use may press to change the current state of land use, a higher extrinsic growth rate of both farming and herding land uses, as explored in the predefined experiments, will generally increase the number of *dilemma events* at equilibrium. This is also shown by the randomized experiment, as intermediate —thus relatively unstable— oases coincides with significantly higher *extrinsic growth* rates (Table 2).

3.4 Selection of intensity

The simulations show very clear positive selection of intensity for both classes of agents, whenever there is no integration (*integ* = 0). *Integration* is once more affecting the relevance of *intensity* in the emergence of a type of oasis, now by entirely suppressing the selection for more intense land use variants. This illustrates again an interesting characteristic of this model arising from analyzing land use patterns and stability: the greater the integration within classes, the less important the intensity of individual land units. When land units are connected, variation in *herding relative maximum intensity* will only be relevant around a relatively confined threshold range. On the other hand, the scenarios where selection exists can be better characterized by considering the different values of *herding relative maximum intensity* and *extrinsic growth* rates (Fig. 8). Selection on *farming intensity*, when there is neither *extrinsic growth* nor *integration* (*ext* = 0, *integ* = 0), and on *herding intensity*, when there is *extrinsic growth* but no *integration* (*ext* = 0.25, *integ* = 0), are both stronger with greater values of *herding relative maximum intensity*. *Extrinsic growth* (*ext* = 0.25, *integ* = 0) modifies the effect of *herding relative maximum intensity* on the selection of *farming intensity*, by shifting it to an opposite trend, in which maximum selection is achieved at fairly stable big oases and small oases are not selecting farming land units for their intensity. Finally, when there is neither *extrinsic growth* nor *integration* (*ext* = 0, *integ* = 0), more intense herding land units always suffer some significant level of selection, though maximum is reached when big oases still present a some opening for *dilemma events* to develop into *oasis degression events* (i.e. *herding relative maximum intensity* = 0.5). Put in fewer words, *extrinsic growth* both enables and compels the concentration of people and resources involved in the most extended land use —farming land use in big oases, herding land use in small oases— by having more intense land units under greater positive selection, whilst the *integration* among them (*integ* = 1) cancels this mechanism.

3.5 Selection of independence

Independence is generally under positive selection (i.e. the more independent, the more successful). Furthermore, there is a positive correlation between *independence* and *herding relative maximum intensity* for all agents under any condition (Fig. 9). This means that a greater potential for the development of herding intensity corresponds to a greater overall selection of *independence*. Similarly to what was seen regarding land use patterns, this effect is modulated by *extrinsic growth* rates and integration levels, through expanding and narrowing, respectively, the variation of selection of *independence* throughout values of *herding relative maximum intensity*.

Considering that *independence* is tested against different information at different moments, depending on the class of agent, selection of this trait shows different patterns of variation. In big oases, nearly all land units are assigned to farming variants and *dilemma events* frequently are resolved as unfavorable to herding. Consequently, the condition for farming land use to be extended (i.e. that the new variants have *independence* greater than the relative extension of herding) will only favor the selection of more independent farming variants until equilibrium is reach (pictured as a moderate upward trend of the index of selection for the *independence* of farming). On the other hand, as a marginal land use in big oases, herding will only present such *footprint* when there is no *extrinsic growth* (*ext* = 0). In this case, most of the native remaining herding variants descend from previously independent and relatively intense *parents*, selected before equilibrium is reached. In contrast, as newcomers can displace the native herding variants by using the marginal land kept as pastures, *extrinsic growth* breaks this pattern and chance becomes the most important factor for a herding land use variant to exist.

In small oases, where nearly all land units are assigned as pasture and *dilemma events* are normally resolved in favor of herding, the conditions for land use variants to remain in the territory filters the greatest values of *independence* for both farming and herding alike. While only the most independent farming land use variants can overcome the great risk of being removed in a territory dominated by herding, more independent herding land use variants are also more likely to be represented, for they are the ones that are able to counteract the *hopeless but stubborn* pressure of farming land use demands.

4. Discussion

Herding and farming, with their related lifestyles (nomadism and semi-nomadism vs. sedentarism), are attested in Central Asian history as coexisting and interacting from Prehistory up to the Soviet land reorganization of the 20th century. This interaction is known to have taken many different forms and many factors have played a role, from cooperation and trade to conflict.

The starting hypothesis of this research was that the coevolution between herding and farming could be considered as a socio-ecological process within a human environment adaptive system (Folke 2006), leading to the enhancement or suppression of Central Asian oases. In this experiment we specifically explored if equilibrium could be reached simply through a mechanism of competition for land use. Our interest was in understanding under which conditions and in which form this equilibrium could be reached, retained or altered as well as which other land use traits may be selected in an evolutionary perspective.

4.1 Land use patterns

Simulation results show the emergence of three classes of oases: *big* (all parcels used for farming), *small* (all parcels used for herding) and *intermediate* (both farming and herding are present in equivalent proportions). It must however be stressed that these categories do not refer to the absolute size of an oasis, but to the extension of farming land use in relation to herding, within the area that could be used for both activities.

This said, the simulations provide the following insights:

- *Bimodality*. In most cases, one land use becomes predominant, and the intermediate setting is the most unlikely outcome.
- *Tipping point*s. The crossing of parameters thresholds can lead to drastic and rapid changes in the equilibrium. This characteristic is consistent with the historical and archaeological evidence for Central Asia and it may help explaining the historical oscillations in land use. The rapid and radical breaks of settlement pattern, which are often visible through the archaeological record from the Bronze Age up to the 20th century, could be showing how an underlying mechanism of competition for land use responds to changes at other levels (e.g. the introduction of horses, the opening and closing of trade routes, the growth and competition of polities).
- *Oasis in borderlands*. The competition for land use is sensitive to *extrinsic growth*. *Extrinsic growth* may be interpreted as a twofold process: (1) the movement of people and resources into the territory and (2) the increase of external pressures over the local production (e.g. market demand, political factors, due to a rise of prices). Consequently, when oases are connected as a network of territories, in which people and resources involved in both activities are circulating through migration, trade or political bonds, intermediate oases may become more and more frequent. This means that a rather closed territory with low permeability will tend to be dominated by one land use, relegating the other to its periphery. In historical terms, this association could provide insights into the role of the porosity of borders (political and geographical) in different parts of Central Asia and of Eurasia in general.

4.2 Farming: further and beyond

The model suggests that farming can spread similarly to an epidemic outbreak, infecting the next parcel of land faster than herding. The basic parameter in epidemiology is the reproductive number, which results from the relation between the spreading rate and recovery rate, under the assumption of the homogeneous mixing of population (Barthelemy et al. 2005). In our model, the analogous to the reproductive number (*ratio of intensities*) is calculated on the basis of the *intensity* of each class of land use and its *integration*, as an expression of the probability that a variant of land use has of taking place instead of another. Simulation results show clearly that when intensities are balanced, farming is always favored.

The predominance of farming in a balanced situation derives from the model's assumption that farming is a sedentary activity and herding relies on mobility. This implies that people engaged in farming have their interests put in specific parcels on a year round basis, for they depend on immovable investments of crop cultivation. On the other hand, people engaged in herding are interested in having enough grazing ground for herds, but only during a specific part of the year. Therefore, only the latter can assess reliable information on the intensity of both land uses (e.g. if a family has abandoned a field or if a herd was decimated by a plague), in order to decide if and how to develop their own activity during the competitive season. It follows that, in the whole set of scenarios, herders will curb their land use inside the territory —e.g. concentrating the herds, changing their routes, selling or butchering animals— more often than farmers. This apparently trivial consideration on the relative advantage of sedentarism with respect to mobility has major consequences if understood in a wider context. For instance, consider the relatively rapid spread of agriculture in the oases of the arid Eurasia, which were previously used as seasonal stations by more mobile people (Rosenberg 1998).

4.3 Herding: united in the margins

Simulation shows that, whereas farming land use has a systematic advantage to grow, herding will only be extended around oases if the people and resources involved can be more concentrated and/or integrated than those dedicated to farming. Considering that *intensity* is constrained by material costs and possibilities, which normally are less flexible, changing *integration* appears more significant for explaining those changes in land use that hardly correlate with environmental or technological factors. A progressive increase of herding integration in relation to that of farming can rapidly turn the tide of land use patterns, transforming a big oasis into a small one. Since *integration* is the connectivity among people and resources involved in the land units of the same class, it can be interpreted as a proxy of territorial identity and political cohesiveness, highlighting the importance for pastoral societies of investing in kinship and group identity reinforcement. This model suggestion confirms ethnographical and anthropological observation on pastoralism in Central Asia (Lindholm 1986) and other regions (Notermans 2003; Sneath 2007). Moreover, we can postulate that the emergence of strong pastoral identities is the result of the pressure of farming on key point of transhumance, such as oases. Archaeologically, this can be associated for example with the well-known nomadic expression of the burial tumulus (*kurgans*). These burials are often interpreted as group identity markers and their presence often indicates territorial borders with respect to the expansion of irrigated agriculture.

It is also particularly significant that in the small oases —the ones in which herding predominates— the selection of *independence* for both farming and herding land use are always higher than in the other two classes of oases, while the number of *dilemma events* is comparatively low. Therefore, the model predicts that small oases with a fairly stable land use pattern will coincide with a divergence of interests between people involved in herding and farming. This prediction fits well with the consideration that, whereas there are abundant cases of well mixed and interdependent economies among regions dominated by farming (e.g. Zeravshan valley in Uzbekistan), there are very few of them in areas where herding is the predominant form of land use (e.g. Semirecheye in Kazakhstan).

5. Conclusions

The present stage of our modeling program was limited to the exploration of the dynamics of competition for land use between the two main livelihoods of historical (preindustrial) times: herding and farming. We consider that the Musical Chairs model provides interesting elements and research inspirations for historians and archaeologists, notably concerning:

1. The epidemic expansion of farmers;
2. The importance of group identity for herders;
3. The relationship between intermediate oasis scenarios, system openness (*extrinsic growth*) and land use instability.

Even if our experience suggests that competition alone is a working explanation for the trends observable in most cases of Central Asian oasis, it does not follows that the Musical Chairs model should be considered the only possible explanation for the extension of land uses in oases. First of all, the model assumptions and dynamics must be further justified by data from real case scenarios. In this sense, there is a need for more explicit accounts of land use in archaeological and historical studies (e.g. Alizadeh and Ur 2007, Abdi 2003), particularly in Central Asian contexts, so this and other hypotheses can be successfully contrasted in the future. Secondly, we are fully aware that land use, as many other phenomena, may be strongly influenced by several processes simultaneously and at different scales in time and space. Therefore, following a growing complexity approach, the next steps of our program modeling will deepen in two aspects, which are characteristics of most Agent-Based models:

1. A ground model, comparable with a realistic geographical setting with explicit land productivity, climatic stress and spatial constraints;
2. Different social constraints and institutions in the emergence and maintenance of land use patterns, such as group behavior, market and polity intervention.

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Conflict of Interest

The authors declare that they have no conflict of interest.

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Table 1

Experimental setting

Constant parameters		
Number of land units		2000
farming intrinsic growth rate		0.04
herding intrinsic growth rate		0.04
Parameters explored	*Predefined experiments*	*Randomized experiments*
Initial extension of farming land use	100 and 200	from 0 to 1000 (uniform distribution)
Initial extension of herding land use	100 and 200	from 0 to 1000 (uniform distribution)
herding relative maximum intensity	0.1, 0.2, 0.5, 1, 2, 5 and 10	from 0.1 to 10 (the division of two numbers picked from an uniform distribution, proximal of a gamma distribution with mean 1)
farming extrinsic growth rate	0 and 0.25[a]	from 0 to 0.25 (uniform distribution)
herding extrinsic growth rate	0 and 0.25[a]	from 0 to 0.25 (uniform distribution)
farming integration	0 and 1[a]	from 0 to 1 (uniform distribution)
herding integration	0 and 1[a]	from 0 to 1 (uniform distribution)

[a] In predefined experiments these parameters were explored in pairs of values; e.g. when *farming integration* = 0, *herding integration* = 0.

Table 2

Statistical descriptives[a] for the randomized experiment

	Total					Cluster 1: Big oases					Cluster 2: Small oases					Cluster 3: Intermediate oases				
Number of cases	2500					1499					892					109				
	μ	σ	Md	min	max	μ	σ	Md	min	max	μ	σ	Md	min	max	μ	σ	Md	min	max
Initial extension of farming land use	485.24	289.10	481	0	999	485.1	290.45	481	0	999	484.97	289.04	477	0	998	489.35	275.32	501	6	940
Initial extension of herding land use	507.77	284.3	505	1	999	504.85	284.19	494	1	999	513.26	281.74	532	3	998	503.01	307.74	467	3	994
farming extrinsic growth rate	0.13	0.07	0.13	0	0.25	0.13	0.07	0.13	0	0.25	0.11	0.07	0.11	0	0.25	0.19	0.05	0.2	0.06	0.25
herding extrinsic growth rate	0.13	0.07	0.11	0	0.25	0.12	0.07	0.11	0	0.25	0.14	0.07	0.15	0	0.25	0.19	0.05	0.2	0.03	0.25
farming integration	0.5	0.28	0.51	0.03	1	0.6	0.25	0.63	0.03	1	0.34	0.26	0.27	0	1	0.5	0.26	0.5	0.02	1
herding integration	0.5	0.29	0.5	0	1	0.4	0.28	0.36	0	1	0.64	0.24	0.68	0.02	1	0.6	0.26	0.6	0.06	1
herding relative maximum intensity	1.44	1.34	1.01	0.11	8.91	0.96	0.8	0.76	0.11	7.94	2.25	1.68	1.7	0.16	8.91	1.4	0.95	1.18	0.25	5.96
% farming	61.55	42.77	94.95	3.95	96.75	95.27	1.17	95.5	82.5	96.75	5.59	1.5	5.15	3.95	17.95	55.64	24.61	63.65	10.75	88.05
dilemma events	16.67	20.04	11	0	150	12.01	13.59	7	0	70	15.75	9.66	14	0	51	88.35	21.54	86	48	150
oasis degression events	8.22	13.01	2	0	93	1.14	2.28	0	0	19	15.36	9.32	14	0	49	47.12	21.99	46	12	93
Herding success ratio in dilemma events	0.4	0.45	0.12	0	1	0.05	0.09	0	0	1	0.96	0.12	1	0	1	0.54	0.24	0.46	0.15	0.96
Index of selection: *intensity* of farming	2.5	0.1	2.5	1.27	3.41	2.5	0.05	2.5	2.1	2.78	2.51	0.16	2.51	1.27	3.41	2.5	0.05	2.51	2.37	2.6
Index of selection: *independence* of farming	3.37	0.51	3.16	2.5	4	3	0.22	2.96	2.5	3.95	4	0	4	4	4	3.36	0.43	3.24	2.72	4
Index of selection: *intensity* of herding	2.5	0.11	2.5	2	2.93	2.5	0.12	2.5	2	2.91	2.51	0.11	2.5	2.08	2.93	2.51	0.05	2.52	2.38	2.70
Index of selection: *independence* of herding	3.02	0.66	2.63	1.13	4	2.51	0.13	2.51	1.13	3.53	3.86	0.11	3.9	3.41	4	3.06	3.06	2.87	2.48	3.85

[a] Statistical descriptives are abbreviated as follows: μ (mean), σ (standard deviation), Md (median), min (minimum) and max (maximum).

Fig. 1 Google Earth snapshots depicting an example of Central-Asian oasis: the plain of the high Surkhan Darya in Southeastern Uzbekistan (a, b). A rectangle (c) is placed over the area represented in the Musical Chairs Model, in which green patches (*agriculture*) and yellow patches (*pastoralism*) illustrate the proportions of land used by each specialization

Fig. 2 The relationships between the factors influencing land use pattern, accordingly to the Musical Chairs model

Fig. 3 The cycle of the Musical Chairs model: the four steps are framed within dashed borders and the submodels are referred as boxes with side bars

Fig. 4 Box plots presenting the percentage of farming land use at equilibrium (*% farming*), for the four different scenarios regarding initial extensions, throughout the seven explored values of *herding relative maximum intensity* in the "*ext* = 0, *integ* = 1" scenario

Fig. 5 The counts of *dilemma events* versus the percentage of farming land use at equilibrium (*% farming*), produced in the randomized experiment. Points represent individual simulations, in which parameters where set to randomly-chosen values (Table 1). The distribution of cases is also presented through histograms above and to the right of the scatterplot

Fig. 6 Box plots presenting the percentage of farming land use at equilibrium (*% farming*), considering different settings of the *herding relative maximum intensity*, *extrinsic growth rates* (*ext*) and *integration* (*integ*).

Fig. 7 Box plots presenting the frequency of *dilemma events* at equilibrium, considering different settings of *herding relative maximum intensity*, *extrinsic growth rates* (*ext*) and *integration* (*integ*).

Fig. 8 Box plots presenting the index of selection for the *farming* (top row) and the *herding* (bottom row) *intensities*, considering different values of *herding relative maximum intensity*, *extrinsic growth rates* (*ext*) and *integration* (*integ*). Note that if a mean equals "2.5" (horizontal dashed line) there is no selection

Fig. 9 Box plots presenting the index of selection for the *farming* (top row) and the *herding* (bottom row) *independences*, considering different values of *herding relative maximum intensity*, *extrinsic growth rates* (*ext*) and *integration scores* (*integ*). Note that if a mean equals "2.5" (horizontal dashed line) there is no selection

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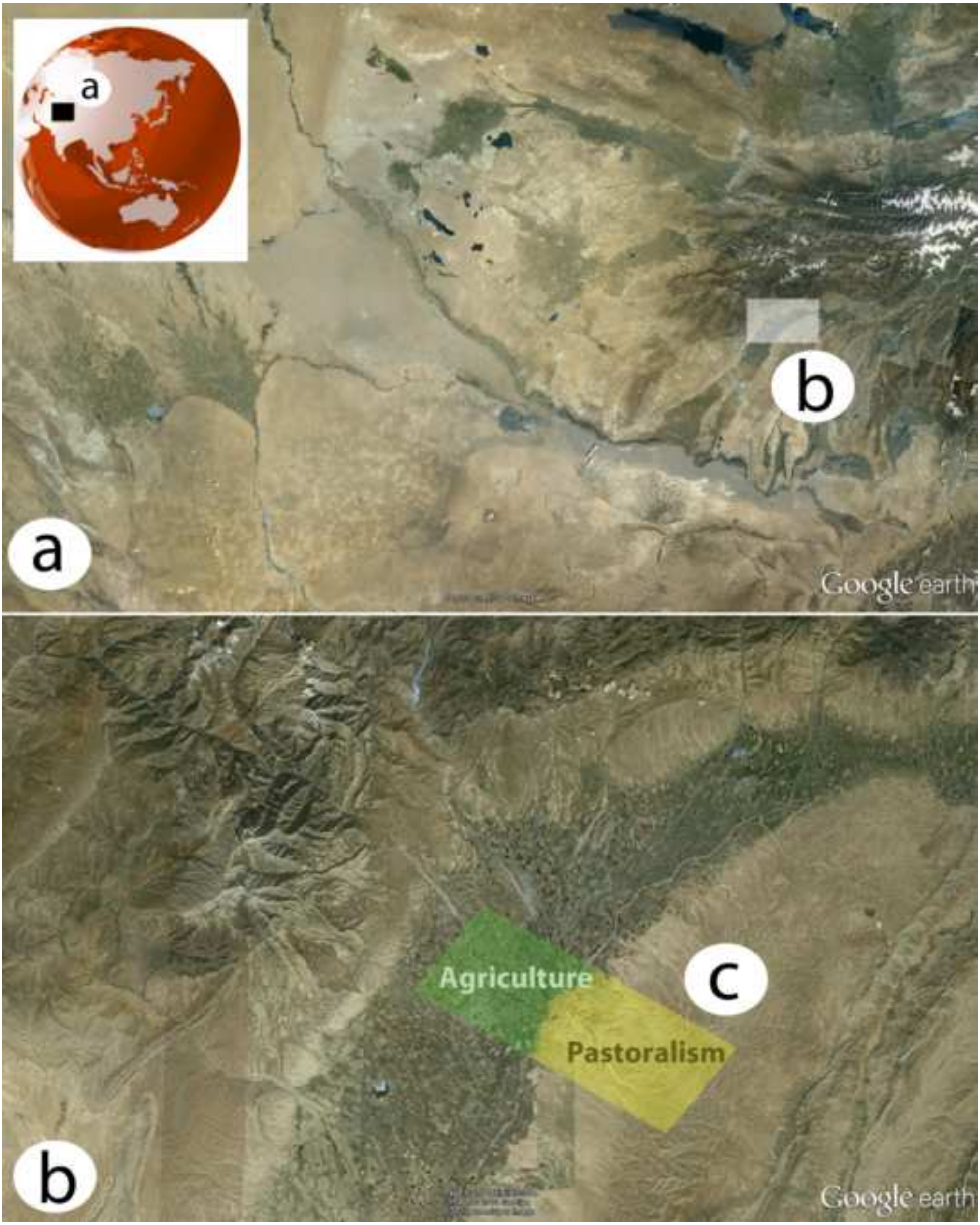

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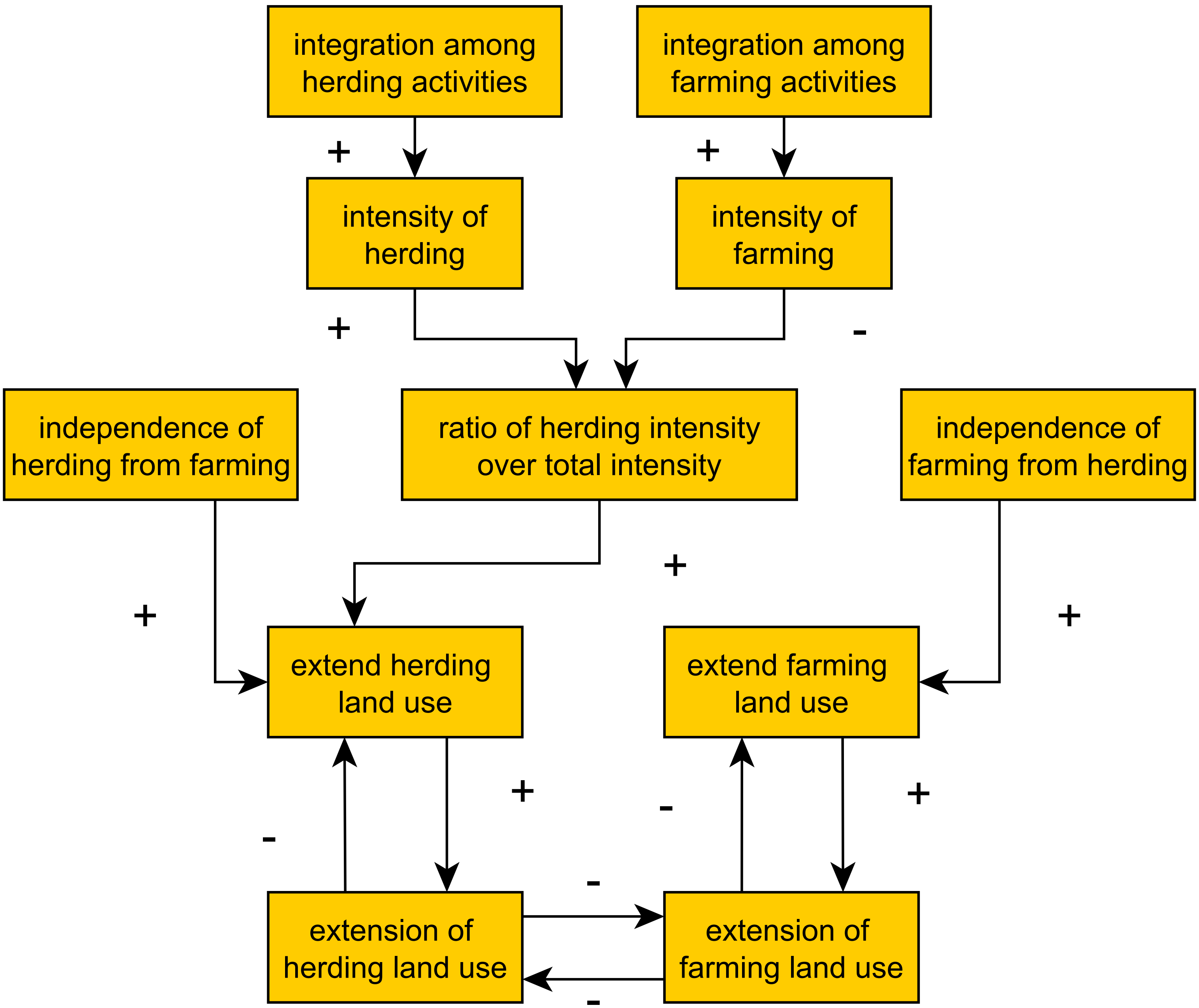

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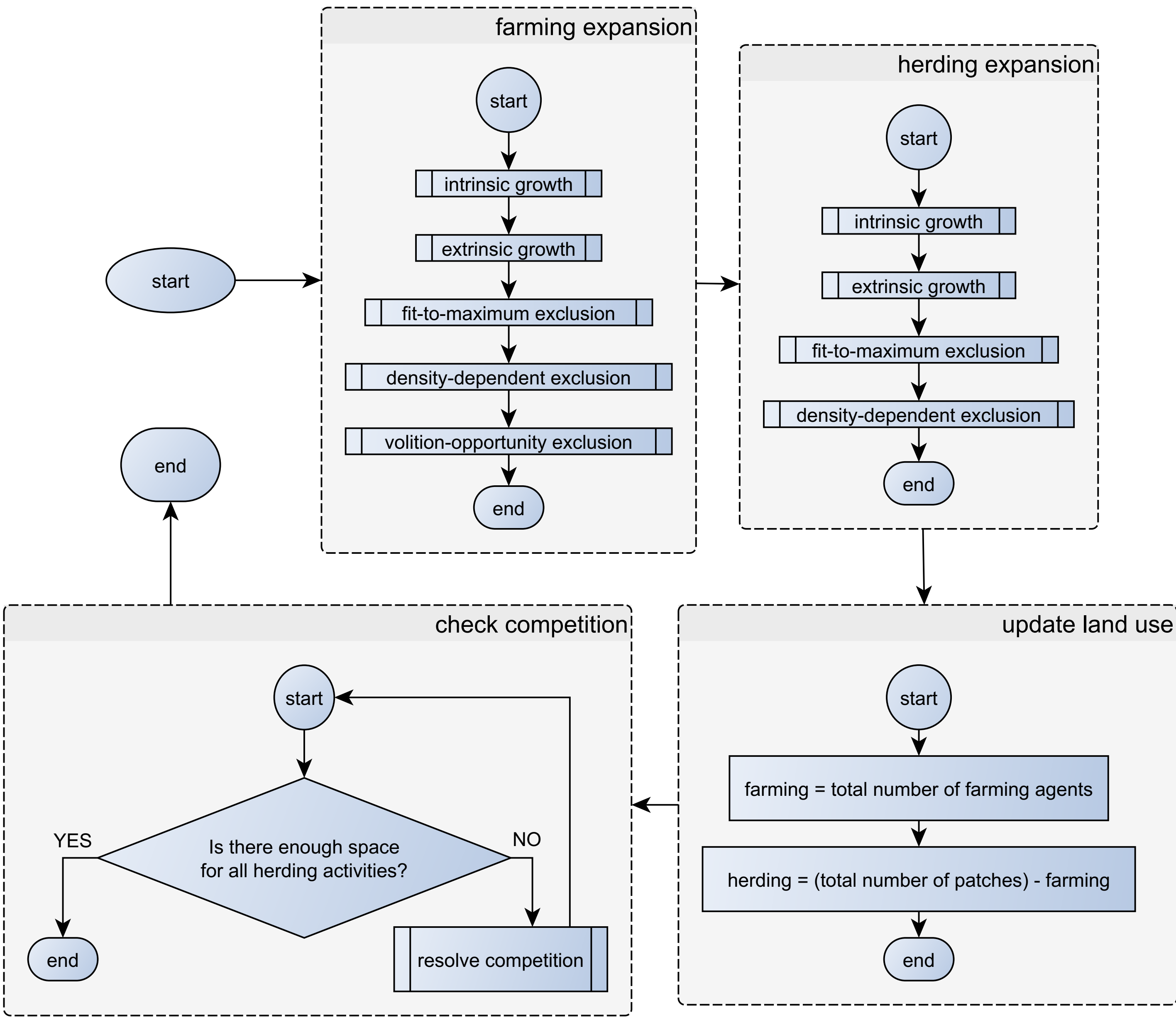

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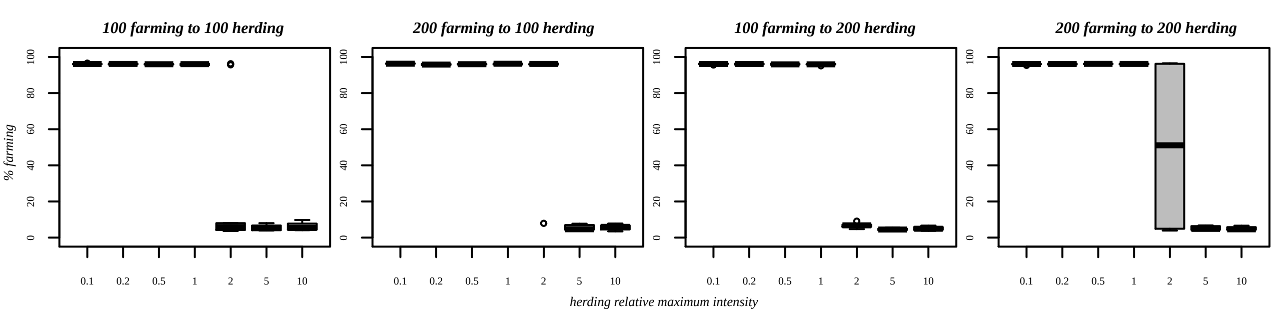

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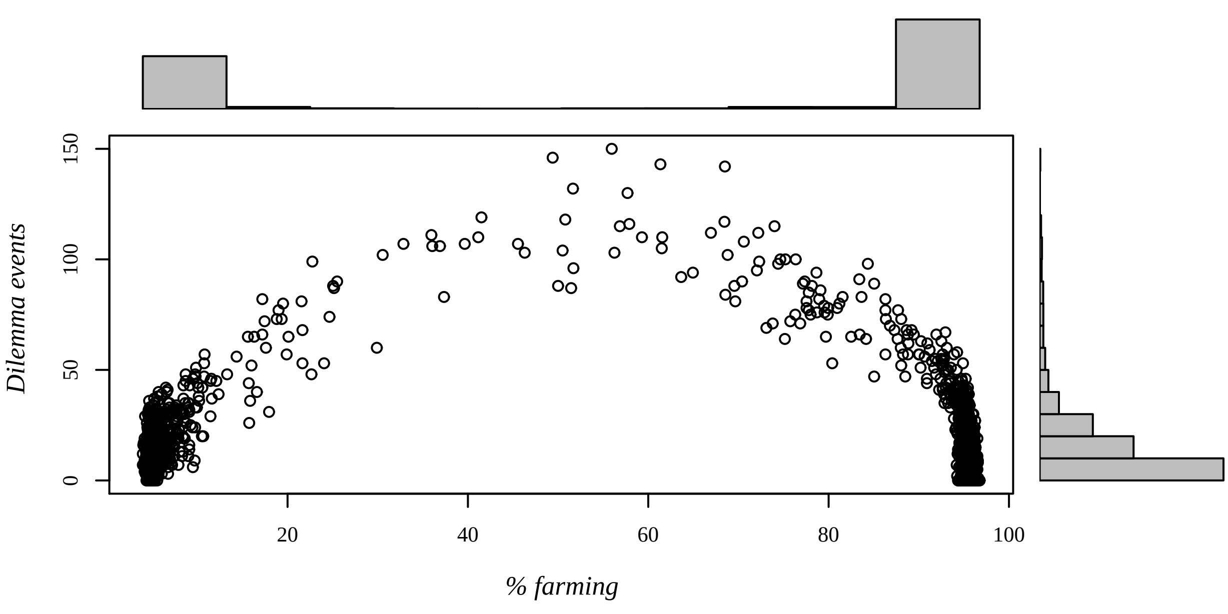

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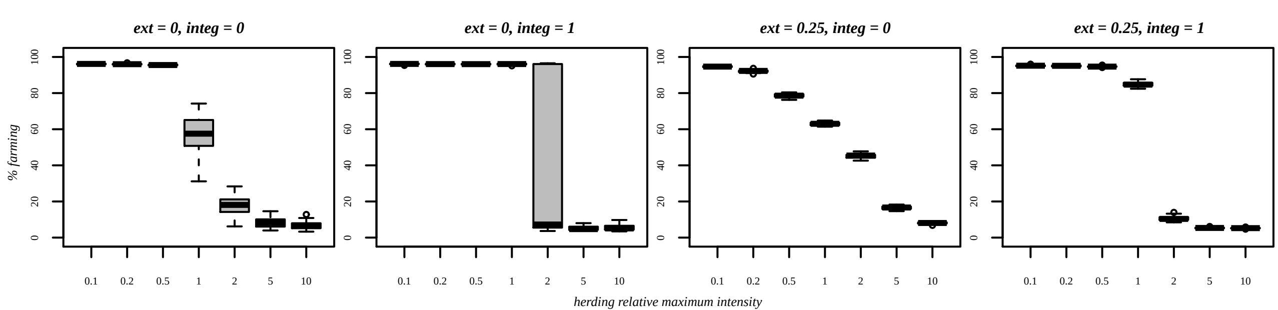

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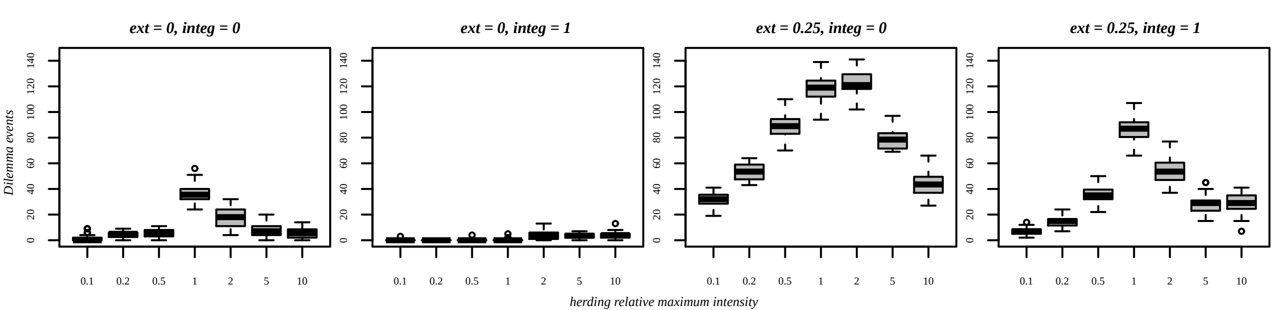

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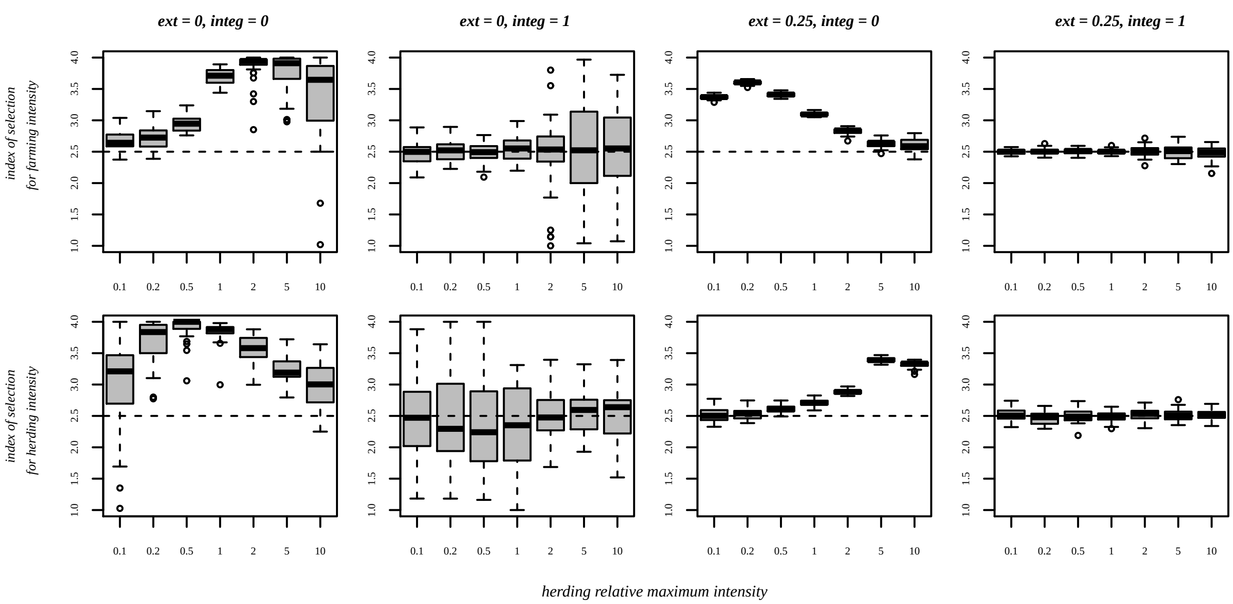

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