The Nice Musical Chairs model. Exploring the role of competition and cooperation between farming and herding in the formation of land use patterns in arid Afro-Eurasia

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Following a strictly theory-building approach, we developed an Agent-Based simulation model, the Nice Musical Chairs model, to represent the competition between groups of stakeholders of farming and herding activities in the arid Afro-Eurasia. The model deepens on questions raised by the results of our former model, the Musical Chairs model, and further introduces three socio-economic mechanisms, which modulate the behavior and performance of stakeholders and their groups. First, we define land use pairing as the awarding, regarding productivity, of any direct cooperation between farming and herding within a group. Second, group management is modeled as the prerogative of a group leadership to manage stakeholders to pursue a particular proportion between farming and herding. Third, we introduce restricted access to pasture as the engagement in territorial control of rangelands in opposition to an open access regime. An exhaustive exploration of scenarios and parameters placed the control over rangelands as the most significant factor in the formation of land use patterns, followed by land use management. While the effect of land use pairing is mild in comparison, it is still a significant factor in group selection, and thus in the persistence of particular land use patterns in the long run.

agent-based model; competition; cooperation; herder-farmer relationship; land use; pastoral systems

Introduction

Relationships between pastoral and farming livelihoods constitute a core aspect of many agricultural production systems, be they documented in ancient times or contemporary societies. Indeed, research has shown that a vast diversity of production systems are and were implemented across the world, in which farming and pastoral activities displayed varying degrees of integration (Adas 2001; Bacon 1954; Barfield 1981; Dandamayev 1979; Gallais 1975; Khazanov 1994; Leshnik and Sontheimer 1975). Such systems cover a wide range, going from livelihoods based on mix and highly diversified production strategies, in which herding and farming activities are intertwined, to strictly specialized livelihoods, where production depends on one dominant strategy. Regarding the latter case, groups often relate to particular livelihoods, which become invested with political or identity significance (Blench 2001; Honeychurch 2014; Salzman 2002).

Moreover, production systems are constantly changing, displaying waves of either abandonment or development of new activities, caused by the adaptation of households and communities to fluctuating socio-economic and ecological conditions (Chatty 2006; Nori and Davies 2007). In the Sahel area, for instance, research pointed towards a process of homogenization in the 1990s, progressively integrating nomadic and semi-nomadic pastoralism into sedentary agricultural systems, due to a variety of factors: repeated droughts, demographic pressure, and policies favoring sedentism and farming (Hussein 1998). A similar process of sedentarization happened in the Soviet Eurasian steppe, where vigorous enforcement of state policies seems to be the primary change driver (Luong 2004; Sabol 1995). Although the subtle material remains of pastoral activities are particularly vulnerable to subsequent agricultural development, archaeologists have shown that such shifts from one livelihood to the other recurrently happened in the past (Abdi 2003, in central Zagros mountains; Alizadeh and Ur 2007, in north-west Iran; Barth 1964, in south Persia; Haiman 1995, in the Negev; Hielte 2004, in south Balkans; Nesbitt and O'Hara 2000, in south Turkmenistan; Newson 2000, in south-east Syria; Pashkevych 2012, in Ukraine and Moldova; Stride 2005, in south Uzbekistan).

The stakeholders of farming and herding—i.e. decision-makers representing families and organizations directly engaged in one or both activities—can interact in different manners, ranging from open conflict (Nori et al. 2005) to strong interdependence and cooperation, sometimes embedded in very elaborate contractual systems (Toulmin 1992; Turner 1999). At the cooperative end of this spectrum, people engaged in farming and herding may be even sharing the same household or family aggregation—which is particularly the case among communities living at higher altitudes, as presented in modern ethnographies (Cariou 2004; Suttie and Reynolds 2003). At the competitive end, however, the people backing farming and herding might crystalize as ethnically-separated groups with conflicting interests, which nurture feuds and, combined with other factors (e.g. climate change, depletion of resources, political and economic external influences), can escalate personal disputes into war. Modern studies and historical accounts from throughout Afro-Eurasia (and beyond) show that the latter situation is likely to happen in areas where either both livelihoods are expanding or land resources are declining (e.g., Ben Salem and Nefzaoui 1999; Fang and Liu 1992). The case of the Sahel in Africa is a good example since it constitutes a buffer zone between the arid areas only suitable for grazing and the most humid areas where both livelihoods can extend. Studies often consider the Sahel as a potential 'zone of conflict' as in the Swallow model of Scoones (Scoones and Cousins 1994).

We use agent-based simulation models to explore socio-ecological phenomena (Epstein and Axtell 1996), specifically, how stakeholders of farming and herding may interact, through different mechanisms and under various conditions, to contribute to the long-term formation of land use patterns. As mentioned by several authors (Madella et al. 2014; Rogers 2013) the use of simulation models allows going beyond data-grounded analyzes (e.g., ethnography, archaeology), which are necessarily limited to specific cases. We use simulation as a way to explore and build theoretical frameworks, which are still empirically grounded. Following a bottom-up approach, we develop and systematically explore models of increasing complexity, which aim at explaining real phenomena balancing parsimony and realistic detail. To this date, most Agent-Based models representing the interaction of herding and farming concentrate on contemporary Africa (Bah et al. 2006; Hailegiorgis et al. 2010; Kennedy et al. 2014; Kuznar and Sedlmeyer 2005, 2008; Skoggard and Kennedy 2012) or focus on either farming (e.g. Christiansen and Altaweel 2005) or herding (e.g. Rogers et al. 2012).

Although acknowledging their contribution, we willingly started the modeling process from scratch to approach this issue from a more flexible explorative design and account for both production strategies. The model that we present here, the Nice Musical Chairs (NMC) model, is the second version of the Musical Chair (MC) model and as such it displays new features.

Material and methods

The Musical Chairs model

The Musical Chairs (MC) model was presented and analyzed elsewhere (Angourakis 2014; Angourakis et al. 2014). However, we deem pertinent to briefly explain it here, since we built the Nice Musical Chairs (NMC) model as a variation of this earlier model. Both models were implemented and explored using NetLogo (Wilensky 1999) and correspondent source codes are available for download (Angourakis 2016a, 2016b).

In the MC model, we consider that landscapes have a finite number of land units (patches) suitable for both production activities (farming and herding). The definition of this area, in the case of arid environments, was inspired in the alluvial cones and plains of Central Asia (i.e. oases).

The MC model is a system in which the smallest units display a high level of specialization in either farming or herding. We understand this property as the existence in a given land unit, at one time, of a single dominant production activity. Although this simplification does not exclude the presence of the other production activity within the same spatial unit, it does imply that such activity is a minor phenomenon there, and so is considered inconsequential for processes involved in defining land use.

Simply put, the MC model is competition for limited space. As in the classic game, an intermittent context (i.e., the absence of music) regulates competition and gives rhythm to players' dynamics. However, the MC model differs significantly from the homonymous game. It discriminates two different classes of players, farming and herding agents, among which players cannot push each other out a chair; i.e., in this model, there is no competition between stakeholders involved in the same activity.

During what we shall call *non-competitive period* (i.e., when music is playing), farming agents remain settled, while herding agents release the land they used and temporarily leave the location. Therefore, the model relies on the assumption that herding is, in fact, *mobile*. During this period, numerous factors of local (*intrinsic*) and regional (*extrinsic*) scales may increase the demand for land use on both activities. The model represents this demand as the addition of new agents. Intrinsic pressure for extending a class of land use is proportional to the number of agents of such class, approximated to a logistic growth function: little pressure with few agents, great pressure with many agents, and again little pressure when approaching saturation. In contrast, the extrinsic pressure is assumed to be independent of local agents, although it also declines with saturation.

During the *competitive period* (i.e., once the music stops), all herding agents, old and new, must find one vacant land unit or else vanquish a farming agent and take its place. This second alternative defines a competitive situation or dilemma event, in which the two forces are calculated as the sum of the agents' strength (*intensity*) and the support of other agents of the same class (class *integration*) and tested against each other. At the end of this period, the system excludes those agents that remain landless. After settling the new land use configuration, the cycle starts again. Given there is a limited and constant number of land units (i.e. chairs), the growing demand for land use will eventually saturate the space available for agents and burst the number of competitive situations. The frequency of land use change is expected to decrease when the system approaches a proportion between farming and herding land use, which balances the increasing demands for expanding both land use classes at every competitive period. Such stable states (i.e. patterns) are also called attractors since they seem to attract trajectories departing from unstable states.

The attractors identified in the MC model relate to the three possible outcomes of any competition between two parties, named A and B: either party A wins, party B wins, or there is a tie between them. In order to characterize these three types of attractors, we performed simulation experiments to assess under which conditions they exist. One of the conditions explored was the maximum competitive strength of agents of one class in respect with agents of the other. We assumed that such strength relates to the potential intensity of the activity, i.e., the number of people and resources involved. We expected this parameter (*herding relative maximum intensity*) to exert a robust effect on the model's dynamics, so the class of agents that is potentially more intense thrives more easily during competitive periods and dominate the landscape in the long run. Although this was indeed the case whenever the difference was great (e.g., on the scale of five against one), farming was clearly favored when balanced land use patterns were expected (Fig. 1(a)).

As stated while discussing the MC model (Angourakis 2014; Angourakis et al. 2014), this bias is due to the asymmetry of conditions under which agents of each activity decide to press for extending their land use. We understand that farming stakeholders colonize surrounding rangeland with a poor estimate of subsequent demand of herds (i.e. the current extent of herding land use). This assumption waves on two other premises, deemed reasonable given ethnographic and historical sources (Barnard 2008; Johnson 1969; Khazanov 1994):

- Herds remain outside the area when farming stakeholders consider expanding;
- Rangeland is open access, hence having no entitlement to any particular stakeholder. Furthermore, herding stakeholders will have a quite reliable assessment of how fruitful it would be to press against farming in a given site since they can directly observe the presence or absence of farming activities.

Whenever the overall intensities of each land use class are similar, we observed that herding stakeholders have the opportunity to expand in the presence of farming by constituting exclusive pastoral groups, strongly independent from local farming. This result is consistent with the general trends observed throughout Afro-Eurasian ancient and modern history (Benjaminsen et al. 2009; Bourgeot 1995; Markakis 1995; Nesbitt and O'Hara 2000; Nori et al. 2005). The expansion of farming correlate with less separation between farming and herding stakeholders ('agro-pastoral' economy), while the predominance of herding is concomitant with the abundance of herding groups that exclude farming activities, at least on a local scale ('pastoral' economy). However, one should not conclude that societies with a stronger pastoral component are necessarily less complex than farming-focused alternatives. Archaeological and historical accounts clearly demonstrate otherwise (Borgerhoff Mulder et al. 2010; Rogers et al. 2015; Sneath 2007). These results merely point out that the reinforcement of social, economic, and political separation between local stakeholders of farming and herding is a mechanism that can efficiently preserve pastoral economies against the injection of farming, given the assumptions of the MC model.

The dynamics of the MC model also illustrated a difficulty of sustaining middle grounds. Most trajectories, under most of the conditions explored, converged in either the predominance or absence of farming, implying that intermediate land use states, although potentially stable, are more easily disrupted. Furthermore, we found clear correlations between frequency of competitive situations (*dilemma events*) and continuity of balanced proportions of farming and herding (Fig. 1(b)), which portray any balanced land use configuration merely as an unresolved situation. In this sense, contrasting with the extremes, midway configurations can be considered to be systems held far from equilibrium, as understood by thermodynamics, where pressure towards states with more entropy is always present. Agreeing with this description, results have shown that these conditions are greatly facilitated by land use demand due to extrinsic factors (Fig. 1(c)), which counterbalances the long-term effects of competition.

The characterization of intermediate land use states as transitory, rather than stable, is not unforeseen, given the binomial nature of the outcomes at any given competitive situation (win/loose) and that there is always pressure to growth (winners are the ones able to demand new lands in the next cycle). The incidence of balanced land use configurations throughout documented history could be caused by ever-changing conditions, from political upheavals to climate change. We can explain the long-term predominance of one activity in a particular region as the result of land use competition under conditions generally favoring that activity. Conversely, areas with intermediate land use states might have been characterized either by the slow decay of one class of land use in favor of the other or by the intense competition between steady, balanced forces, feed by opposite external influences (i.e. *buffer zone*).

Nevertheless, the abundance of ethnographic and historical examples of non-competitive relationships between stakeholders of farming and herding encouraged us to investigate other mechanisms that may have acted as obstacles to free competition, potentially favoring the emergence of intermediate land use patterns. The NMC model explores how the dynamics of land use competition may interact with explicit group dynamics, in which the given social arena constrains the opportunities for both cooperation and competition.

The Nice Musical Chairs model

Motivation

Drawing on the theoretical framework proposed by McCown, Haaland, and Haan (1979), we considered different types of linkages that can underlie interactions between sedentary farming and mobile livestock keeping. In consonance with the central concept of the MC model, McCown and others stressed the existence of competitive linkages between farming and herding: the two livelihoods are up to some point competing for the same resources (i.e., water, fertile soils). As observed in several ancient and contemporary cases, such competitive pressure can evolve into open conflicts (Hagmann and Mulugeta 2008; Nori et al. 2005). In contrast, these authors also emphasize the existence of positive linkages, which can be either ecological or related to exchange. Ecological linkages refer to the establishment of mutualistic relationships between cultivated plants and livestock: crops may constitute a source of fodder for livestock (e.g., Spengler et al. 2014) while manure provided by animals can help crops grow (Jones 2012). The exchange linkages can be beneficial too, as each livelihood strategy produces goods demanded—and often not produced—by the other (e.g.

exchanging grains for dairy products; Khazanov 2001). Therefore, the interaction between farmers and herders can be not only competitive but also cooperative.

Beyond the framework of McCown and others, the interactions of people engaged in farming and herding can also be conditioned by political linkages. By both uniting and separating people, these are the keystone for group formation and maintenance. Such linkages may be particularly strong among those sharing the same livelihoods, defining distinct groups of farmers and herders. However, there is also abundant evidence of tight political linkages across these livelihoods, from the division of labor within households to patron-client contracts and capital interdependence (Black-Michaud 1976; Cariou 2004; Dandamayev 1979; Hoffmann-Salz 2015; Renger 1995; Suttie and Reynolds 2003).

Political linkages also tend to be asymmetric, which causes—and is further sustained by—unequal and hierarchical social structures (e.g., Black-Michaud 1976; Bourgeot 1995). To the extent that there are political linkages, decisions of stakeholders regarding land use are not completely free. Instead, they depend on the mainstream opinion within a group, often conveyed by one or few individuals considered legitimate representatives. Such group leaders will have the prerogative to direct common resources to an arbitrary—part utilitarian, part traditional—agenda. Nevertheless, this top-down pressure will itself depend on the cohesion of the group and how respected is the invested authority.

Due to this variety of linkages, relationships between stakeholders of farming and herding are bound to be complex, as well as the land use dynamics they produce. People engaged with these livelihoods can benefit from reciprocating with each other, engaging in political linkages, and consequently improve their economic performance; but at the same time, as they expand due to demographic or economic growth, they may eventually compete for usable land. The trade-off between these facets is a key aspect to understand the overall dynamics of the whole production system. It affects the behavior of individuals and the survival and expansion of the social groups and their practices, consequently driving the long-term trajectory of land use patterns. By developing and exploring the NMC model, we intend to apprehend how this two-sided mechanism conditions the overall dynamics of traditional agricultural systems, specifically those based on farming and herding in arid environments.

Design details

Similarly to the MC model, the NMC model implies there is competition for land between farming and herding. However, it also presents several new features designed to explore more complex interactions between stakeholders. These new aspects deepen on:

- Social structure among stakeholders;
- Opportunities for cooperation between the two activities;
- Role of leadership in managing land use and enforcing particular economic models;
- Open and restricted access regimes regarding pastureland.

Overall, they allow exploring how decision-making concerning land use may be related to both environmental and institutional constraints.

The NMC model is a derivation of the MC model, as they both rely on the same core mechanism: land use competition between discrete units of farming and herding.

This mechanism remains broadly intact. However, two modifications entailed several adjustments (Fig. 3). First of all, we made a significant improvement in the base model by using a permanent population of agents. Instead of having two classes of land use agents, being continuously created and destroyed, we settle with one class. This class represents land units and conceals the information on the actual stakeholders using or pressing to use the land. Land units differ by a single variable indicating whether farming, herding or nothing is being performed there (*landUse*, Table 1). Although this modification complicates some procedures, it reduces the computational complexity of simulations, making any exploration much faster. Hereafter, we will refer to these agents as patches (after NetLogo's terminology) though we remind that, as in the MC model, the position of such units is irrelevant. Secondly and more importantly, all patches in use are related to another kind of agents, i.e. groups, representing collections of individual decision-makers sharing a common identity, regardless of land use class—i.e. groups are not assumed to be fully specialized in a livelihood. By introducing explicit and potentially mixed groups we freed two parameters of the MC model, farming and herding *integration*, and discarded the former agent trait *independence*. Furthermore, we seize this opportunity to enable stakeholders of the same land use class to compete among themselves, given that they do belong to different groups.

Stakeholders using a patch may share their group identity (*myGroup*, Table 1) with others, hence preventing competition and inducing cooperation. However, a group is also an entity on its own, having their properties and processes (variables, parameters, and procedures). One of the group-specific variables, *groupEffectiveness* (Table 2), has an unusually broad effect on group dynamics. This variable represents the extent to which the group holds as a collaborative framework for stakeholders. It is a function of size (*groupSize*, Table 2) and a parameter fixed for each simulation run (*effectivenessGr*, Table 3)—generally, the bigger the group, the lower its effectiveness (Fig. 2).

Groups influence patches' states through three processes:

(1) Group members do not compete and support the interests of their fellows against other groups;
(2) Group members cooperate towards the mutual improvement of productivity (*pairing*);
(3) The group as a whole actively pursues an internal proportion between farming and herding (*targetFarmingRatio*, Table 2), derived by whatever interests are perceived to be legitimate (*management*).

Groups are intentionally defined in a very broad sense (e.g., families, ethnic groups, communities, inhabitants of one village) and are assumed to be based indistinctively on kinship and corporate relationships. Our intention is to account for most of the institutional dimension of stakeholders interactions, considered to act both in ad hoc competitive situations and more general collective behavior (Rogers 2013). Although simple, this representation still can generate rich theoretical implications regarding how and under which conditions social structures relate to specific land use patterns.

The cycle of the NMC model (Fig. 3, Appendix A) is quite similar to the one of the MC model. However, the changes in the base model and the introduction of explicit groups and their functionalities entailed not only new procedures but also several adjustments in the procedures used for expanding the land use and resolving competitive situations.

First, growth and expansion (*growth*, *farming expansion* and *herding expansion*), which return the pressure for extending land use, are now group-level processes. Density is relevant only concerning the land use of the group at hand. In this sense, a group's pressure to expand a land use class will be constrained only by its current extension in comparison to the remaining land. If there are opportunities for cooperation among farming and herding (i.e. *pairing*), stakeholders are able to exert more pressure towards extending their land use class by being associated up to a particular number of counterparts of the other land use class. The base value of intrinsic growth (*baseIntGrowth*, Table 3) can be increased up to a percentage (*optimalGrowthIncrease*, Table 3), depending on the land use configuration within the group (*FarmingRatio*, Table 2). The maximum intrinsic growth rate is fully realized in a group whenever the inner proportion between farming and herding achieves a certain value (*optimalFarmingRatio*, Table 3, Fig. 4). This mechanism represents potential advantages of cooperation between farming and herding stakeholders, regarding land productivity, assuming that greater productivity consequently increases the demand for land use.

We exploited another opportunity derived from implementing explicit groups: explore the consequences of how stakeholders understand pasture tenure. If they consider pasture as open access land, each patch used for herding will not be entitled to particular stakeholders and their groups. Herding stakeholders of a group may choose different sets of patches from one year to another. Assuming that herds will arrive at the location roughly at the same time, open access offers the opportunity for all groups practicing herding, big or small, to claim the use of a minimum number of patches, previous to the resolution of competitive situations. Furthermore, the decision made by farming stakeholders to extend over open access pastures is poorly informed: it is not possible to precise if a patch will be needed by herds of their group, or claimed for herds of another group. As in the MC model, stakeholders will base such decision in the estimation of how likely it is that the expansion of farming land use will curb the herding activity of their group. Specifically, this estimation is the ratio between the extent of their group´s herding land use and the global amount of patches used for herding.

In contrast, when access is limited on a group basis, the group's herds will return by default to the same patches, which the growing land use of other groups may or not dispute. Given that growth depends on group size, this institution facilitates the expansion of larger groups with a significant proportion of herding. Farming stakeholders will be then able to recognize their own group's herding patches and, when pressing against other group's territory, they must resolve the dispute before actually changing the land use (details in Appendix A).

As mentioned, the concept of land use competition is broader in the NMC model, since we allow for within-class competition. This possibility asked for a drastic change of design in the procedure *check competition*, though not so much regarding the actual resolution of competitive situations (*resolve competition*, details in Appendix A). Putting aside the term dilemma events as used in the MC model, the NMC model distinguishes four types of competitive situations: farming pressing farming (FF), farming pressing herding (FH), herding pressing herding (HH), and herding pressing farming (HF). A competitive situation occurs when a stakeholder of one group decides to dispute land used by stakeholders of another group. Note that FH competitions will only be possible if groups retain pastures as their property.

Once the expansion procedures point how many competitive situations exists in every patch, *check competitions* resolves all competitive situations of a given kind following a prescribed sequence. Since farming involves the use of the same land throughout the year, we assume that farming stakeholders are the ones to act first—hence, FF and FH precede HH and HF competitive situations. Furthermore, we assume that stakeholders prefer to acquire land already used for the purpose at hand, rather than investing in new infrastructures, in the case of farming, or encountering the resistance of sedentary inhabitants, in the case of herding. Although all competitive situations could involve some form of violence, we understand that the conversion of farmlands into pastures entail the most dramatic type of event. Consequently, FF precedes FH, and HH precedes HF. In the case there is more than one contender of the same class for a single patch, the system resolves the respective competitions in a random order.

When resolving a competitive situation (*resolve competition*, details in A1), stakeholders belonging to the same group support themselves as a single force when competing for space against other groups. As mentioned above, this aspect parallels the class-level integration in the MC model, although support can now be performed also between stakeholders of different land use classes. The competitive strength of a group is positively related to the number of patches used by that group (*groupSize*), but it also depends on the group's effectiveness (*groupEffectiveness*), which is inversely related to size (Fig. 2).

In the NMC model, we chose to set aside the whole issue of land use intensity, which would correspond to the competitive strength of stakeholders using a patch. We consider that the implications of this aspect are already clear from the MC model:

- The overall intensity ratio between farming and herding can be a determinant factor in the formation of land use patterns;
- Under balanced overall intensity ratios, farming is favored;
- The trend towards intensification due to competition can be counteracted by group support.

However, we acknowledge that these implications could be revisited in more complex models, for example, by including different potentials for productions in each patch.

Additionally, there is no trait of either stakeholders or groups that restrain their decision to press against the land use of another group—in contrast to the MC model, which included the agent trait *independence*. Given that groups are now explicit, a competitive event occurs every time a pressing stakeholder randomly chooses a patch of another group.

In the NMC model, the integrity of groups may peril since some stakeholders have the opportunity to change to another group deemed more advantageous, consequently breaking either kinship or corporate bonds to build new ones (*change groups*, Fig. 3). Stakeholders will be looking for the best combination of group size and effectiveness, the group's competitive strength (Figure2, bottom). In addition to groups present, stakeholders will also account for the potential group containing all defective patches of the same group during the same cycle (i.e. group fission). Group authorities can hinder this behavior by reducing the rate of such opportunities, from a maximum (*maxGroupChangeRate*), proportionally to their current score of effectiveness (*group change*, details in Appendix A).

Finally, groups may be able to pursue a particular configuration within its domain (*targetFarmingRatio*) through shifting land use class of some of their patches, again proportionally to their effectiveness (*group management*, Fig. 3). The targeted farming ratio of each group is randomly assigned and constant throughout the simulation, thus assumed to be an arbitrary group tradition that is completely independent of land use dynamics (*no* learning process involved). We adopt this strong assumption for the sake of identifying and measuring any selective pressure acting on groups, once management is performed. As management impacts the scale of intrinsic demand generated in the next cycle and thus modulate the probability of expansion of groups, we would expect that targets are key for groups to become large when the system approaches an attractor. Consequently, we can interpret trends in the distribution of the targets of the biggest groups (*bigGroupTarget*) as the outcomes of an evolutionary process, where factors influencing intrinsic demand act as selective pressure on groups. Which land use policy will be more successful under a specific condition?

Expectations

Given results obtained in the MC model, we anticipate that, overall, farming will be favored. Concerning the mechanisms involved in group dynamics, we should be able to observe the emergence of one prominently big group since there is a positive feedback linking group size and the overall probability of expansion. The frequency of opportunities for stakeholders to re-consider their group affiliation (*maxGroupChangeRate*) should not change this outcome. Medium-to-large groups are the best choices in terms of competitive strength: the size of groups form a composition and, therefore, the expansion of one group will always imply a general decrease in other groups' size. For the same reason, the farming ratio of the big group will not be too far from the overall farming ratio of the territory. However, lower values of the parameter *effectivenessGr*—which modulates both group strength and enforcement of fidelity—should be able to limit the scope of centralization, yielding more fragmented group structures and more diverse land use patterns.

The potential for increasing productivity by pairing patches with different land use is expected to aid in the emergence and maintenance of mixed groups and formation of intermediate land use patterns (whenever optimal farming ratio is not in the extremes). Additionally, land use management should increment diversity of land use patterns since expanding groups pursue arbitrary farming ratios (hence deviating from the attractor). If there is a prominently big group, the land use pattern should resemble this group's targeted farming ratio. Moreover, if pairing has any effect on land use expansion, groups targeting farming ratios closer to the optimum should be able to extend their land use more frequently than others.

Finally, whenever pastures are open access, herding land use should suffer from a systematic disadvantage against farming, as seen in the MC model, and should remain well distributed among groups (i.e., groups with herding have the same probability of claiming first the next available patch). In contrast, restricted access is expected to facilitate more even land use configurations (i.e. no differences due to mobility) and, since stakeholders recognize pastures as group territory, it should allow for groups to accumulate herding patches, excluding more efficiently the incursion of other groups.

Experiment design

To explore both separated and combined effects of the different mechanisms introduced in the NMC model, we defined eight scenarios accounting for all possible configurations of pairing, management, and access regimes (Table 4).

In scenarios Ao, Bo, Co, and Do stakeholders that consider pasture as open access land, involving no formal relationship between a herding stakeholder—and the respective group—and the land used in a given cycle. In contrast, in scenarios Ar, Br, Cr, and Dr herding stakeholders act and are recognized as the 'owners' of the pasture they used. Ao and Ar are minimal scenarios, which combine only group definition (within cooperation/between competition) with the underlying mechanism (growth, expansion, and competition). Built on this minimum, scenarios Bo/Br and Co/Cr include the *pairing* and the *management* mechanisms, respectively, while Do/Dr combine them all together.

For each scenario, we performed one experiment of 1000 simulation runs aimed at characterizing attractors of that scenario under all possible conditions, as represented by explored values of all nine parameters (Table 3, not including *total_patches*). Following the computational analysis of Santos et al. (2015), we applied the Latin Hypercube Sampling (LHS) technique (McKay et al. 1979) for capturing all possible interactions between the state variables and the parameters. Thanks to this statistical technique, each experiment sampled evenly the nine-dimensional parameters' space, within ranges explored (Table 3).

To understand the nature of the effect of within-class competition (FF, HH), which was absent in the MC model, we repeated all sets of experiments allowing only between-class competition (FH, HF). In the light of this second batch of experiments, we found justified to disregard within-class competition as a relevant factor in the formation of land use patterns. Results on this other version of the model are presented and commented in Appendix B.

Finally, all simulations were executed in a space comprising 500 patches and ran for 500 steps, each step representing an iteration of the model's cycle (Fig. 3). This configuration left sufficient time span to allow trajectories to reach or approach an attractor while longer simulations did not present different behaviors. As in the MC model, the model is sufficiently path-independent to endorse us focusing the analysis on identifying and characterizing final states rather than trajectories.

We measured the final states of simulations with four global variables, mostly capturing two aspects used for characterizing attractors (Table 5). First, we assess the territory's degree of specialization as the percentage of patches used for farming over the total number of patches (*farming*). Second, we also describe the states of the model through the distribution of land among groups. We may depict the diversity (*numberGroups*) and degree of centralization (*bigGroupSize*) of decision-making regarding land use. Through these variables, attractors in the NMC model are characterized by presenting big-to-small and specialized-to-mixed groups. For instance, we interpret a state displaying a predominance of one big group mainly composed of one land use class as a *centralized* and *specialized* landscape.

Results

The first general observation taken from experiments is that there is considerable consistency between the MC and NMC models. Although we modified several aspects to implement the mechanisms involved in group dynamics, recurrence of competitive situations can still generate results analogous to the MC model, the first of which is the tendency to converge around clearly-defined attractors. Moreover, the NMC model also displays a bias favoring the expansion of farming. Particularly, if there is no land use management or restricted access to pasture (Ao and Bo), balanced configurations are unstable states that eventually converge in farming-focused centralized territories (Fig. 5 and 6, top-left; Animations 1 and 2). This result is very much similar to the results obtained with the MC model under full integration of land use classes (when integ=1, in Angourakis et al. 2014: Fig. 6). Under these two scenarios, once a group becomes sufficiently large, farming is gradually extended at the expense of herding, resulting in exceptionally specialized and centralized land use pattern.

Unexpectedly, the introduction of land use pairing (Bo) is inefficient in modifying this monotone tendency. This mechanism produces only a slight leaning towards the optimal farming ratio—notice that the optimum was fixed in each simulation at a different value from zero to one, so this effect is observable in Bo as a greater spreading respect to results in Ao. The mechanism awarding cooperation is not enough to preserve land use diversity in the long run. In fact, results suggest that the advantage for a group having its farming ratio near the optimum—i.e. a higher growth rate—becomes irrelevant when its size becomes much bigger than others. Groups encompassing around half of all land units will win virtually all competitive situations, and consequently continue to expand, even when their growth rate is considerably slower than those of competitors. Therefore, a big group grows independently of their farming ratio, allowing it to drift far from the optimum. We observe this phenomenon across all scenarios with pairing (Bo, Br, Do and Dr) and it is still happens when the general effectiveness of groups is relatively small. With low values of *effectivenessGr*, several small groups will continually—but unsuccessfully—defy the dominance of a relatively large group, having only a slight effect on the territory land use pattern (see details in Appendix B).

In contrast to scenarios Ao and Bo, when groups are entitled to pastures (Ar and Br) the single attractor is an even configuration within a centralized territory (Fig. 5 and 6, top-right; Animations 3 and 4). As expected, restricted access to rangelands allows for balanced land use patterns to co-occur with herding centralization. Given that restricted access neutralizes the bias towards farming, the overall growth of farming and herding even out each other, despite the implication of centralization for competition observed in scenarios with open access. Nevertheless, this will only apply if there is no additional bias towards the growth of one or another class (e.g., distinct and very unbalanced growth rates for each land use class). Also, by comparing results of scenarios Ar and Br, we confirm that pairing is not causing the formation of balanced land use patterns, although the effect of this mechanism can still be identified by the attraction of land use pattern towards the optimum in each simulation (i.e., again, meaning greater dispersion).

Under the scenarios above, the principal factor conditioning land use patterns is competition, mainly through the expansion of a single group. In contrast, this influence declines when groups manage their land use (Co, Do, Cr, and Dr). Confirming our expectations, management—as driven by fixed and blind traditions—do increase the diversity of stable states (Fig. 5 and 6, bottom; Animations 5 to 8).

Concerning scenarios with open access to pasture (Co and Do), and comparing them with their parallels without management (Ao and Bo), stable states are more diverse both regarding land use pattern (percentage of farming) and degree of centralization (size of the biggest group). In these scenarios, there is a greater probability of observing intermediate land use patterns. However, the development of prominently big groups specialized in farming, which was the undisputable attractor when management was absent, is still discernible. In contrast, the combination of management and restricted access (Cr and Dr) enables groups pursuing very different traditions to thrive and centralize the territory under the same conditions. This setting evens out the probability of any of the possible land use configurations to emerge as stable state—up to the point where all parameters are irrelevant (see Appendix B). Remarkably, scenarios Cr and Dr are the only ones that can produce centralized herding-focused territories that are stable in the long run. Overall, when groups are managing their land use, pairing is shown again to be a minor factor in shaping attractors. When comparing Do-Dr with Co-Cr respectively, we expected pairing to be an important selective factor for groups and their targeted farming ratio; we found only a weak—though still observable—effect.

Considering restricted access, management, and pairing as binomial parameters (i.e. presence/absence of the mechanism), we assessed more clearly the relative importance of each aspect and compared them to the impact of the other nine parameters (Fig. 7). Restricted access to pasture and land use management are confirmed to be the two most important factors in the model, having a significant effect on both the proportion of land use classes (i.e. percentage of farming) and the level of centralization (the size of the biggest group). Although the analysis places pairing as a minor factor, it should rank in the third position regarding the percentage of farming, given that is reasonable to account for the importance of *optimalFarmingRatio* and *optimalGrowthIncrease*, which only apply when pairing is enabled.

Throughout all scenarios explored, the model displayed a little dependence on parameter setting, mainly being affected by the influence of intrinsic and extrinsic growth rates (*baseIntGrowth* and *maxExtGrowth*) and the constraints given to group development (*effectivenessGr* and *maxGroupChangeRate*). Initial conditions (*init_farming*, *init_herding*, and *init_groups*) and parameters regulating pairing (*optimalFarmingRatio* and *optimalGrowthIncrease*) have a much weaker effect. The detailed sensitivity analysis is available in Appendix B.

Discussion

The results obtained for the Nice Musical Chairs model revisit the main observation drawn from the previous Musical Chairs model. In the four scenarios with open access to pasture (Ao to Do), competition consistently generates a bias towards farming land use. The consequence of this bias towards farming is clearer in scenarios Ao and Bo. There, we always observe a progressive emergence of large farming groups, which tend to cover nearly all the landscape in the long run. Without any interference from group management, stakeholders tend to extend farming and overwhelm most of the pastoral land use, including that of their group. Moreover, even with group management (Co and Do), there is still a clearly farming-biased dynamics. Overall, the lack of restriction to accessing and using rangelands generates a ‘Wild West’ phenomenon, where agents of sedentary land use expand as if the remaining land were freely available.

An example took from archaeology, the millenary extension of sedentary agriculture in the area of Surkhan Darya, south Uzbekistan (Stride 2005), show that similar dynamics might have happened in the past. There, starting by the end of the third millennium B.C. farming was progressively extended from the surroundings of secondary rivers to the central alluvial plains, which are today entirely cultivated. The long-term expansion of farming in this region was resilient even in front of the influx of ethnic groups traditionally relying on herding, occurring up to the fourteenth century A.D.. The NMC model suggests that such process might not necessarily be the outcome of a centralized organization promoting farming (sensu Wittfogel 1957), though it could still be the case according to scenarios Co and Do. Instead, farming expansion can also be explained by the combination of three factors: (1) growth of both activities, (2) competition among stakeholders, and (3) a sustained context of weak political organization and centralization. This explanation appears more reasonable than the self-explained hydraulic state, at least in the context of Central Asia (Stride et al. 2009).

The NMC model also allowed us to identify implications of each of the new features introduced. First, land use pairing is not enough to counter the dynamic produced by competition. Mutually beneficial linkages between sedentary agriculture and pastoral activities are usually described as drivers of balanced land use patterns (Hussein 1998). According to our results, this may not be the case in the absence of group management institutions and, especially, of clear land tenure regimes applied to rangelands.

Second, we observe a very clear divergence depending on the modality of access to pastureland (scenarios o versus r). Interestingly, a systematic tropism of the system towards farming exists only in the absence of regulation (scenarios o). The existence of restricted access to pastures is sufficient to sustain an approximately equal number of farming and herding units in the long run (Fig. 5, Ar). Moreover, balanced land use patterns are associated with the emergence of big groups, which never occur under an open access regime (Fig. 6). Among the aspects examined, presence/absence of access regulation is the one with the greatest weight (Fig. 7), specifically regarding the development of pastoral activities in significant proportions of land.

Archaeological research on different historical and geographical contexts show that territorial markers associated with pasture were quite common in the past, and are often related to the resilience of herding economies. A clear example is the use of zoomorphic megalithic sculptures or ‘verracos’ by Iron Age peoples of Vettonia (western plateau of Iberian Peninsula). As called by Greek and Roman authors, the ‘vettones’ based their economy on extensive animal husbandry, mainly of cattle, and exploited vast rangelands around well-spaced sedentary settlements. The ‘verracos’ are considered to have been used primarily for marking and symbolically protecting critical pastures far from settlements (Ruiz Zapatero and Álvarez Sanchís 2008, p. 226). Although initially ascribed to single familial units, people progressively recognized them as emblems of entire communities through elite organization and competition (Sánchez-Moreno 2011). Even after the Roman conquest, the population of this region continued to invest in signs of access regulation related to rangelands. Throughout the Roman period, inhabitant placed cairns with inscriptions (Ariño et al. 2004) and, during the Middle and Modern Ages, authorities enforced a sophisticated legal apparatus to regulate and protect the extensive network of migratory glens (Gómez-Pantoja 2001).

Thousands of kilometers away, in the Koksu river valley in Semirech’ye region, southeast Kazakhstan, where pastoralism was the dominant livelihood up to the 20^{th} century A.D., a similar millenary zeal for the usufruct of critical pastures is observed. Starting from the Bronze Age, the population of the valley invested in rock-art and monumental burials near winter settlements. According to Frachetti (2008, p. 158), those were used in part to communicate ownership or control over winter pastures (lowlands), among other key assets, while most of the community were away at summer pastures (highlands). This case is particularly illustrative of our model since the fertile lowlands are also the area where sedentary agriculture is feasible.

Through the lens of our model, creation and maintenance of territorial markers and regulations regarding pastures, such as those of Vettonia and Semirech’ye, is the key factor in sustaining the whole land use system, and particularly in safeguarding the practice of herding in front of farming. Several scholars reached similar conclusions, though analyzing aspects that lie beyond the scope of our model, such as the effect of partiality of state regulations in contemporary times (Blench 2001; Butler and Gates

2012; Cleaver et al. 2013; Hagmann and Mulugeta 2008; Kavoori 1999; Robinson et al. 2012). The emphasis on efficient mediating institutions also seems to be the fundament of the policy of rangeland devolution, by which modern states attempt to recover traditional and local organizational structures to manage the herding activity in a more efficient, equitable and sustainable way (Ngaido and Kirk 2000; Nori et al. 2008).

Third, among all the explored scenarios, we see that emergence of medium-to-large groups specialized in herding is only made possible when group management is introduced (in Fig. 5 and 6, the larger spread towards the left in scenarios C and D, when compared to A and B). Management, although favoring a greater diversity in number and size of groups, as well as in land use configurations, is not sufficient on its own to lead to the emergence of large herding groups (Co and Do). It is only when restricted access to land is in conjunction with management that such groups may occur (Cr and Dr). Therefore, emergence and maintenance of a region of large groups specialized in herding—often named pastoral societies, such as the vettones or the Bronze Age population of Semirech'ye—depend on the conjunction of at least two constraints, restrictive access to pasture and group management, and not only on one or another of these. Ultimately, given that management and restrictive access—as defined in the NMC model—are probably correlated in real cases, it is valid to postulate that the real constraint behind these is the level of organization within groups, i.e. their ability to coerce divergent interests within and to be recognized outside as political entities.

Large pastoral systems are then dependent on having efficient institutions to regulate and manage land use, and large herding groups are not the consequence of the competition between groups, as in the case of large farming groups (Ao), but one of the possible outcomes of a stronger socio-political organization. Beyond the necessary institutional context, a centralized herding territory may only exist if the prominent group has a herding-focused tradition. Although pairing undoubtedly plays a significant role in conditioning the emergence of groups with one strategy or another, it did not meet our expectations as a driver for selection of group's targeted farming ratio. For instance, even when the optimal proportion of farming is zero (i.e. farming never improves the group's productivity), the emergent group may still devote some land units to farming. However, if mechanisms to change traditions were to be included in the model (e.g. generational replacement with learning), the context defined by the optimal farming ratio might become more relevant in configuring a territory's land use pattern.

Conclusion

The present work gives new light on different factors likely to affect land use dynamics in a context where stakeholders of farming and herding compete for limited space. According to a former model, the Musical Chairs model, competition between mobile livestock keeping and sedentary agriculture lead, under most conditions, to the overall dominance of one land use class over the other. Moreover, we observed a clear bias towards the formation of land use patterns specialized in farming. In the current model, the Nice Musical Chairs model, we postulate three mechanisms that might modify the trends observed: restricted access, management, and pairing. Of those three, the interdependence between activities—that we expected to be a potential driver for fostering balanced land use patterns—was found insufficient to modify the dynamics caused by competition. Conversely, we identified the regime applied to accessing rangelands as a key factor in the formation of land use patterns. A territory could require strong institutional setting and group organization, particularly for defining the ownership of pasturelands, to reach and sustain a balanced proportion of farming and herding. Weakening such institutions would quickly lead to a profound transformation in the system's dynamics, mainly towards specialization in farming or socio-political fragmentation.

The Nice Musical Chair model is a set of interconnected theoretical assumptions—i.e. a conceptual formalization of real-world processes—and is not an exhaustive representation of any case study. However, it emphasizes processes described in several other publications, including both theoretical and case-focused contributions, from which we have identified, modeled, and simulated mechanisms of transversal nature (social, economic, political, and ecological). These mechanisms, together with their constraints, were postulated to be relevant factors in the interaction of farming and herding stakeholders and the land use patterns that follow. Through this process, we built a new theoretical framework that expands the one presented with the Musical Chairs model. We believe this framework can enlighten the interpretation of historical, ethnographical and archaeological observations, and we emphasize in particular that it shows the strong connection between weakening or collapse of group-level institutions and the drift of balanced landscapes towards agriculture-dominated heartlands.

Acknowledgements

Financial support for research in this paper was mainly provided by the project Simulpast 'Simulating the Past to Understand Human Behaviour' (CSD2010-00034, CONSOLIDER-INGENIO program, funded by MICINN-Spanish Ministry of Science and Innovation). The research was also supported by the R&D&I project CAMOTECCER (HAR2012-32653, funded by MINECO-Spanish Ministry of Economy and Competitiveness). A. Angourakis worked on this paper through the FPI contract (BES-2013-062691), M. Salpeteur through a contract funded directly by the SimulPast project, and V. Martínez through the post-doctoral contract Juan de la Cierva (JCI-2011-10963), all funded by MINECO. We are most grateful to J. I. Santos and M. Pereda (INSISOC, Universidad de Burgos) for their assistance in performing the LHS and random forest procedures. We are also grateful to M. Lake and M. Altaweel (University College of London) and to the anonymous reviewers for their useful comments.

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Table 1. Patch (land use unit) state variables

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Name	Description
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intGrowthF ***intGrowthH***	Rate of intrinsic growth for land use among (farming or herding) patches of the group
farmingRatio	Proportion of farming patches with respect to total belonging to the group
targetFarmingRatio	Proportion of farming patches with respect to total belonging to the group, desired by group representatives
groupDemandF ***groupDemandH***	Number of patches demanded for farming or herding due to group growth

Table 3. Parameters

Name	Description	Exploration range
total_patches	Total number of patches	-
init_groups	Initial number of groups	10-100
init_farming ***init_herding***	Number of patches initially used for farming or herding	10-240
baseIntGrowth	Base value of the intrinsic growth for land use per patch, for both land use classes	0.01-0.1
maxExtGrowth	Maximum value of extrinsic growth for land use, for both land use classes	0-0.1
effectivenessGr	Effectiveness gradient or Number of patches in a group with the maximum competitive strength possible (see Fig. 2)	5-500
maxGroupChangeRate	Maximum rate in which patches can change groups	0-1
optimalFarmingRatio	Percentage of farming within a group that allows patches to generate the maximum demand for land use	0-1
optimalGrowthIncrease	Maximum increase of growth for land use per patch, in terms of percentage of base intrinsic growth due to benefits of land use pairing (Fig. 4)	0-200

Table 4. Scenarios

Code name	Access	Pairing	Management	Simulation runs
Ao	Open access	No	no	1000
Bo	Open access	Yes	no	1000
Co	Open access	No	yes	1000
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Cr	Restricted access	No	yes	1000
Dr	Restricted access	Yes	yes	1000

Table 5. Global state variables

Name	Description
countLandUseF ***countLandUseH***	Number of patches used for farming or herding
farming	Percentage of farming patches over total number of patches
numberGroups	Number of groups using, at least, one patch
bigGroupSize	Number of land use patches of the biggest group

Figure captions:

Fig. 1 Summary of main results of the Musical Chairs model. Percentage of farming at equilibrium is plotted against (a) ratio between overall intensities of land use, (b) percentage of land use dilemma events and (c) overall external pressure regarding extrinsic land use demand. Each point represents data from a simulation with randomized parameters. On the left, dashed lines mark the expected percentage of farming (50%) given balanced overall intensities (i.e. 1); the curve and the gray area represent nonlinear regression curve (GAM method) and standard error, respectively (see randomized experiments in Angourakis et al. 2014)

Fig. 2 Penalization of group effectiveness depending on group size (variable) and effectiveness gradient (parameter). The function presents two simple rules: (a) the smaller the group, the more effective it will be; and (b) the lower the effectiveness gradient is, the smaller groups will be driven to be

Fig. 3 The cycle of the Nice Musical Chairs model

Fig. 4 The effect of the optimal farming ratio in group's land use demand. While the minority intrinsic demand is automatically set at maximum, the majority intrinsic demand will be penalized depending on how far the group's farming ratio is from optimum (left) and how big is the increase in demand produced by matching this optimum (right)

Fig. 5 Count of simulation runs stabilizing at different land use proportions (i.e. percentage of farming) and respective density projections (lines) for each of the eight scenarios explored

Fig. 6 Percentage of farming versus the number of groups and size of the biggest group at the end of simulations. Lines represent generalized additive model (GAM), using a cubic regression spline, for each variable

Fig. 7 Ranked parameter's importance concerning farming and size of the biggest group of all scenarios, calculated as percentage of mean squared error (MSE) increase using a random forest regression procedure (Liaw and Wiener 2002; R Core Team 2015)

Fig. 1

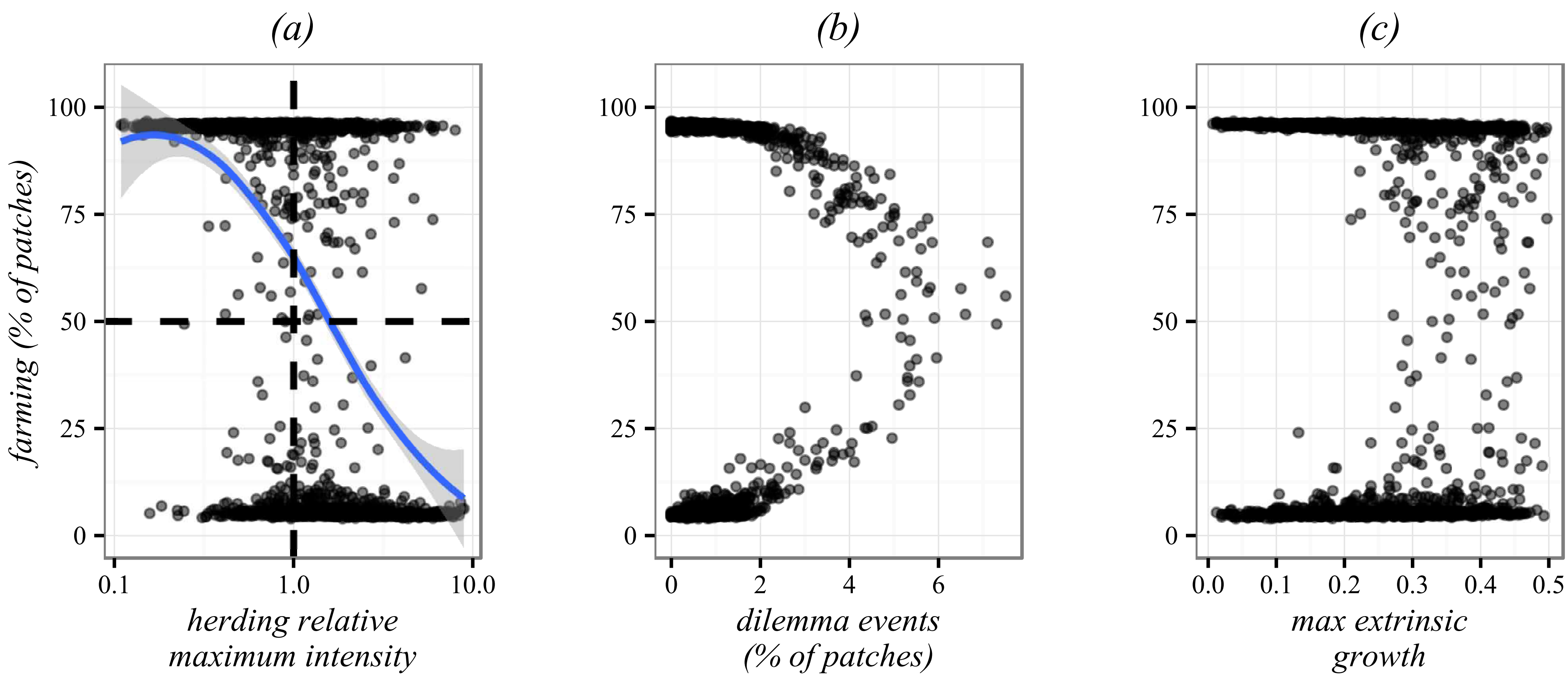
(a)
(b)
(c)
farming (% of patches)
100
75
50
25
0
0.1
1.0
10.0
herding relative
maximum intensity
0
2
4
6
dilemma events
(% of patches)
0.0
0.1
0.2
0.3
0.4
0.5
max extrinsic
growth

Fig. 2

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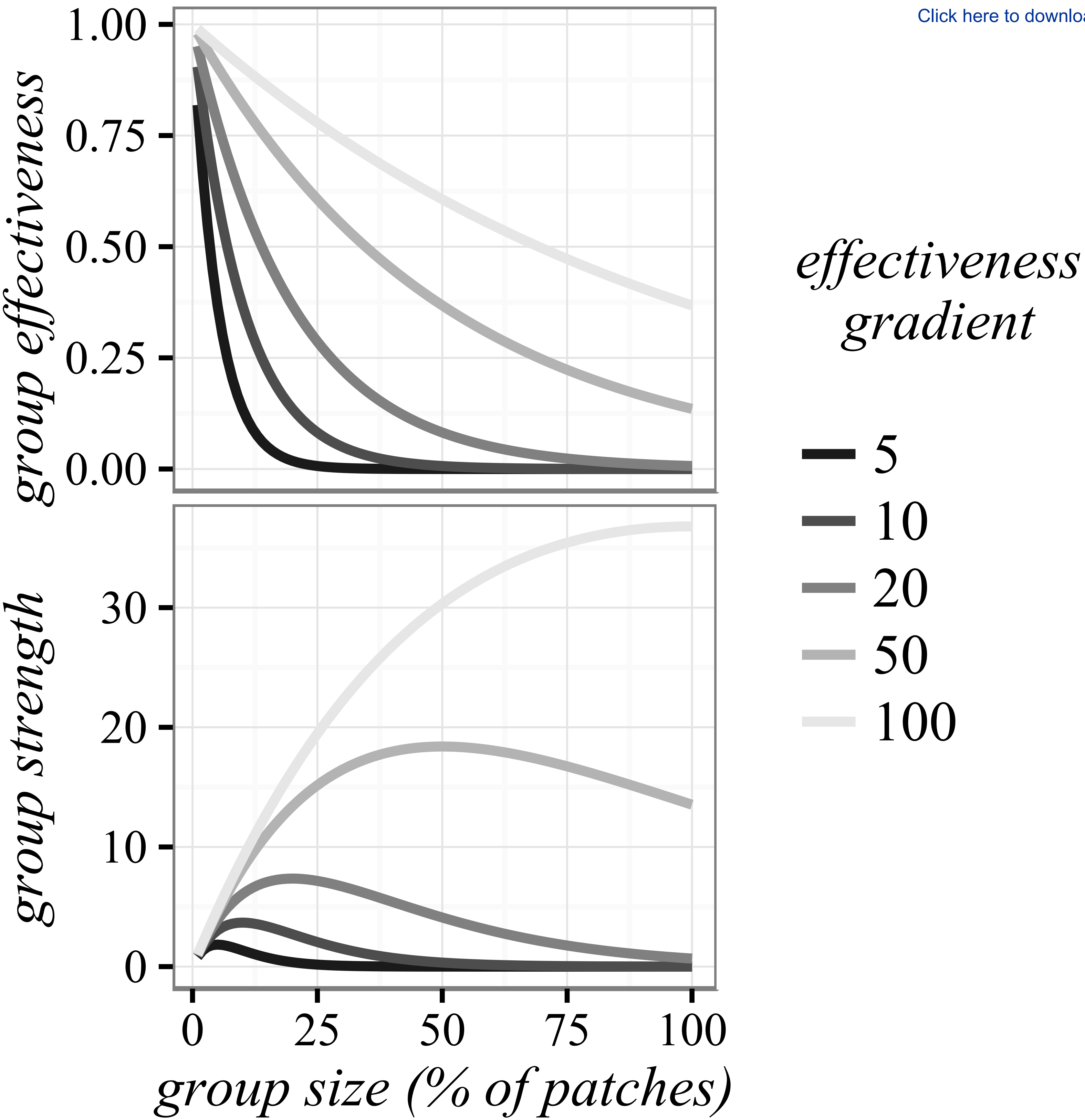

Fig. 3

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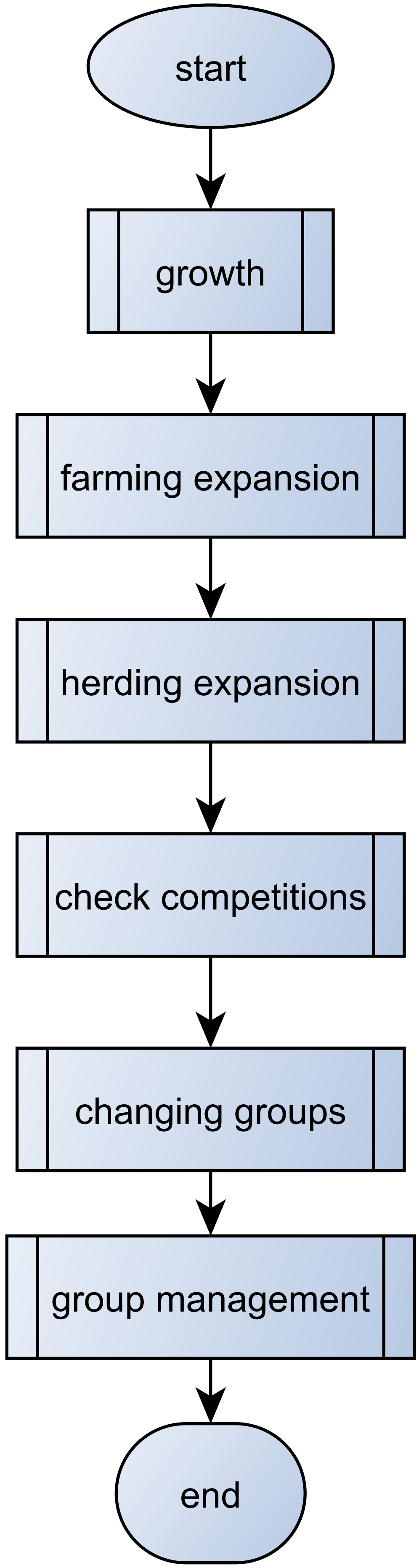

Fig. 4

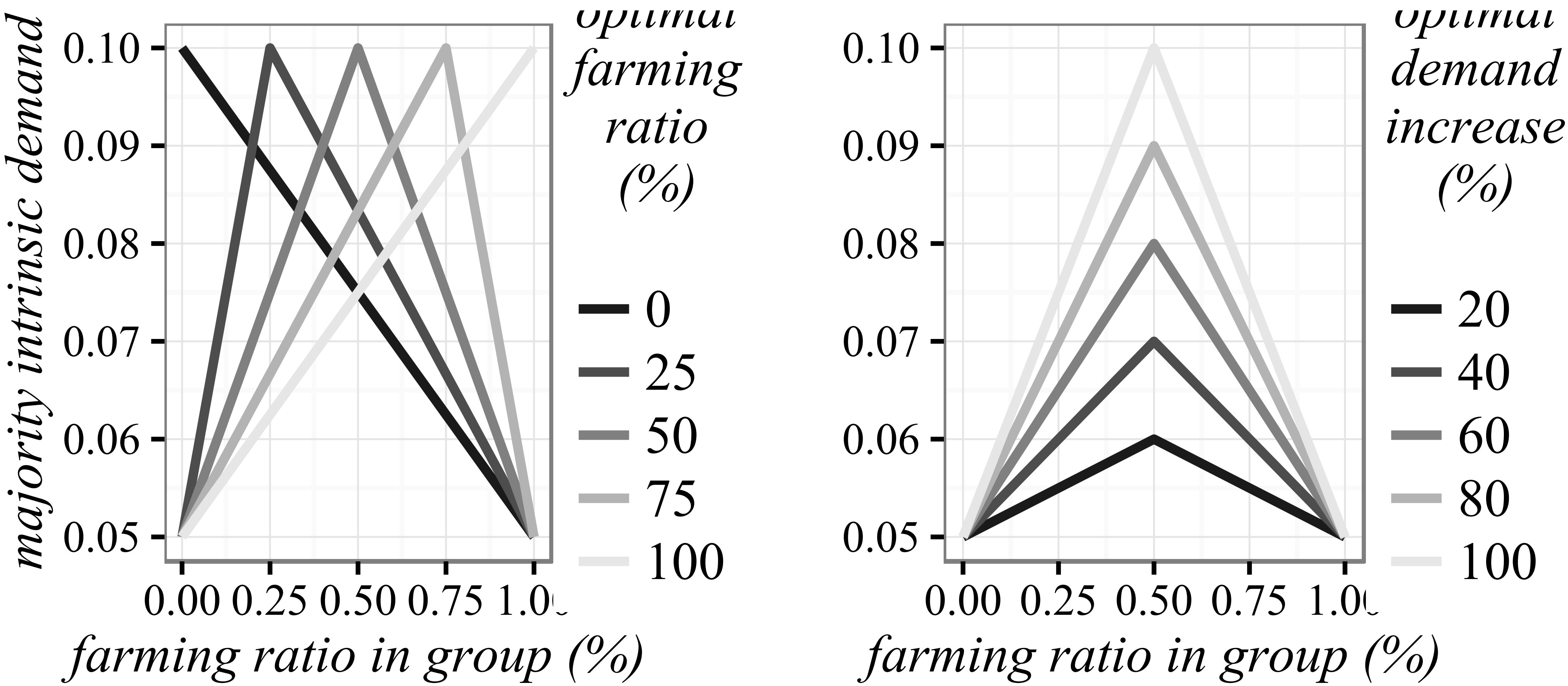
majority intrinsic demand
0.10
0.09
0.08
0.07
0.06
0.05
0.00
0.25
0.50
0.75
farming ratio in group (%)
farming
ratio
(%)
0
25
50
75
100
0.10
0.09
0.08
0.07
0.06
0.05
0.00
0.25
0.50
0.75
farming ratio in group (%)
demand
increase
(%)
20
40
60
80
100

Fig. 5

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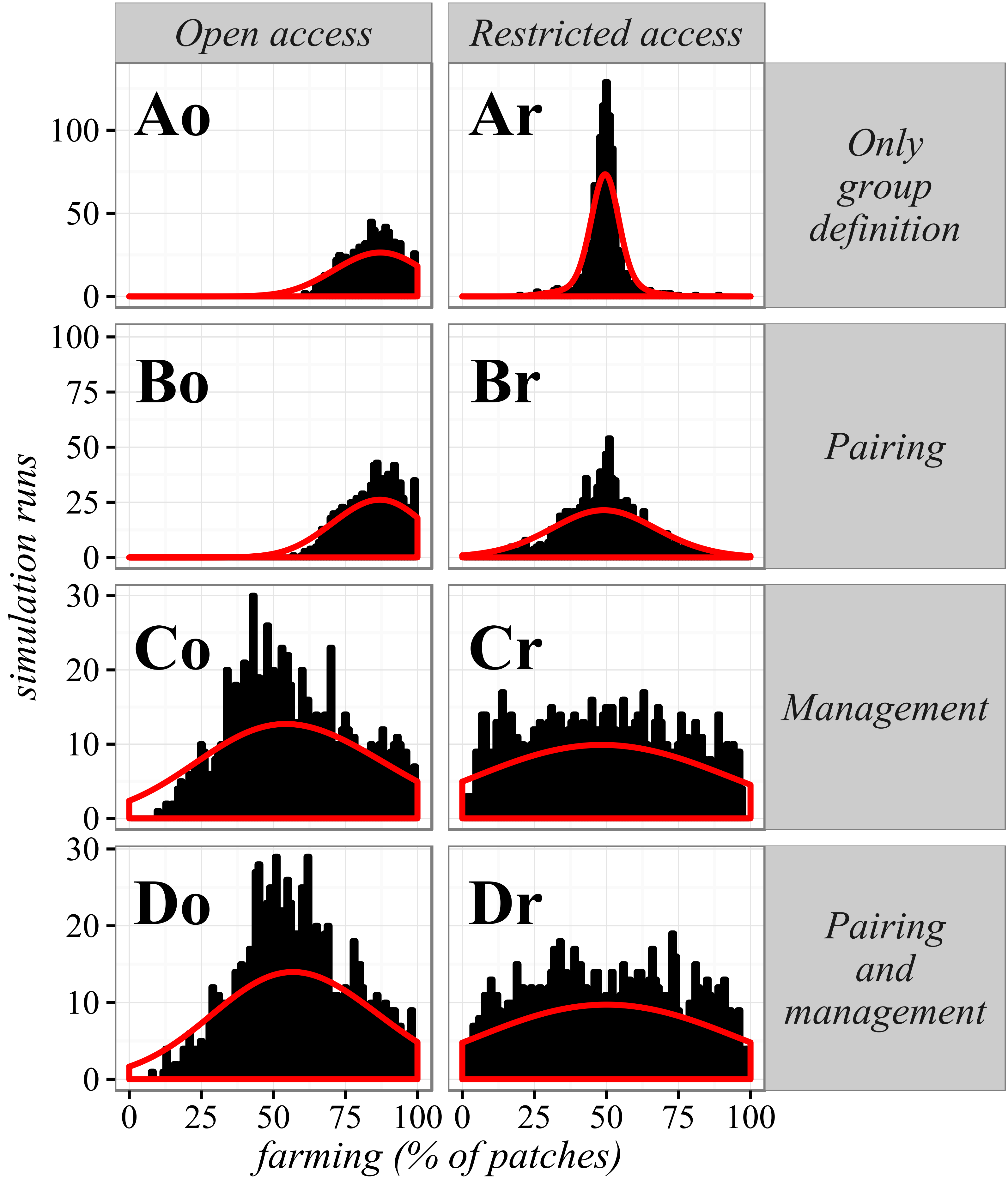
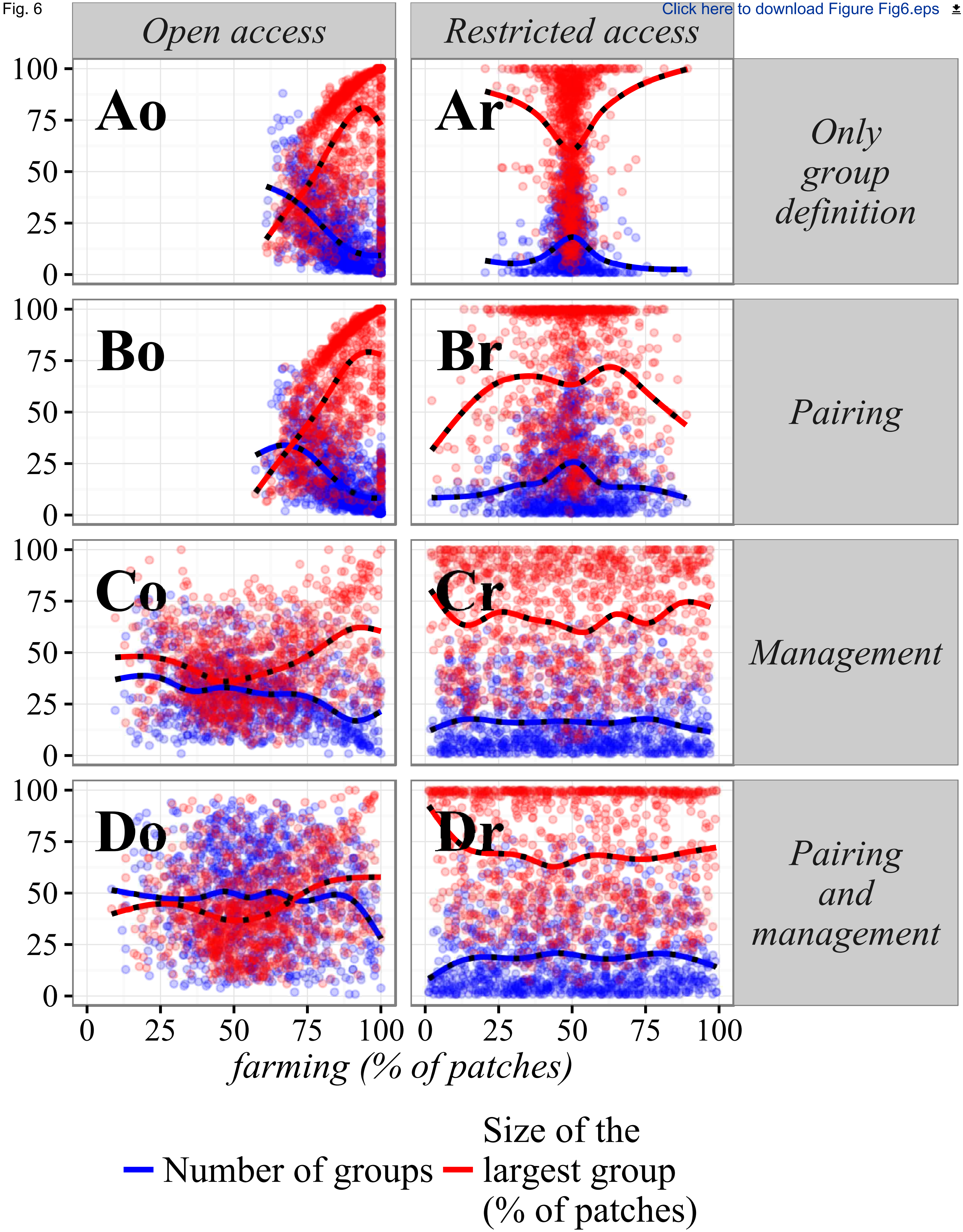
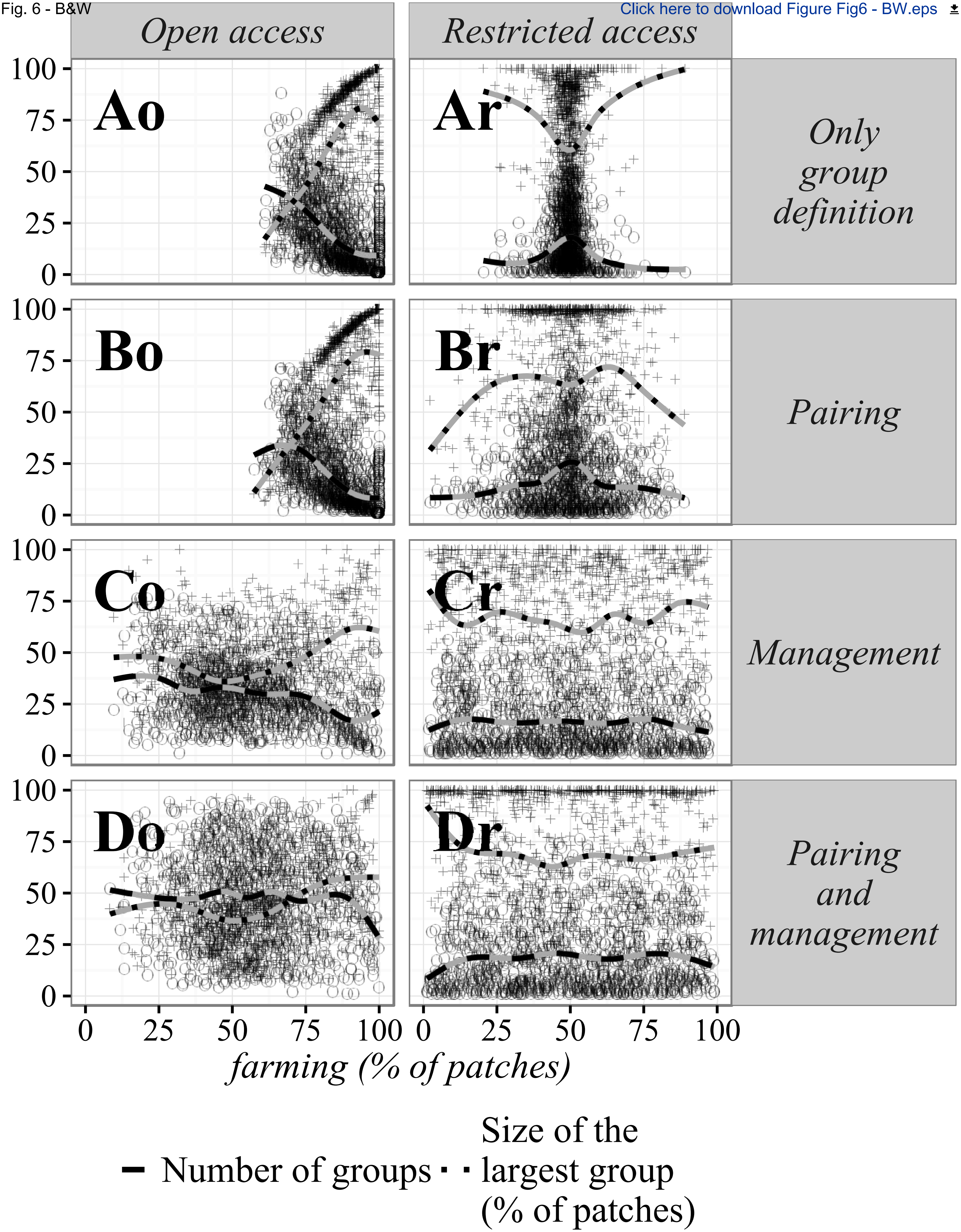


Fig. 6



Open access
Restricted access
Only group definition
Pairing
Management
Pairing and management
Ao
Ar
Bo
Br
Co
Cr
Do
Dr
100
75
50
25
0
farming (% of patches)
Number of groups
Size of the largest group (% of patches)

Fig. 6 - B&W


Open access
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Ao
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Dr
Only group definition
Pairing
Management
Pairing and management
100
75
50
25
0
0
25
50
75
100
farming (% of patches)
Number of groups
Size of the largest group (% of patches)

Fig. 7

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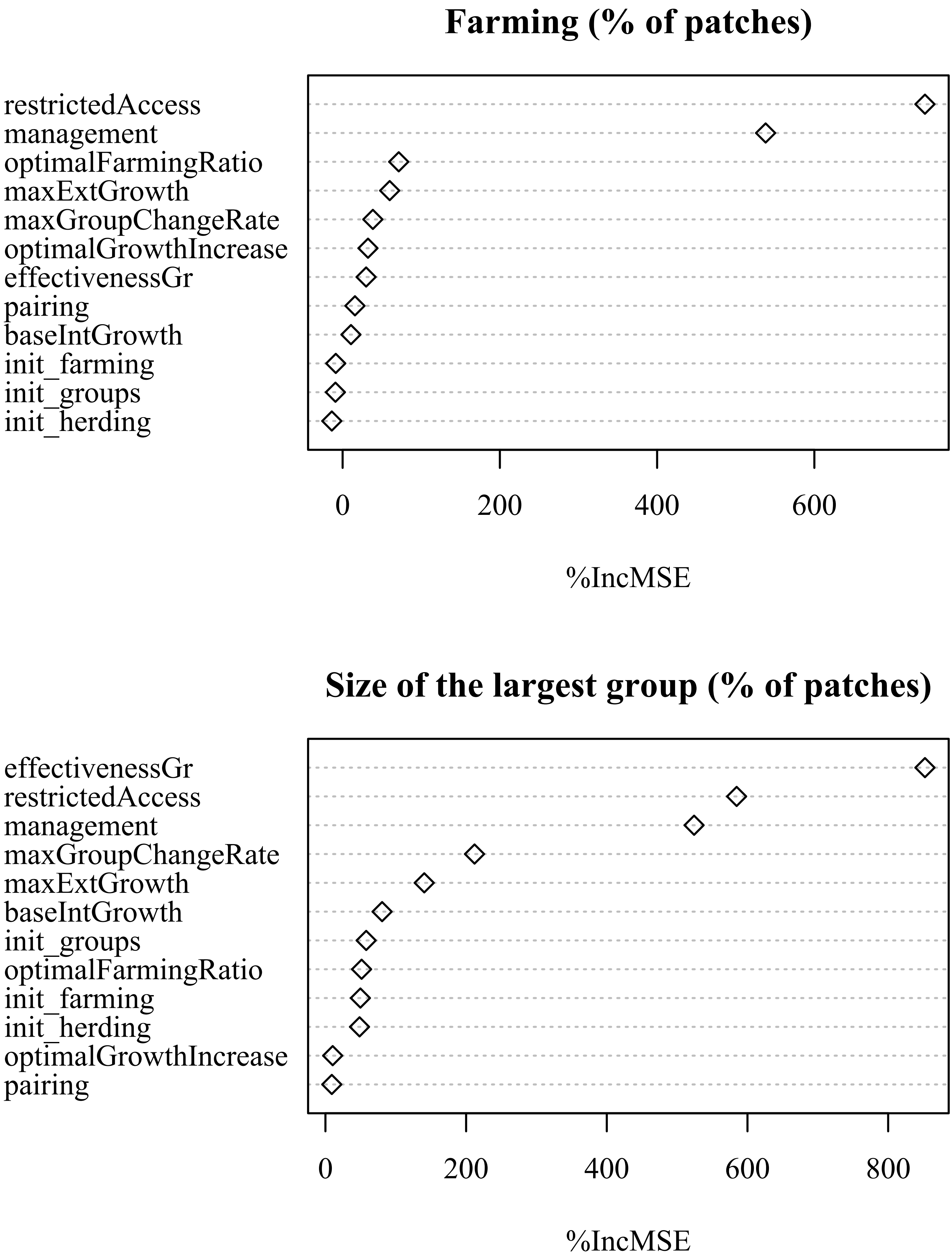

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Animation 1. Scenario Ao

Animation 2. Scenario Bo

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Animation 6. Scenario Do

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Animation 6.mp4

Animation 7. Scenario Cr

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Animation 7.mp4

Animation 8. Scenario Dr

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