Exploración y modelización de patrones socioecológicos y tecnoculturales en sociedades preindustriales de zonas áridas afro-eurasiáticas

Una aproximación multidisciplinar desde métodos cuantitativos

Andreas Angourakis

4. Simulación de sistemas socioecológicos

Resumen de capítulo • Este capítulo es representativo de la actividad investigadora del doctorando en la modelización de sistemas socioecológicos, en el contexto del proyecto SimulPast. Empieza con una introducción general a las líneas de investigación tratadas en los artículos (sección 4.1). A continuación, se dispone en orden cronológico las tres publicaciones relacionadas con el caso de estudio 5 del proyecto SimulPast, *La construcción de oasis en Asia Central*. El primer artículo explica el modelo *Musical Chairs* y hace una lectura de sus resultados (sección 4.2). Este modelo explora las implicaciones de una propuesta de mecanismo para la competencia por el uso de suelo entre agricultura sedentaria y ganadería móvil. Aunque liderado por el doctorando, este trabajo contó con la colaboración y respaldo de un grupo particularmente numeroso y variado de miembros del proyecto. El capítulo de libro, escrito de manera autónoma por parte del doctorando, profundiza sobre la estructura lógica de este mismo modelo y su valor explicativo en relación con referencias arqueológicas e históricas (sección 4.3). El segundo artículo da continuación a los trabajos anteriores, presentando un nuevo modelo, *Nice Musical Chairs* (sección 4.4). Este modelo permite investigar los efectos de cuatro mecanismos socioecológicos en la dinámica creada por la competencia por el uso de suelo. En este trabajo, se aprecian las contribuciones de M. Salpeteur y su perspectiva etnográfica, así como de los directores de la tesis y su perspectiva histórico-arqueológica. El capítulo cierra con el artículo sobre el modelo *Food for all* (sección 4.5), que trata la emergencia y sostenibilidad de la cooperación en el almacenamiento de alimentos en sociedades de pequeña escala. Éste trabajo se desliga de los tres anteriores al no tratar el caso de estudio 5, pero aún pertenece al contexto del proyecto SimulPast. El artículo combina de manera especialmente fluida las diferentes especialidades e intereses de los autores, todos miembros del proyecto, entonces activos en diferentes casos de estudio.

Resum de capítol • Aquest capítol és representatiu de l'activitat investigadora del doctorand en la modelització de sistemes socioecològics, en el context del projecte SimulPast. Comença amb una introducció general a les línies tractades en els articles (sección 4.1). A continuació, es disposa en ordre cronològic, les tres publicacions relacionades amb el cas d'estudi 5 del projecte SimulPast, *La construcció d'oasi a l'Àsia Central*. El primer article explica el model *Musical Chairs* i fa una lectura dels seus resultats (sección 4.2). Aquest model explora les implicacions d'una proposta de mecanisme per a la competència per l'ús de sòl entre agricultura sedentària i ramaderia mòbil. Encara que liderat pel doctorand, aquest treball va comptar amb la col · laboració i suport d'un grup particularment nombrós i variat de membres del projecte. El capítol de llibre, escrit de manera autònoma per part del doctorand, aprofundeix sobre l'estructura lògica d'aquest mateix model i el seu valor explicatiu en relació amb referències arqueològiques i històriques (sección 4.3). El segon article dona continuació als treballs anteriors, presentant un nou model, *Nice Musical Chairs* (sección 4.4). Aquest model permet investigar els efectes de quatre mecanismes socioecològics en la dinàmica creada per la competència per l'ús de sòl. En aquest treball, s'aprecien les contribucions de M. Salpeteur i la seva perspectiva etnogràfica, així com dels directors de la tesi i la seva perspectiva histórico-arqueològica. El capítol tanca amb l'article sobre el model *Food for all* (sección 4.5), que tracta l'emergència i sostenibilitat de la cooperació en l'emmagatzematge d'aliments en societats de petita escala. Aquest treball es deslliga dels tres anteriors en no tractar el cas d'estudi 5, però tot i pertany al context del projecte SimulPast. L'article combina de manera especialment fluida les diferents especialitats i interessos dels autors, tots membres del projecte, llavors actius en diferents casos d'estudi.

Chapter summary • This chapter is representative of the research activity of the candidate in modelling socio-ecological systems, within the context of the SimulPast project. It begins with a general introduction to the research lines addressed in the articles (sección 4.1). Next, it follows, in chronological order, the three publications related to case study 5 of the SimulPast project, *Oases construction in Central Asia*. The first article explains the *Musical Chairs* model and makes an interpretation of its results (sección 4.2). This model explores the implications of a mechanism proposed for the competition for land use between sedentary agriculture and mobile livestock breeding. Although led by the doctoral student, this work had the collaboration and support of a particularly large and varied group of project members. The book chapter, written autonomously by the doctoral student, delves into the logical structure of this same model and its explanatory value in relation to archaeological and historical references (sección 4.3). The second article gives continuation to the previous works, presenting a new model, *Nice Musical Chairs* (sección 4.4). This model allows the investigation of the effects of four socio-ecological mechanisms in the dynamics created by the competition for land use. In this work, the contributions of M. Salpeteur and his ethnographic perspective, as well as those of the directors of the PhD and their historical-archaeological perspective, are appreciated. The chapter closes with the article on the *Food for all* model (sección 4.5), which deals with the emergence and sustainability of cooperation for food storage in small-scale societies. This work is separated from the previous three by not dealing with case study 5, but it still belongs to the context of the SimulPast project. The article combines in a particularly fluid way the different specialties and interests of the authors, all members of the project, then active in different cases of study.

4.1. Introducción

La línea de modelización de sistemas socioecológicos engloba la actividad del doctorando en relación con los objetivos del proyecto SimulPast. En concreto, se han realizado tres publicaciones sobre ***la competencia entre agricultura sedentaria y ganadería móvil en oasis*** (sección 4.2, sección 4.3 y sección 4.4) y una sobre ***la emergencia y sostenibilidad de la cooperación en el almacenamiento de alimentos en sociedades de pequeña escala*** (sección 4.5).

El primer tema se seleccionó y desarrolló en el contexto del caso de estudio 5 del proyecto SimulPast, *La construcción de oasis en Asia Central.* Este caso de estudio tuvo como objetivo construir y explorar modelos de simulación que abordan la cuestión de cómo se generaron los patrones de uso de suelo en Asia Central en períodos previos a la industrialización. La aproximación ha sido *teórica*, buscando justamente construir nueva teoría sobre un tema que por lo general sufre la falta de una conceptualización sistemática.

Al tratar este tema, se ha considerado que los ***patrones de uso de suelo*** son realidades materiales en constante formación, producidas por una serie de contingencias a diferentes escalas, del individuo al sistema socioecológico, abarcando diferentes dimensiones del comportamiento humano (p. ej., demografía, parentesco, economías doméstica y política). A pesar de esta diversidad de factores, los patrones de uso de suelo pueden ser clasificados dentro de un conjunto finito de estados. Estos estados son definibles a través de indicadores como la *proporción* y *distribución* de clases de uso de suelo, la *frecuencia del cambio endémico* de las mismas (i.e. inestabilidad), la *centralización* de los procesos de toma de decisiones, la *especialización* de los grupos, la *intensificación* económica, el *desarrollo* de las *fuerzas productivas*, la acumulación y circulación de la *riqueza* y, finalmente, la *resiliencia* del sistema frente a perturbaciones exógenas (e.g., cambio climático, rupturas económicas, cambios políticos a gran escala).

Para modelizar los oasis de Asia Central, se distinguieron dos clases generales de uso de suelo, la ***agricultura sedentaria*** (*i.e.* parcelas de cultivo y estabulación de animales; "*farming*") y la ***ganadería móvil o extensiva*** (*i.e.* pasto de uso estacional; "*herding*"). Las muchas variaciones posibles cabrían en una u otra clase, dependiendo de la naturaleza efectiva del paisaje correspondiente (*granjas* o *pastos*).

Consecuentemente, los patrones a los que se pretendían dar explicación fueron concep-

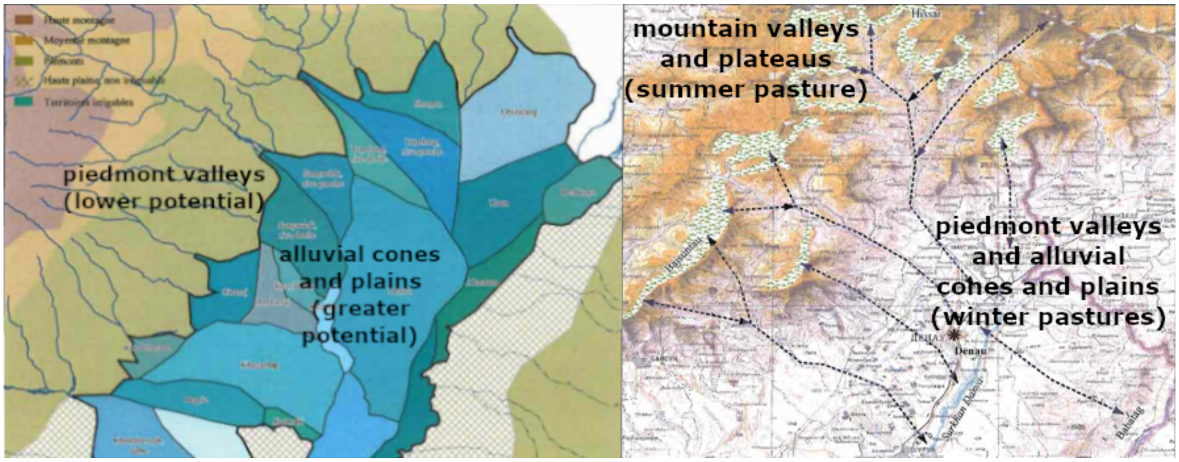

Figura 4.1: Comparativa de extractos de las figuras 24 y 45 de Stride (2005), representando las áreas agrícolas predominantemente irrigadas de la llanura del Alto Surkhan Daria (izquierda) y los pastos de verano y principales rutas de trashumancia en el norte de la provincia (derecha).

tualizados como una “frontera”, dibujada por el contraste entre la agricultura sedentaria y la ganadería móvil en lo referente al tipo e intensidad del uso del espacio. La agricultura sedentaria tiende a *ocupar* los conos y planicies aluviales, donde tiene mayor potencial, mientras que la ganadería móvil *utiliza*, de manera estacional, un territorio mucho más amplio y disperso, incluyendo los valles y mesetas de media y alta montaña (figura 4.1).

El interés en la interacción entre estas dos clases de uso de suelo vino motivado por evidencias arqueológicas e históricas en diferentes oasis en Asia Central. Estos oasis—sobre todo los mejor estudiados, como el de Samarcanda (Stride, Rondelli y Mantellini 2009)—presentan cambios no lineales y de ritmo variado en la extensión de zonas irrigadas, sugiriendo mecanismos más complejos que los postulados por modelos tradicionales (p. ej., Wittfogel 1957).

El principal interrogante de partida era el papel que pudiera haber tenido la población pastoril, dado que su actividad es en gran medida *invisible* en el registro arqueológico de Asia Central. A menudo se ha interpretado a esta población como un elemento exógeno a la dinámica de los oasis (Stride, Rondelli y Mantellini 2009). En regiones como la del Surkhan Daria y Samarcanda, la presencia de grupos de pastores suele ser asumida como limitada a las áreas que contienen monumentos funerarios preservados (*kurgan*) y arte rupestre. Éstas y otras estructuras atribuidas a grupos de pastores se

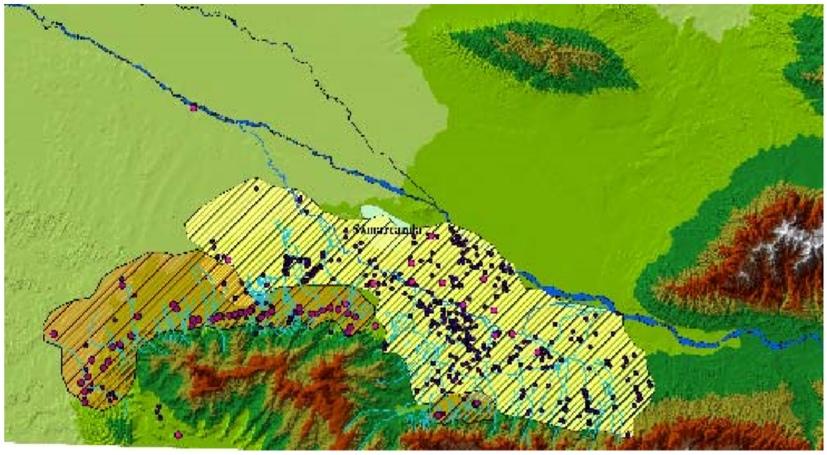

Figura 4.2: Reproducción de la figura 3, capítulo 6, página 302, de Franceschini (-@Franceschini2007). Subtítulo original: *Áreas de poblamiento de nómadas (naranja) y sedentarios (amarillo) en base al DEM obtenido del mapa topográfico 1:100000* (.Aree di popolamento dei nomadi (arancione) e dei sedentari (giallo) su base DEM ottenuta da mappa topografica 1:100000").

encuentran normalmente en aquellas zonas no afectadas por los avances históricos de la agricultura de irrigación (p. ej., Franceschini 2007, ver figura 4.2). Asimismo, desde la historiografía, los territorios de estos grupos se relegan a tramos de *terra incognita* entre los oasis (zonas “sin nombre” en la 2.9, sección 2.2.2; ver también la problemática asociada a la definición de los grupos sacas, sección 2.2.4, pp. 44-47).

Sin embargo, otros trabajos han señalado que la asociación entre las evidencias arqueológicas, por un lado, y la actividad pastoral no es necesariamente correcta. Alizadeh y Ur (2007), por ejemplo, han demostrado en un contexto similar (estepa de Mughan, noroeste de Irán) que múltiples olas de avance de la agricultura de irrigación crea una *zona de destrucción* que puede invisibilizar cualquier actividad pastoral anterior (figura 4.3).

Después de una etapa de discusión con un numeroso y variado grupo de investigadores (ver coautores de Angourakis et al. 2014, sección 4.2), se ha seleccionado la competencia por el uso de suelo entre agricultura sedentaria y ganadería móvil como el mecanismo central desde el cual se explorarían otros factores. Como se argumenta en los tres trabajos (sobre todo en Angourakis 2014, sección 4.3), esta dinámica de competencia se ha documentado histórica y etnográficamente en regiones donde existe contacto recurrente entre la práctica, por un lado, de cultivo y crianza intensiva y, por otro, de crianza extensiva, sea ésta trashumante, seminómada o nómada. Por ejemplo, se han

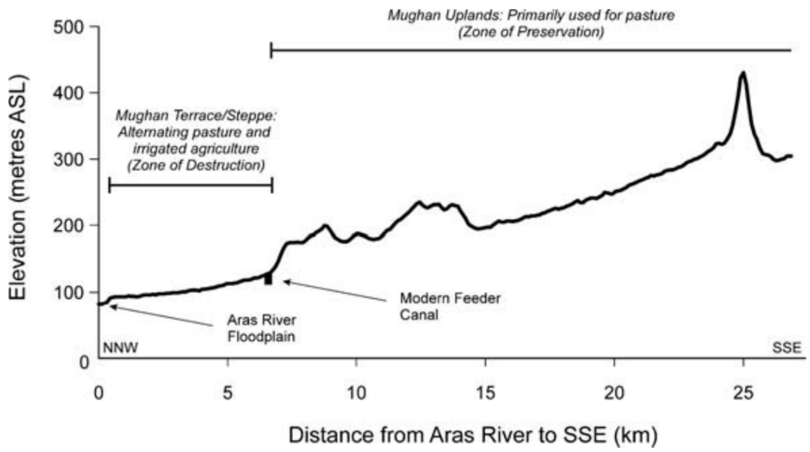

Figura 4.3: Reproducción de la Figura 7 de Alizadeh y Ur (2007). Subtítulo original: *Zonas de destrucción y preservación en la estepa Mughan (exagerado verticalmente). Ver figura 6 para la localización de esta sección* ("Zones of destruction and preservation on the Mughan Steppe (vertically exaggerated). See Figure 6 for location of this section").

identificado en la bibliografía casos en el Sahel occidental, Egipto, el Creciente Fértil, Tracia y Macedonia, Irán, Afganistán, Pakistán y Asia Central, incluyendo casos en la estepa euroasiática.

A partir de la publicación del modelo *Musical Chairs*, el doctorando siguió con colaboraciones más puntuales con otros miembros del proyecto. La meta ha sido explorar cómo otros mecanismos, formalizados a partir de conceptos en la bibliografía, podrían afectar la dinámica y el resultado a largo plazo de la competencia por el uso de suelo (figura 4.4). El segundo artículo incluido en este capítulo (Angourakis et al. 2017, sección 4.4) presenta el modelo *Nice Musical Chairs*. Este modelo permite la exploración de mecanismos de hasta cuatro ámbitos: dinámica de grupos (*Group dynamics*), "emparejamiento" de usos de suelo (*Pairing*), gestión desde liderazgo de grupo (*Management*) y régimen de acceso a la pastura (*Pasture tenure*).

El segundo tema, ***la emergencia y sostenibilidad de la cooperación en el almacenamiento de alimentos en sociedades de pequeña escala***, se ha abordado también en el contexto del proyecto SimulPast. La iniciativa surgió con la invitación de A. L. Balbo para contribuir en un número monográfico sobre este tema. La intención era aplicar la modelización basada en agentes (ABM) para explorar hipótesis sobre la resiliencia de las instituciones de cooperación dedicadas al almacenamiento de alimentos. La principal inspiración fueron los trabajos de Ian Kuijt (2008, 2009). Estos trabajos

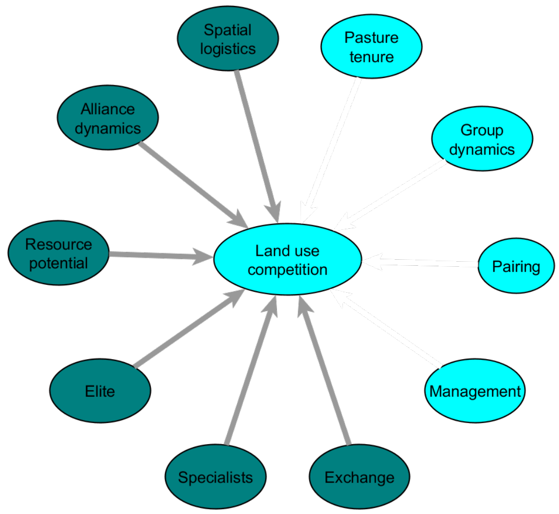

Figura 4.4: Mecanismos considerados para exploración en el caso de estudio 5 del proyecto SimulPast. Se destacan aquellos que efectivamente se incluyen en los dos modelos publicados.

posicionan el almacenamiento de alimentos en el centro del proceso que culminó en el origen de las primeras comunidades agrícolas, tratando específicamente las evidencias del Neolítico precerámico en el Levante, Próximo Oriente.

El objetivo reflejado en el artículo (Angourakis et al. 2015) es el de investigar cómo se establecen y se mantienen las instituciones cooperativas relacionadas al almacenamiento y gestión de los alimentos en comunidades de este tipo. Se trató de una exploración de hipótesis sobre las condiciones que promueven o dificultan la cooperación, incluyendo factores frecuentemente postulados en la bibliografía (p. ej., fluctuaciones y cambio climático, nivel de desarrollo tecnológico y especialización de la dieta). Finalmente, se busca identificar qué implicaciones tienen estas instituciones para la supervivencia de la comunidad como un todo, evocando una discusión aún más general sobre la sostenibilidad de los bienes comunes dentro de la teoría económica. Después de realizada la publicación, esta línea se ha considerado concluida, al menos por lo que concierne el desarrollo de la tesis.

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

Esta sección corresponde al siguiente artículo:

Angourakis, A., Rondelli, B., Stride, S., Rubio-Campanillo, X., Balbo, A.L., Torrano, A., Martínez, V., Madella, M., Gurt, J.M. (2014). Land Use Patterns in Central Asia. Step 1: The Musical Chairs Model. *Journal of Archaeological Method and Theory*, 21: 405-425. http://dx.doi.org/10.1007/s10816-013-9197-0.

Los anexos correspondientes a esta publicación se encuentran en la sección A.2.1.1 del Apéndice.

Resumen El pastoreo y la agricultura sedentaria coexistieron en Asia Central durante varios milenios como principales opciones de producción económica preindustrial. Se sabe que la relación entre las personas que practican diferentes variantes de estos modos de subsistencia ha sido dinámica. Entre las muchas explicaciones posibles, exploramos esta dinámica modelando mecanismos que conectan las decisiones agregadas con los patrones de uso de suelo. En el marco del proyecto SimulPast, mostramos aquí los resultados del paso 1 de nuestro programa de modelado: el modelo Musical Chairs (juego de las sillas). Este modelo abstracto basado en agentes describe un mecanismo de competencia por el uso de suelo entre la agricultura sedentaria y el pastoreo. El objetivo es explorar cómo la movilidad, la intensidad y la interdependencia de las actividades pueden influir en el patrón de uso de suelo. Después de realizar un conjunto de experimentos dentro del marco de este modelo, comparamos las implicaciones de cada condición para la corroboración de patrones específicos de uso de suelo. También se discuten algunas implicaciones históricas y arqueológicas. Sugerimos que la extensión general de la agricultura sedentaria en oasis puede explicarse por la competencia por el uso de suelo entre la agricultura y el pastoreo, asumiendo que se desarrolla con poca o ninguna interferencia de contingencias climáticas, geográficas e históricas.

Resum El pastoralisme i l'agricultura sedentària coexistiren a Àsia central durant varis milenis com a principals opcions de producció econòmica preindustrial. Se sap que la relació entre les persones que van practicar diferents variants d'aquestes maneres de subsistència ha estat dinàmica. Entre les moltes explicacions possibles, vam explorar aquesta dinàmica modelant mecanismes que connecten les decisions agregades amb els patrons d'ús de sòl. En el marc del projecte SimulPast, mostrem aquí els resultats del pas 1 del nostre programa de modelatge: el model Musical Chairs (joc de les cadires). Aquest model abstracte basat en agents descriu un mecanisme de competència per l'ús de sòl entre l'agricultura sedentària i el pastoralisme. L'objectiu és explorar com la mobilitat, la intensitat i la interdependència de les activitats poden influir en el patró d'ús de sòl. Després de realitzar un conjunt d'experiments dins el marc d'aquest model, comparem les implicacions de cada condició per a la corroboració de patrons específics d'ús de sòl. També es discuteixen algunes implicacions històriques i arqueològiques. Suggerim que l'extensió general de l'agricultura intensiva en un oasi pot explicar-se per la competència per l'ús de sòl entre l'agricultura i el pastoralisme, assumint que es desenvolupa amb poca o cap interferència de contingències climàtiques, geogràfiques i històriques.

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

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Abstract Herding and farming coexisted in Central Asia for several thousand years as main options of preindustrial 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.

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Keywords Land use · Central Asia · Agent-based modeling · Coevolution · Herding and farming

Introduction

In Central Asia, the main variants of preindustrial 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 twentieth 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.

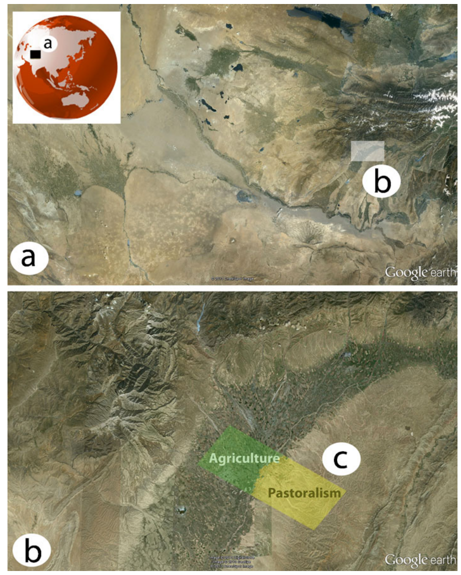

Fig. 1 Google Earth snapshots depicting an example of Central-Asian oasis: the plain of the high Surkhan Darya in Southeastern Uzbekistan (**a**, **b**). A *rectangle* (**c**) is placed over the area represented in the Musical Chairs model, in which *green patches* (*agriculture*) and *yellow patches*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

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 coevolutionary 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.

Materials and Methods

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 as follows: (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 the 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 the 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.

The Musical Chairs Model

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 as follows:

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 as follows (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.

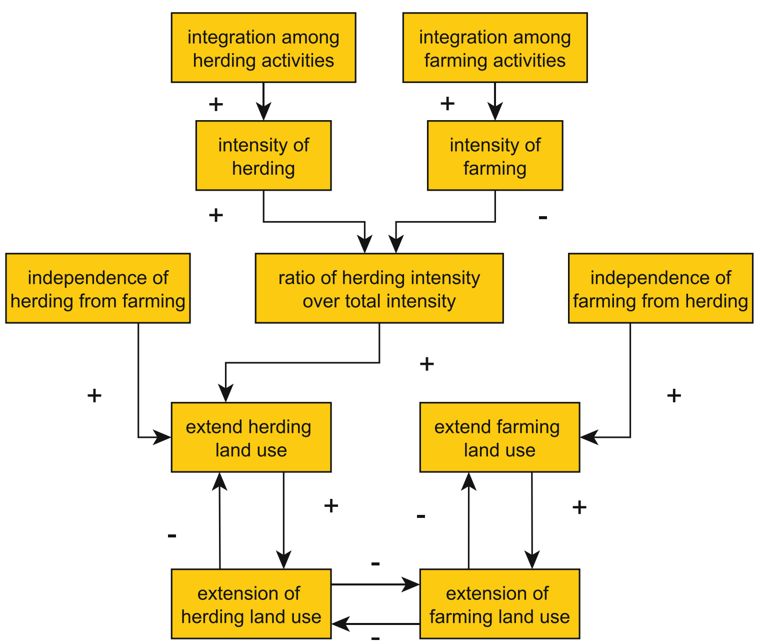

Fig. 2 The relationships between the factors influencing land use pattern, accordingly to the Musical Chairs model

(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 the chairs previously used by players representing herding land use. Once the 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.

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).

Steps 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.

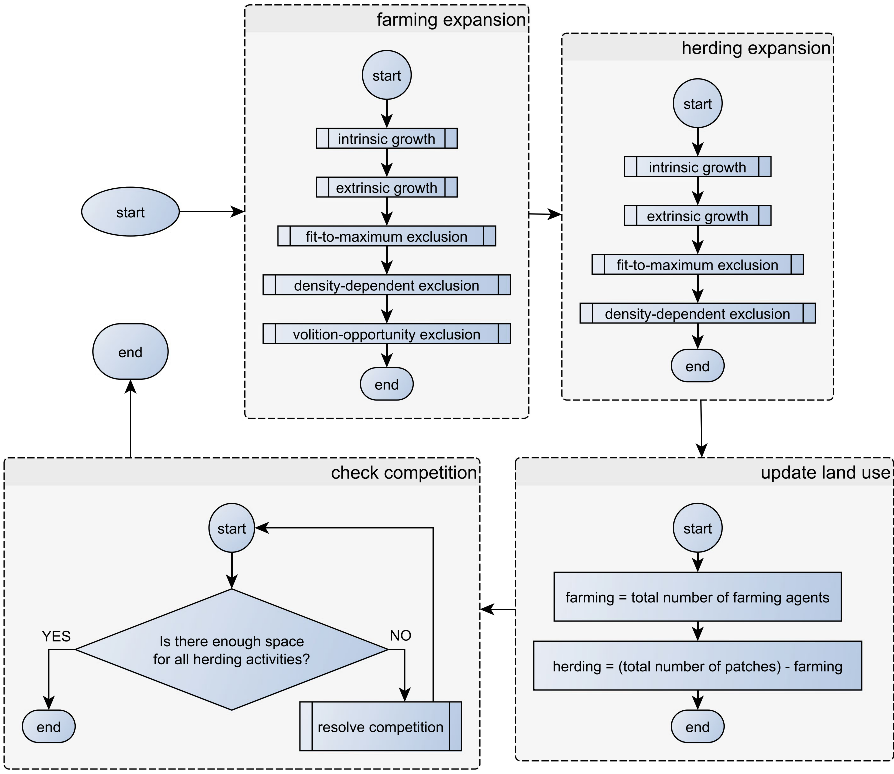

Fig. 3 The cycle of the Musical Chairs model: the four steps are framed within *dashed borders* and the submodels are referred as boxes with *side bars*

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, while 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, according 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.

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, 1,120 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 2,500 runs was undertaken, exploring a broader range of parametric settings in a stochastic manner. All experiments were executed in a world with 2,000 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.

Results

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

Table 1 Experimental setting

Constant parameters		
Number of land units		2,000
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 1,000 (uniform distribution)
Initial extension of herding land use	100 and 200	From 0 to 1,000 (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

these conditions, while settings with unbalanced initial extensions are more favorable for initially most of the 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 indicating that these parameters have no statistical value for explaining the diversity of outcomes.

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.

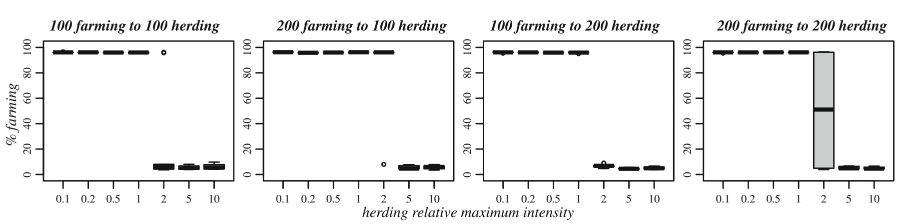

Fig. 4 Box plots presenting the percentage of farming land use at equilibrium (% *farming*), for the four different scenarios regarding initial extensions, throughout the seven explored values of *herding relative maximum intensity* in the "*ext*=0, *integ*=1" scenario

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	2,500					1,499					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	289.19	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

Table 2 (continued)

	Total					Cluster 1: big oases					Cluster 2: small oases					Cluster 3: intermediate oases				
Number of cases	2,500					1,499					892					109				
	μ	σ	Md	min	max	μ	σ	Md	min	max	μ	σ	Md	min	max	μ	σ	Md	min	max
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	0.05	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)

Classes of Land Use Patterns Three classes of oases emerge, qualitatively distinguished by their trend in land use patterns as follows (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

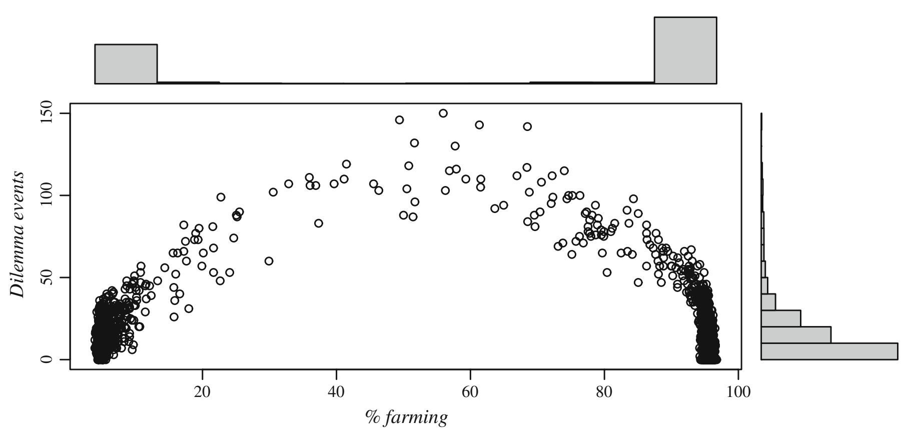

Fig. 5 The counts of *dilemma events* versus the percentage of farming land use at equilibrium (% *farming*), produced in the randomized experiment. Points represent individual simulations, in which parameters where set to randomly chosen values (Table 1). The distribution of cases is also presented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

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.

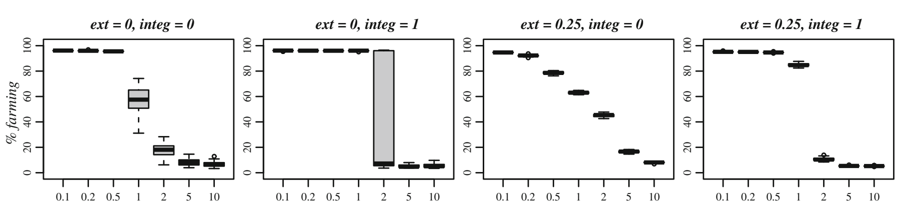

Fig. 6 Box plots presenting the percentage of farming land use at equilibrium (% *farming*), considering different settings of the *herding relative maximum intensity*, *extrinsic growth rates* (*ext*), and *integration* (*integ*)

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 assumption sound reasonable and realistic considering ethnographic and anthropological sources (Johnson 1969; Khazanov 1994; Barnard and Wendrich 2008). 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).

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

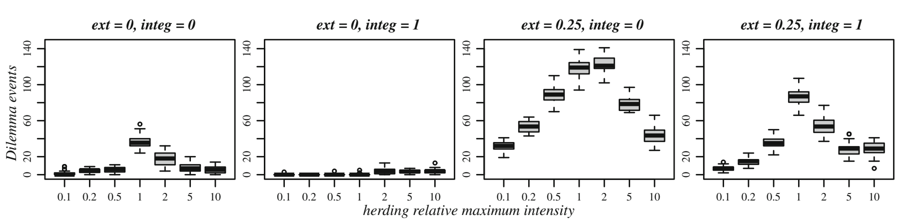

Fig. 7 Box plots presenting the frequency of *dilemma events* at equilibrium, considering different settings of *herding relative maximum intensity*, *extrinsic growth rates* (*ext*), and *integration* (*integ*)

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).

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),

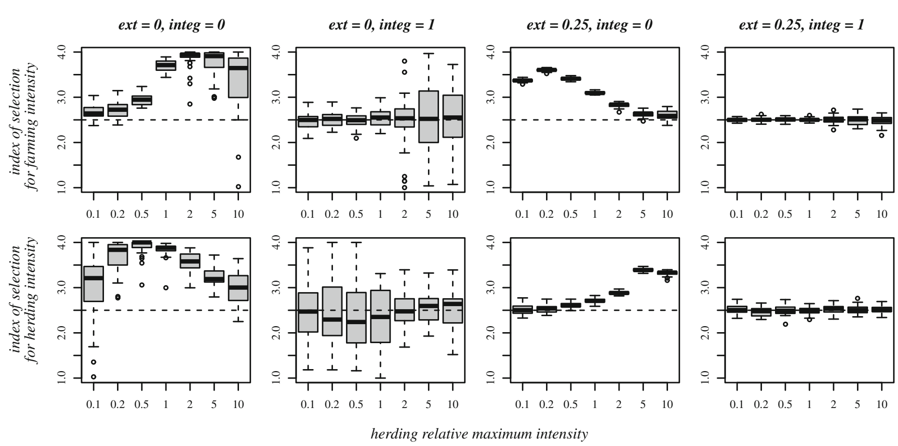

Fig. 8 Box plots presenting the index of selection for the *farming* (*top row*) and the *herding* (*bottom row*) *intensities*, considering different values of *herding relative maximum intensity*, *extrinsic growth rates* (*ext*), and *integration* (*integ*). Note that if a mean equals "2.5" (*horizontal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

more intense herding land units always suffer some significant level of selection, though the maximum is reached when big oases still present 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, while the *integration* among them (*integ*=1) cancels this mechanism.

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 the 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

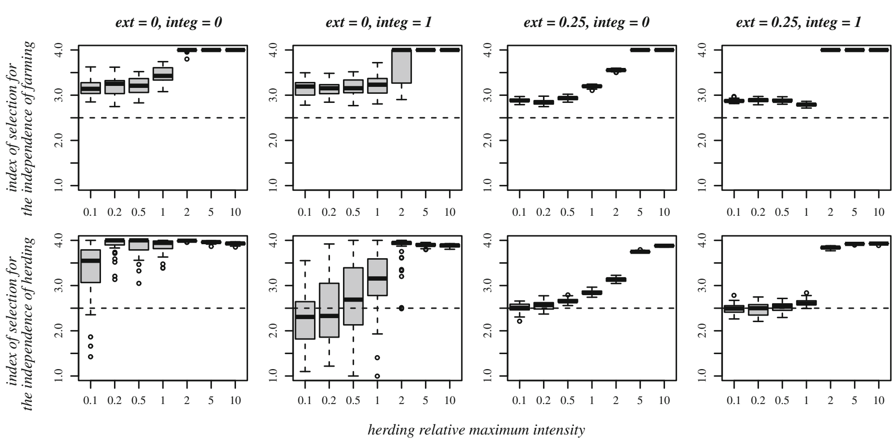

Fig. 9 Box plots presenting the index of selection for the *farming* (*top row*) and the *herding* (*bottom row*) *independences*, considering different values of *herding relative maximum intensity*, *extrinsic growth rates* (*ext*), and *integration scores* (*integ*). Note that if a mean equals "2.5"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

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.

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 twentieth 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 socioecological 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.

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 being 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 in 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

twentieth 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.

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).

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).

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 the following:

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 follow 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 as follows:

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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4.3. Exploring the Oases of Central Asia: a model of interaction between mobile livestock breeding and sedentary agriculture

El contenido de esta sección es la transcripción del siguiente capítulo de monográfico:

ANGOURAKIS, A., 2014. Exploring the Oases of Central Asia: a model of interaction between mobile livestock breeding and sedentary agriculture. En: B. ANTELA-BERNÁRDEZ y J. VIDAL (eds.), *Central Asia in Antiquity: Interdisciplinary Approaches*. Oxford: BAR International Series, pp. 3-23.

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La paginación y la numeración de subsecciones y figuras han sido adaptadas a la tesis.

Resumen Asia Central es un área en la que las principales variantes de las producciones económicas preindustriales coexistieron durante varios milenios. Se sabe que la relación entre las diferentes actividades económicas ha sido inestable, con abundantes ejemplos de conflictos a diferentes escalas geográficas y la mayoría de los lugares han visto cambiar los patrones de cambio de uso de la suelo hasta principios del siglo XX. Aquí presentamos y discutimos un modelo de interacción entre ganadería móvil y agricultura sedentaria, el modelo Musical Chairs (juego de la silla). El modelo se implementa mediante el modelado basado en agentes y describe un mecanismo de competencia por la tierra entre las dos estrategias económicas. Para complementar una publicación anterior (Angourakis et al. 2014), este artículo profundiza en el análisis de suposiciones, implicaciones y estados estables (es decir, atractores) involucrados en este modelo. Discutimos nuestros resultados a la luz de casos arqueológicos e históricos y concluimos con la definición de líneas para futuras exploraciones.

Resum Àsia central és una àrea en la qual les principals variants de les produccions econòmiques preindustrials van coexistir durant varis milenis. Se sap que la relació entre les diferents activitats econòmiques ha estat inestable, amb abundants exemples de conflictes a diferents escales geogràfiques i la majoria dels llocs han vist canviar els patrons de canvi d'ús de sòl fins a principis del segle XX. Aquí presentem i discutim un model d'interacció entre ramaderia mòbil i agricultura sedentària, el model Musical Chairs (joc de la cadira). El model s'implementa mitjançant el modelatge basat en agents i descriu un mecanisme de competència per la terra entre les dues estratègies econòmiques. Per complementar una publicació anterior (Angourakis et al. 2014), aquest article aprofundeix en l'anàlisi de suposicions, implicacions i estats estables (és a dir, atractors) involucrats en aquest model. Discutim els nostres resultats a la llum de casos arqueològics i històrics i concloem amb la definició de línies per a futures exploracions.

Abstract Central Asia is an area in which the main variants of pre-industrial economic productions coexisted for several thousand years. The relation between the different economic activities is known to have been unstable, with abundant examples of conflict at different geographical scales and most places having seen shifting patterns of land use change right up to the early 20th century. Here we present and discuss a model of interaction between mobile livestock breeding and sedentary agriculture, the Musical Chairs model. The model is implemented using Agent-Based modelling and describes a mechanism of competition for land between the two economic strategies. To complement a previous publication (Angourakis et al. 2014), this article deepens on the analysis of assumptions, implications and stable states (i.e., attractors) involved in this model. We discuss our results in light of archaeological and historical cases and conclude by defining lines for further exploration.

Keywords land use; oasis; Central Asia; agent-based modeling; coevolution; herding and farming

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4.3.1. Modelling land use in oases of Central Asia

4.3.1.1. The problem and its context

For at least three millennia, Central Asia was the stage of frequent interaction between the main variants of pre-industrial food production, ranging from fully nomadic pastoralism to modes of agriculture highly reliant on irrigation. Given that most of this subcontinent is too arid to sustain sedentary agriculture, this interaction was not ubiquitous, but in fact concentrated in what we came to call *oases*. Regarding Central Asia and most of the arid Eurasia, oases are equivalent to alluvial cones and plains, whose rivers are mainly feed by distant rainfall and the seasonal melting of glaciers and snow cover (Oberhansli 2011).

Oases themselves attest that the aforementioned interactions were not at all stable. Both historical and archaeological records revealed several situations in which land use radically changed (Stride 2005, in Southern Uzbekistan; Nesbitt and O'Hara 2000, in Southern Turkmenistan; Alizadeh and Ur 2007, in North-Western Iran; Abdi 2003, in Central Zagros; Newson 2000, in South-Eastern Syria). Starting with the very diffusion of agriculture, it appears that farming-i.e. crop cultivation and small-scale livestock breeding-was able to progressively claim the use of oases. As oases are first and foremost natural havens for animals and water-demanding plants, many wild species and the livelihoods relying on them-such as hunting, fishing and gathering-found themselves competing for (and losing) these key sites against this new sedentary lifestyle and its constructed ecosystem (Rosenberg 1998). The latter development and implementation of technologies to control the flow of water, although widening the oasis itself, have further empower this process, rendering also marginal lands more and more attractive to cultivation.

Contrasting with its relationship with hunting, fishing and gathering, farming displayed more complex interactions with the different varieties of mobile livestock breeding. The latter, generally called *pastoralism*, emerged in a secular process alongside farming itself, driven by the relentless demand of animal products of the growing sedentary population. As the productivity of arid lands is highly constricting to livestock breeding and only a reduced number of animals can be sustained throughout the year in the same locality, mobility proved to be the best strategy to meet this demand at the long run. In fact, the 'herding solution' was probably not given by any human enlightenment, but it presented itself as the obvious way to proceed with animals that were already highly migratory in the wild (e.g., Martin 2000: 22, on gazelle behavior).

Even though livestock breeding is an integrated part of any farming economy across

Afro-Eurasia, the increasing specialization in the mobile varieties cause some people to develop specific interests, which often diverged from those engaged in farming. Although a complete independence between these livelihoods is hardly the case-and for most scholars, it is virtually impossible (e.g., see Khazanov 1994)-, this divergence do produces very tangible cultural distancing. A Sumerian fable, telling of the dispute between Enkimdu the farmer and Dumuzi the herder for the hand of the goddess Inanna (Pritchard 1955: pp.41-2; Moscati 1960: pp. 42-3), exemplifies how socially significant this situation can be, even within the same cultural community. Once Inanna declares to favor the proposal of Enkimdu, Dumuzi defends himself by comparing their products:

Enkimdu, the man of the canals, the ditches and the furrows,
The farmer, what advantage has he over me?
Let him give me his black garment,
In return I will give him, the farmer, my black ewe;
Let him give me his white garment,
In return I will give him, the farmer, my white ewe;
Let him pour for me his finest beer,
In return I will pour for him, the farmer, my yellow milk;
Let him pour for me his sweet beer,
In return I will set before the farmer my curdled milk.
After I have eaten, after I have drunk,
I will leave for him the extra fat,
I will leave for him the extra milk:
The farmer, what advantage has he over me?

Although Inanna ultimately chooses Dumuzi to marry, a moral point of the fable is the further reconciliation of the rivals, having Enkimdu the farmer also bringing his gifts to the goddess. Therefore, not only this fable indicates that there was indeed a clear divergence of interests between the stakeholders of these activities, but also that it was a significant social problem to be coped with. Being it true for Southern Mesopotamia, as early as the third millennium B.C., there is no reason not to expect it in other latter contexts of arid Eurasia, many of which entail cultural differences forming prior to proper interaction.

Probably the main cleavage between farming and herding is the one regarding the use of land. It is suggestive that the goddess Inanna embodied -among other things- both fertility and identity of the land. Farming and herding activities are indeed qualitatively different regarding land use, involving different logistics, ecological constraints and timings. Although our research pursues the conditions in which there is competition for land use between these two livelihoods, they are not necessarily mutually exclusive, as they can even draw upon each other (e.g. fodder for manure), provided that they are sufficiently coordinated (Stride et al. 2009). We should also keep in mind that the value of land for these livelihoods is diametrically different: herding implies visiting different pastures throughout the year, often within a vast territory, with little or no investment on particular patches of land; farmers on the other hand will only be interest in the few areas where cultivation is feasible, which shall be altered through intensive-and costly-activities.

Despite these caveats, there is no reason to automatically assume that there is a complete separation between the niches of farming and herding activities, at least in terms of land use. Saving all differences, both boil down to requiring land surface and its biomass capacity, mainly limited by soil moisture in the growing seasons.

The various forms of mobile livestock breeding in arid Eurasia, which array from daily local movements to long distance non-linear movements, have all one aspect in common: oases are benchmarks. Overall, herders have many incentives to visit and stay as long as possible in oases. Even if the quality and abundance of pastures *in* and *around* oases is inferior to the ones elsewhere (e.g. high altitude pastures during summer), the harsh seasonal cycle and the scarcity of denser vegetation will regularly impose oases as indispensable refuges to herds. These incentives are not only ecological (i.e. access to water, higher temperature in winter), but also social, political and economic, given that oases enable herders to congregate with their families, clans and tribes, plus having access to trade-and sometimes pillage-opportunities offered by the settled population. These latter incentives would of course be closely related to how much area can be covered with less than a day journey from the settlements of an oasis. In this sense, it should be also taken into account that herding leaves very little and dispersed archaeological footprints (Barnard and Wendrich 2008, Cribb 2004), though it was already proved to be directly assessable in marginal lands (e.g., Rosen 1993).

Excluding the waterlogged alluvium, we assume that the area that can be used to grow farms, including both the natural oasis and the adjacent (potentially irrigable) plains, are also interesting for stationing herds during a given season. Consequently, in order to both farming and herding to use the same patch of land, coordination is needed, specifically to adjust the timing and intensity of each activity. For instance, it would be necessary for herds to leave the fields during the growth of crops, while fields should be already harvested or left in fallow if animals where to graze upon them.

All the work we developed rest on the assumption that there is no *a priori* coordination between farming and herding, such that they can coexist in the same area within an oasis at exactly the same time. Even if both activities are carried out in the same social fabric, with no clear-cut distinction between *farmers* and *herders*, we expect to observe some incompatibility between their simultaneous materializations in the context of oases. Another way of understanding this assumption is that, *if* and *when* cultivated fields are openly available for grazing, the herds feeding on them would not actually change its land use (i.e. farmlands would remain as such).

The lack of coordination between farming and herding could be simply the by-product of social distancing and a general disregard for livelihoods different from oneself. However, given that both interests would be favored by increasing coordination, it is probably the case that people deciding on how to carry out these activities are just not good enough predictors. A great deal of unpredictable events can prevent a fully coordinated situation, especially if they happen when people engaged in farming and herding are not fluently communicated. Different crops have often different growing seasons and the ripening term can fluctuate, depending on unpredictable environmental factors; herds' numbers can vary drastically between good and bad years and the spell of extreme climatic events (e.g. droughts, blizzards) can force herds to suddenly change their pace and route; fields can be extended to supply new demands or allocate new settlers; and, at any rate, socio-political events in the local and regional sphere will constantly affect in a rather complex manner the practice of both farming and herding.

Consequently, our research question narrows down to what mechanisms-if any-solves the reiterated dilemma between farming and herding regarding land use (i.e. which is to be carried out in a given patch of land), leaving aside for the time being the possibility of perfecting coordination. Moreover, we will be interest in understanding the implications of the proposed mechanisms for the configuration of different land use patterns among oases.

4.3.1.2. Our approach

In the framework of the *SimulPast* project, financed by the Spanish government, groups of different background came together to unravel the processes involved in archaeologically-inspired case studies. One of such case studies, centered in the interaction of sedentary and nomadic population of oases in Central Asia, shaped the work published here and elsewhere (Angourakis et al. 2014). We followed a bottom-up approach to address this question in the theoretical arena, meaning that we first reduce the problem to some elemental aspects (the model), and then increasingly add complexity to this core (versioning the model), while contrasting the implications of each version against archaeological and historical cases.

Although choosing the aspects to be incorporated in a model is inevitably a very explorative and discursive procedure, to fit them together in a single coherent system binds us to better specify definitions, to make explicit most underlying intuitions, to sacrifice most of the complexity observed in reality and, sometimes, to acknowledge contra-intuitive implications of the mechanism represented. The present article collects the last and most mature version produced during this arduous process, though it should be still considered work in progress. To the date, we have developed and explored only the first "core version" in our approach, an Agent-Based model called Musical Chairs, which will be briefly explained in the next section.

Before properly entering the issue at hand, some important notes are made below, regarding what is a model and what aspects of our model are developed here. A model is a representation of a phenomenon, so the miniature of a railroad and Newton's laws of mechanics are both perfectly valid models. Formally, models can be defined by the combination of relationships and the assumptions on which they depend on, which as a whole should represent a phenomenon. This is, of course, easier said than done, particularly regarding computational modeling, as several examples in the literature attest to how complicated and self-centered models can turn out to be.

The most extended approach to explain computational models is by far the one focusing on the description of the elements and their relationships, as they are formally implemented in computer code (e.g. equations, objects, classes). Thus, the preoccupation is often to show the validity of the model as being computationally consistent. However, few authors put effort into exposing and evaluating the assumptions on which elements and relationships depend, so that the implications of the model are truly appreciated in the light of the conditions to be met. Any model can be valid if its assumptions are confirmed in at least one case; however, few models-if any-can be said to represent a phenomenon under *any* conditions.

This other side of models is of great importance in science, being that it holds the meaning of the model itself and its relevance as a tool to facilitate knowledge in a specific field. It is by contrasting its assumptions with the context of real cases that the value of a scientific model can be accessed. Furthermore, once assumptions are made clear, it is much easier to modify the model by relaxing or removing them, or by adding entirely new ones. In this sense, a *computational* model with no logical structure other than the definitions found in computer code is bound to be only this, a computational model; though, to do them justice, such models can be very useful as templates to develop new models. This is the case, for instance, of a model of bouncing balls without any specification on the conditions in which these bounce (e.g. gravity, elasticity of materials, attrition).

4.3.2. The Musical Chairs model

4.3.2.1. Overview

Since a full description of our model can be consulted elsewhere (Angourakis et al. 2014), together with a detailed discussion of its results, this paper delves especially into its assumptions and the corresponding implications. Nonetheless, it is obligatory to introduce some brief notions on the elements and relationships of the model, and how they play out in it.

Briefly said, the Musical Chairs model consists of two populations competing for positions inside a limited two-dimensional space. Its name comes from the classical children's game, in which players move around a group of chairs accompanied by music and, once music stops, must find a free chair to sit. 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, must leave the game. Despite similarities, our model differs from it in four essential aspects:

1. Players 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 challenge is determined by new players constantly entering the game. Consequently the game never ends.
4. Standing 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) and 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.

Finally, the two classes of players behave according to different rules. Players representing variants of herding land use must stand and move each time music is playing (i.e. herds need to leave seasonally), while those corresponding to farming land use 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 will be realized and which will disappear Figure 4.5, *Figure 1* in the original.

Implementation and simulation of the Musical Chairs model were done using Netlogo (Wilensky 1999).

4.3.2.2. The logical structure

As remarked above, the logical structure behind the design of a model must be addressed in order to apply it in disciplinary fields other than Computer Science. In short, the logical structure of a model is the map of dependencies between the assumptions that *must be true for the model to be valid*. It is actually the outcome of reverse engineering a model, going from its highly simplified mechanism back to the observations that inspired it. Such a map must capture how more fundamental assumptions converge in more complex assumptions, utterly having all assumptions implied in the mechanism described by the model. As any kind of reasoning, this structure can be always mounted by even

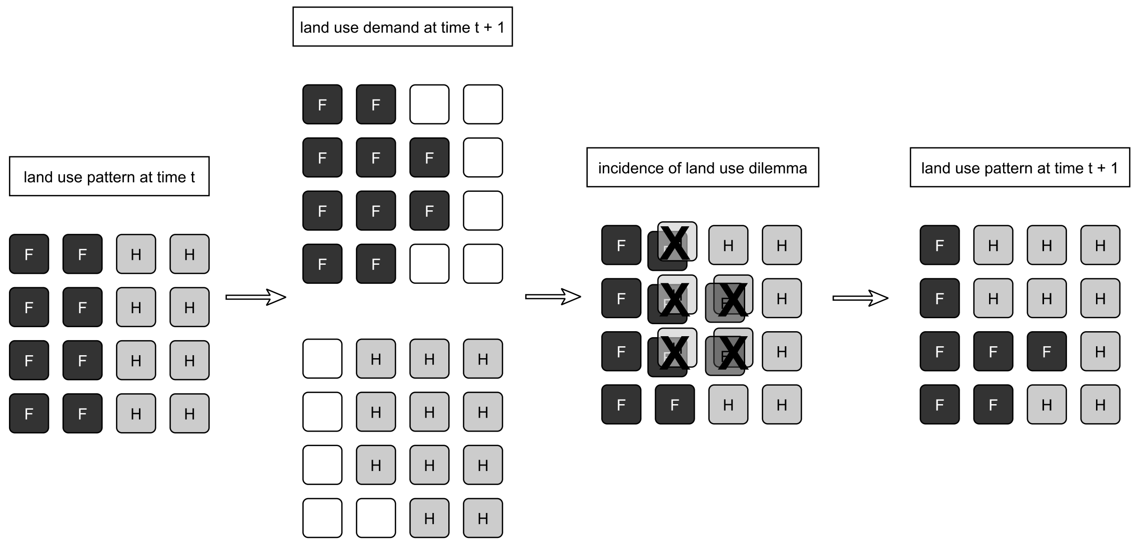

Figura 4.5: The phases of the model

more fundamental assumptions; e.g. here we assume that both farming and herding exist as human livelihoods, and so the model cannot be applied to the Paleolithic. The decision on where to stop splitting hairs is of course arbitrary, depending on pragmatism and plain common sense.

The list bellow enumerates all 16 assumptions deemed as necessary to the full understanding of the model's implications. Even though some ordering of assumptions was performed from the more fundamental to the more complex, numbers may be regarded only as references to Figure 4.6, *Figure 2* in the original.

1. *On the extension of food-producing activities.* Farming and herding involve far larger extents of land than any other field of activity, such as those concerning hunting, fishing, gathering, storing, manufacturing, trading or mining. Housing, stabling and the various types of farming facilities are accounted as inherent components of the respective activities.

2. *On the exclusiveness between food-producing activities.* Farming and herding activities are mutually exclusive regarding land use, at least during one phase of the cyclic movement of herds.

3. *On the categorization of land use.* The use of a land unit can be approximated to either farming or herding activities. Such approximation does not imply that

other activities cannot occur simultaneously in a given patch; it only means that the one stressed is the most widespread within the land unit. This assumption depends on assumptions 1 and 2.

4. *On the mobility implied in land use classes.* Farming is a sedentary activity and herding is a mobile activity. This assumption depends on assumption 3.

5. *On the land tenancy regime implied in land use classes.* Farms are private and pastures are communal. Even though farms can also be partially or fully considered communal, such form of commons is mostly nominative: i.e. while property lies with higher community authorities (e.g. villages, clans, temples, aristocratic elites and monarchs), the particular persons (and their families) are those responsible of exploiting it. On the other hand, a proper exception to this assumption is the existence of private pastures, which seems to abound especially when farming reaches a regional peak of development, and pastures are scarce in the proximity of settlements. As this phenomenon concurs also with substantial fodder cultivation and commercial livestock breeding, one straightforward interpretation is that pasture privatization is closely related to a general growth of market economy along the main trade lanes. For sake of simplicity, we consider livestock enclosures and fodder cultivation to be different forms of farming land use. This assumption depends on assumption 3.

6. *On the variation of land use.* Land use varies in intensity and independence of the land use of the alternative activity. Intensity stands for the concentration of productive factors-including people, livestock and crops-while independence expresses how much the local activity depends on productive factors also engaged in the alternative activity. For instance, a meadow punctuated with small farmsteads engaged in herding corresponds to a variant of herding land use with medium to low intensity and independence. Correspondingly, the pastures used to graze a king's flock will have a high score of intensity (i.e., it involves many herders and animals) but probably a relatively low independence of farming (i.e., a king may also rely on the tribute of local farmers). This assumption depends on assumption 3.

7. *On the integration of land use classes.* The whole of the land used for the same kind of activity (i.e. all farmlands, all pastures) has a particular degree of integration, accordingly to which the productive factors involved in each patch depend on

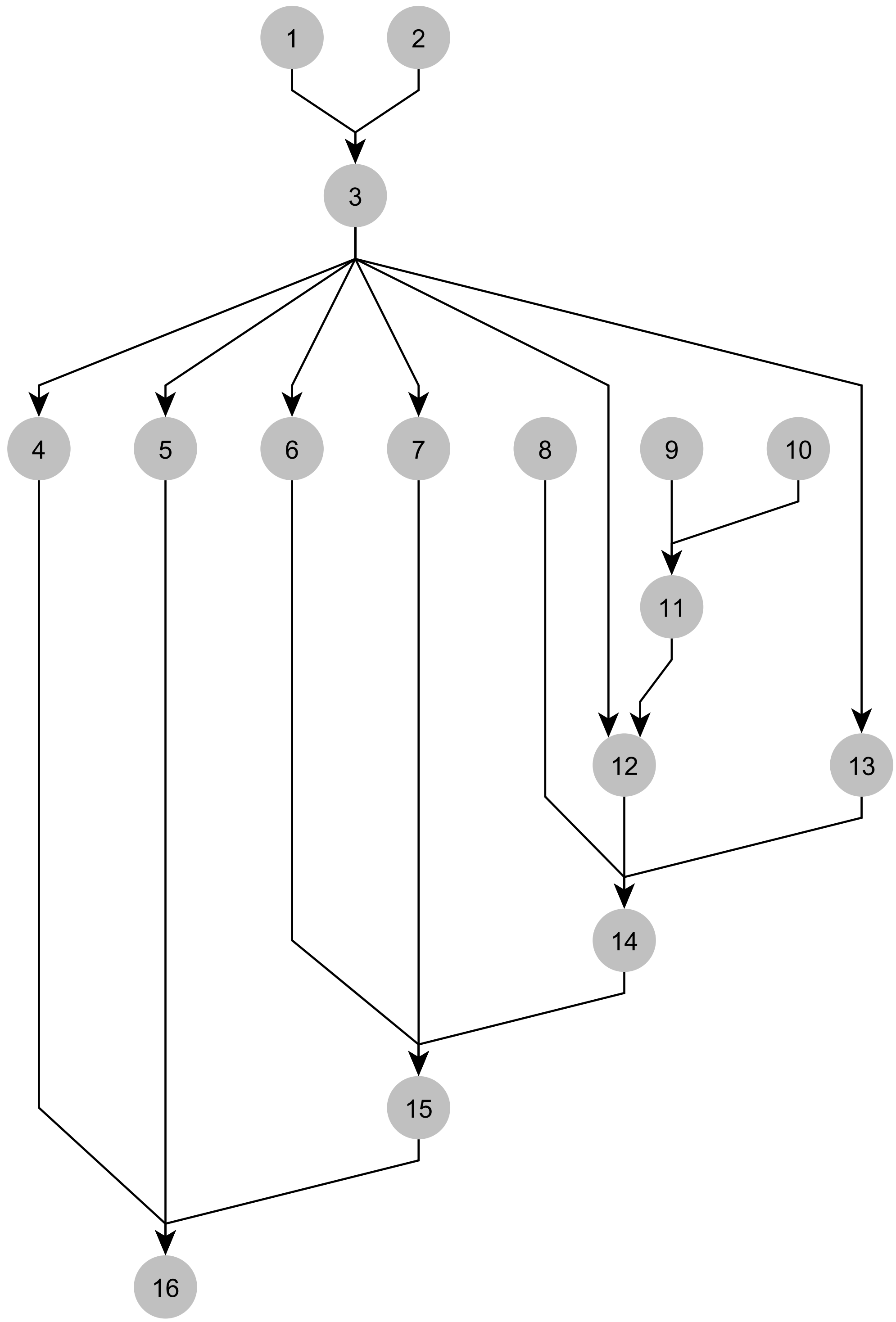

Figura 4.6: The dependencies between the assumptions of the model, as referenced in the text. Arrows point to the dependent assumption.

each other. Dependency between variants of the same class of land use is a proxy of the strength of the social fabric shared by people relying on the same livelihood. Such degree of integration can be given by numerous factors, ranging from plain logistic requirements, such as the cooperation among farmers for the maintenance of dams and canals (e.g., Mukhamedjanov 1994), to complex group identity re-enforcers, such as tribal obligations and ceremonial reunions (e.g., Barth 1964). This assumption depends on assumption 3.

8. *On the growth of land use demand*. There is generalized growth of the economy, implying population growth, wealth accumulation and, last but not least, an increasing demand for land.

9. *Ceteris paribus or on the immutability of other constraints*. There are constant environmental and technological constraints. The change in either of them would change the area represented in the model and the maximum intensity allowed for each type of land use. Although it seems a rather extreme assumption, following a modeling rationale, it simply states that neither environmental nor technological constraints depend on the outcome of the model-i.e., the land use pattern. Considering that this assumption may be still too unrealistic, further relaxation could be done by partially internalizing these factors, for instance, representing two feedback mechanisms: one where innovations allow further intensification and a higher intensity increases the chance of developing further innovations; another where intensification decreases productivity on the long-run, through salinization or overgrazing, and so restricts intensity itself.

10. *On the welfare imperative*. The production generated by the respective activities is the main criterion of decision-makers to promote or assign a given land use.

11. *On the extensive imperative*. Given the assumption 9, increasing the intensity of activity will increase the production per land unit, but will reduce the productivity per person or resource invested. Therefore, decision-makers, if producers or representative of producers (e.g. tribal chiefs, elder councils), will prefer to extend their activity rather than intensify it. A direct implication is that these decision-makers will restraint growth (i.e. redirecting people and resources to other activities), if extending their land use is not possible. Even if such decisions are made at the household level, we assume that people prefer to migrate or even change their livelihood rather than to lead a poorer lifestyle. This not implies

that high-level decision-makers (e.g. aristocratic elite) would not perceive intensification as interesting, as it does increase the aggregate production and thus their own wealth. However, this latter possibility was not explored in the present model. This assumption depends on assumptions 9 and 10.

12. *On the impossibility of competition within land use classes.* The variants of a class of land use do not compete for the same patch of land. Although particular individuals, families, groups or organizations engaged in the same activities may compete for land, we assume that the land use pattern -under the terms we express it- does not depend on the outcome of this dynamics. The direct implication of this assumption (and those on which it depends) is that any trend observed in land use pattern should respond to the dynamics of farming and herding competing for land against each other. Note that this assumption must be discarded if, against assumption 11, we assume that land use change is promoted by decision-makers interested in intensification. If this were the case, less intensive land use variants would be replaced by more intense variants of the same class, without any intervention of the alternative class of land use. This assumption depends on assumptions 3 and 11.

13. *On the possibility of land use change.* The main land use within a land unit can change from farming to herding, and vice versa, within the passing of the cyclic movement of herds. This assumption holds the possibility that land formerly used by one activity can be used by the other, without any interim period of abandonment longer than a cycle. It can be more easily accepted if considered that, while land is in fact used, it may not be initially as productive as those with well-established infrastructures (e.g., irrigation systems may take time to function properly). This assumption depends on assumption 3.

14. *On the existence of land use dilemmas.* Economic growth beyond the available land units poses the dilemma of whether a land unit will be used mainly for farming or herding. This assumption depends on assumption 8, 12 and 13.

15. *On the factors involved in land use change.* The shift of main land use in a given land unit is caused by a complex chain of events, approachable as a stochastic process (i.e., involving random variables). However, it also significantly depends on four factors acting in three levels:

a. *Extension*. What opportunities there are of further extending a class of land use? The less saturated land use class is favored.

b. *Independence*. How much competing variants are independent of those of the alternative class? Given that there are sufficient opportunities (level a), the variants with greater independence are favored.

c. *Ratio of intensities*. Given that the two competing variants are sufficiently independent (level b), what land use has the greater number of productive factors involved? It breaks down into two factors:

   I. *Intensity*. How intense are the competing variants of land use? The variants with greater intensity are favored.
   II. *Integration*. How well each class of land use is integrated? The most integrated class is favored.

This assumption depends on assumption 6, 7 and 14.

16. *On the mechanism of land use change*. Farming and herding activities have different constraints regarding the use of land. To extend farming, new immovable facilities (e.g. fields, canals, stores, barns, houses) need to be set when herds are elsewhere, so deciding whether or not to actually set them depends on the presence/absence of herding (*extension*), not in the specific characteristics of herds and herders (*ratio of intensities*). In contrast, herds will need the local pastures only once farming activities are already underway; hence the decisions taken by herding stakeholders (e.g. of whether or not to maintain the route or the current size of the flock) are made with a good estimation of the whole situation. This assumption depends on assumption 4, 5 and 15.

Considering the number and the interdependencies of the assumptions made, their implications could only be assessed by implementing and simulating a computational model. Again, both design details and simulation results of our model are presented elsewhere (Angourakis et al. 2014).

4.3.2.3. Implications

Leviathan: intensity and integration. As represented in the Musical Chairs model, integration is a costless relationship of reciprocity between unequal elements, so all land use variants will always have a better chance of persisting when associated with other variants within its class, whatever their intensity. The *aggregated* intensity will always increase with the number of associated variants. Whenever there is some integration among variants of each class, the change in intensity of productive factors in a given time is neither factor nor effect of the existing land use pattern (i.e., no intensification is causing or caused by land use competition). If we assume that the concentration of productive factors is correlated to the frequency of archaeological remains, this implication yields an archaeological parallel: the inequality of land use intensities within an integrated territory correspond to an observable inequality of site presence and size among land units at a local scale.

Bidding for land use: overall intensity. Even though the variance of intensity among land use variants is not causally related to land use pattern, an inequality between the overall intensities of farming and herding will strongly condition the land use pattern at equilibrium (see Attractors). Similarly to the socioeconomic status of buyers during bidding, the overall intensity of each class of land use dictates the probability that a farming variant overcomes a herding variant, and vice versa. In this sense, the activity with the greatest overall intensity will have more chances of extending itself at the expense of the other.

Fortune favors the bold: timing and information bias. As stated in assumption 16, the decisions on extending farming and herding are made at different times and with different information. Farming is extended independently from the intensity and integration of herding, assuming that herding is on average as intense and integrated as farming. Therefore people pressing for extending farming are blind to the true nature of the situation; they are unable to perceive the stable land use pattern (i.e., *attractor*) and may insist even when conditions are unfavorable to farming. While this aspect entail a higher risk to farming stakeholders-e.g., immovable investments may be utterly lost-, it will in fact facilitate the extension of farming on the long-run, whenever the difference between overall intensities is relatively small (up to a ratio of one-against-two favoring herding).

To compete or to cooperate: the selection of independence. Any restraint during a competitive situation will be relevant only to the extent that farming is somewhat dependent on herding, and vice versa. Therefore, a relatively independent variant will have a greater chance of persisting and extending itself under any conditions. However, the persistence of a variant is checked on the long-run by the resolution of dilemma events, which in turn depend solely on the aggregated intensity backing up the variants involved. Overall, independence has two opposing implications: it increases the chances of a class of land use persisting to the detriment of the other, but it also exposes new investments in land use to the risk of future unfavorable land use changes.

4.3.2.4. Attractors

The Musical Chairs model is a dynamical system-i.e., it evolves with time- and as such may converge towards particular states, called attractors. Attractors are by definition *stable*, meaning that small punctual or noise-like perturbations will only temporally move a system away from it. Although a single system can have several kinds of attractors, the Musical Chairs model displays only one: the stationary point. Stationary points are steady states of a system, meaning that all variables are maintained in-or very near-particular values. This feature allows a very straight-forward exploration, since our interest will rely only on comparing conditions to states, and not on the system's trajectories towards such states.

Another important property of dynamical systems is how consistent attractors are throughout variations of conditions (i.e., setting of parameters). If an attractor remains qualitatively the same when conditions change, we may call it *structurally stable*. However, the Musical Chairs model presents qualitative differences between attractors, depending on the conditions. We summarized this diversity in three classes of attractor, separated by range of land use pattern, i.e., the proportion of land units used for farming (Figures 3, 4, 5, and 6).

Big oasis. Big oases are attractors in which farming is carry out on most of the land units ($> 80\,\%$), implying that it is an *artificially augmented oasis*. Big oases display the lowest counts of land use dilemmas and changes per year and have the least selective pressure over the independence of land use variants. Accordingly to this model, such a state is expected when farming is generally more intense and integrated than herding. Furthermore, this state can only be truly an attractor if the external pressure (e.g., regional land use demand) is kept at low levels, otherwise the system may shift into another class of attractor.

Small oasis. Conversely, small oases are those attractors in which the major land use is

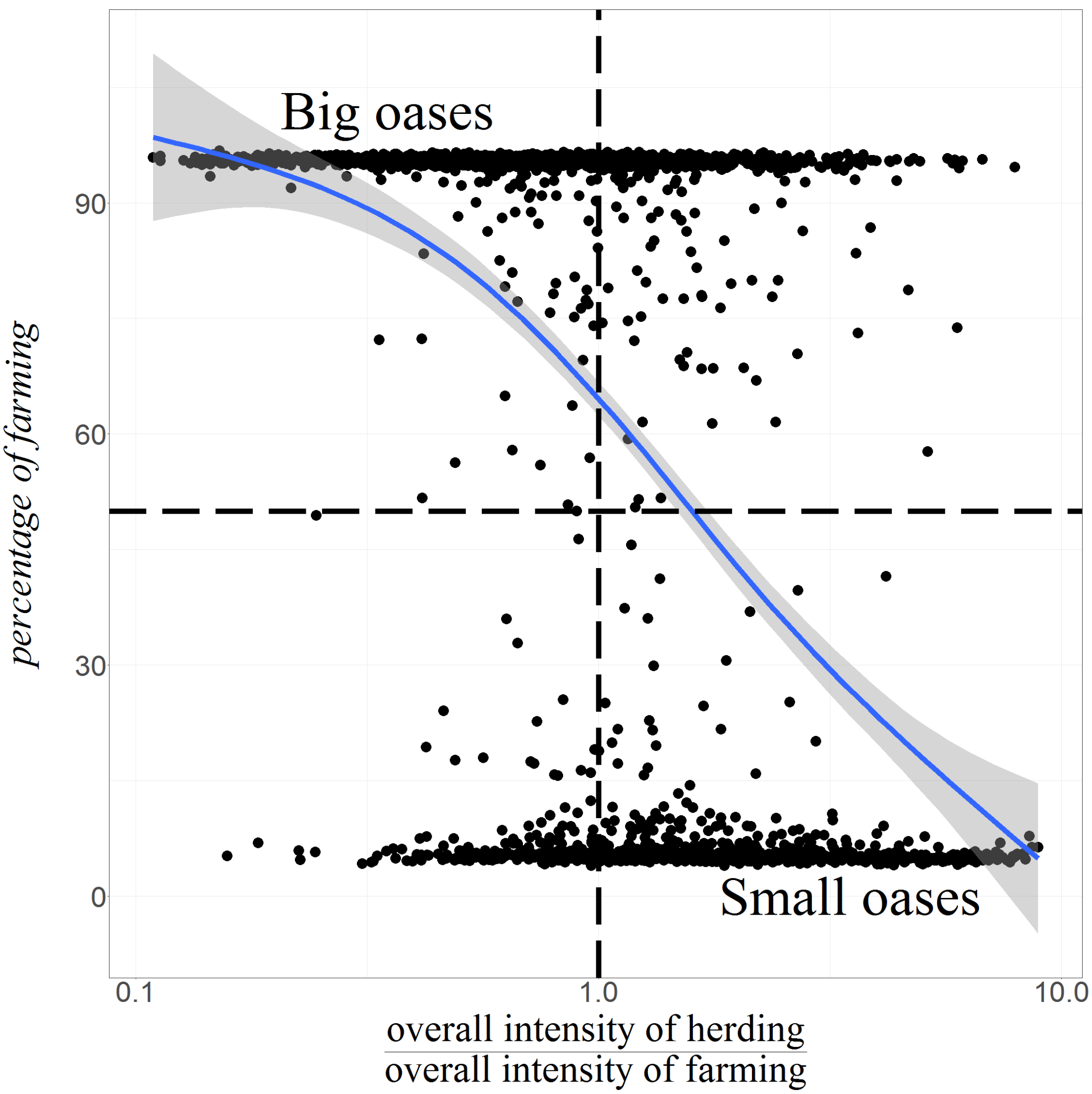

Figura 4.7: The percentage of farming at equilibrium versus the ratio between overall intensities of land use. Each point represents data from a simulation with randomized parameters (see randomized experiments in Angourakis et al. 2014). The line and grey area represent a nonlinear regression curve (GAM method) and its standard error, respectively.

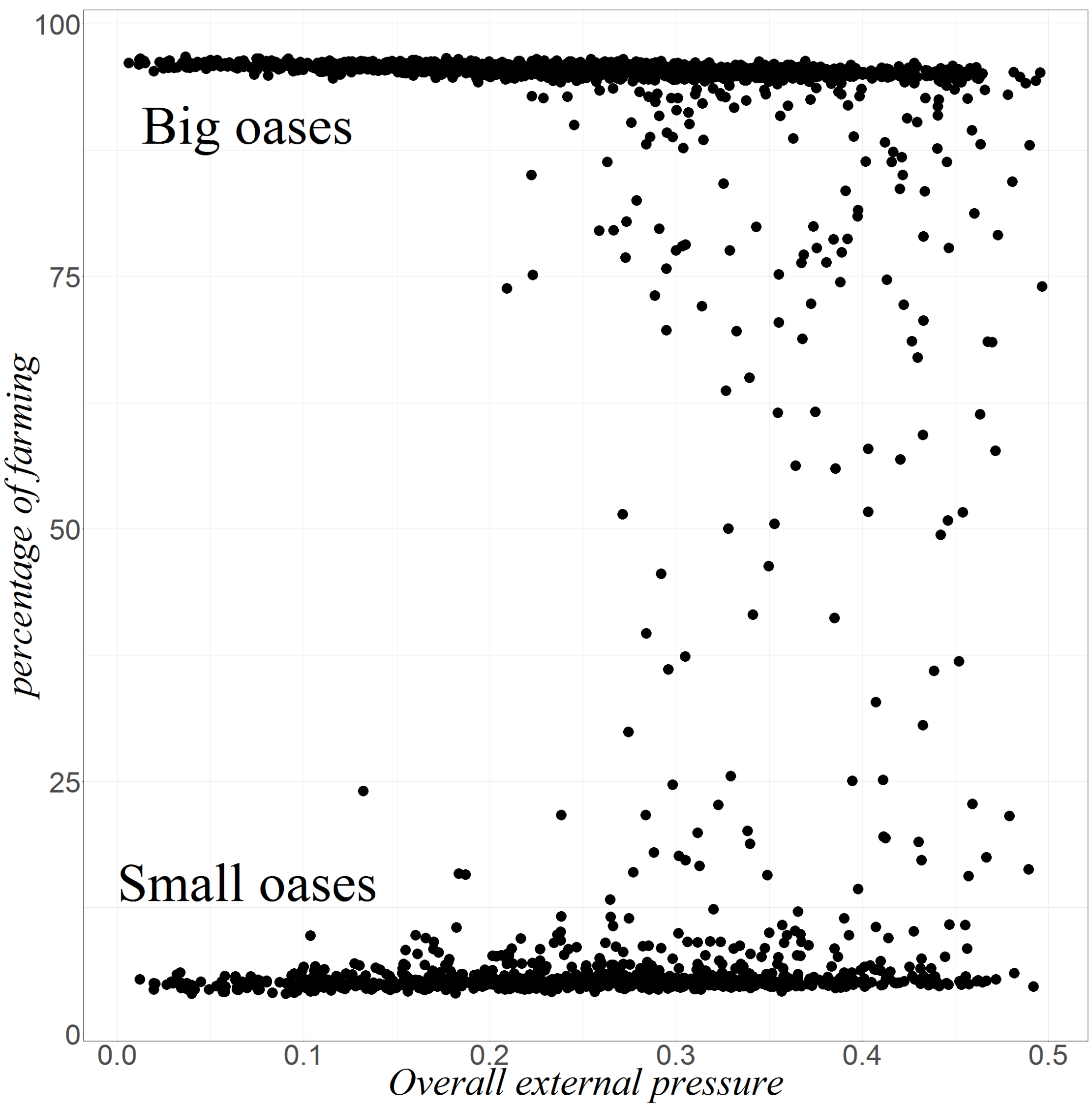

Figura 4.8: The percentage of farming at equilibrium versus the overall external pressure (i.e., the extrinsic land use demand). Each point represents data from a simulation with randomized parameters (see randomized experiments in Angourakis et al. 2014).

herding and farming is a marginal activity ($< 20\,\%$). Such scenarios would correspond to small riverine farming plots surrounded by the steppe-grassland landscape. Small oases correspond also to relatively low frequencies of land use dilemmas and changes, while the selection of independence between land use variants is the strongest. Similarly to big oases, this state is expected when the major land use is generally more intense and integrated than the alternative, though in this case herding is the one to be widespread. Also in the case of big oases, true stability do not exists if the external pressure is too great.

Intermediate oasis. Finally, intermediate oases are attractors in which there is no clearly predominant land use (20-80 %). Intermediate oases present high frequencies of land use dilemmas and changes, and an intermediate strength of selection over independence. Such states tend to be stable-i.e., be an attractor- when farming and herding are roughly similar in intensity and integration. However, unlikely the other two classes of attractor, intermediate oases seem to be *sustained* by relatively high levels of external pressures.

4.3.3. Discussion

4.3.3.1. Insights

The model yields four expectations regarding real "oases":

Inherent viability and systematic bias. A land use is more likely to spread around an oasis when it is favored by the plurality of factors affecting its overall intensity, from soil characteristics to labor organization and available technology. However, if assumed that farming and herding are equally feasible-and so have similar overall intensities-, the model predicts oases to be more often 'big' than 'small' (Figure 4.7, *Figure 3* in the original).

Overcoming the farming advantage. Given the systematic bias backing farming land use, change favoring herding must be caused by three kinds of transformation:

1. Greater herding intensity, lower farming intensity or both. Such effects would be achieved, for instance, by soil salinization, which causes farming to be less productive while herding is unaffected.
2. More herding integration, less farming integration or both. Integration is a proxy of the strength of the social institutions pressing for each activity. Therefore,

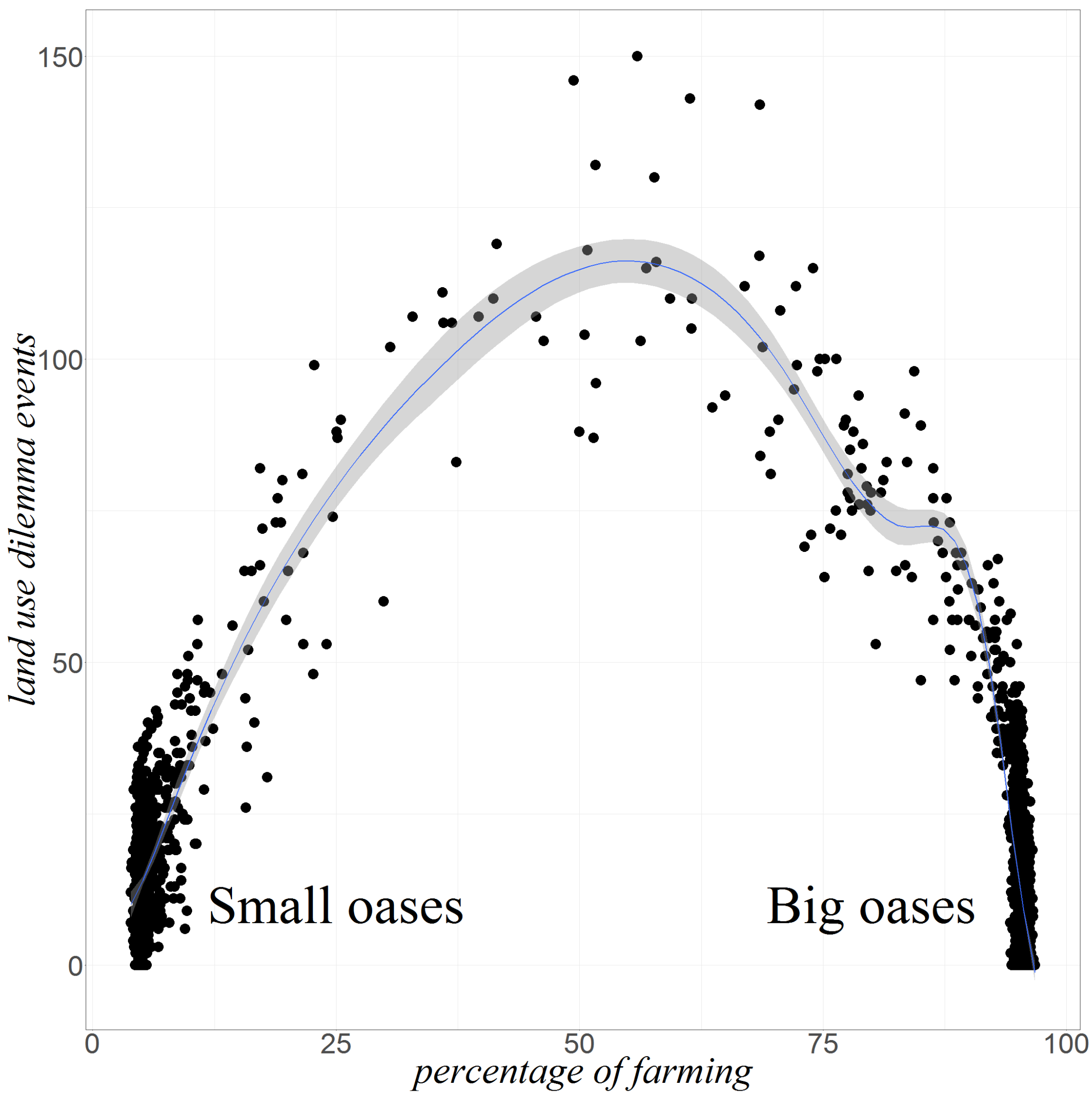

Figura 4.9: The percentage of farming at equilibrium versus the correspondent count of land use dilemma events. Each point represents data from a simulation with randomized parameters (see randomized experiments in Angourakis et al. 2014). The line and grey area represent a nonlinear regression curve (GAM method) and its standard error, respectively.

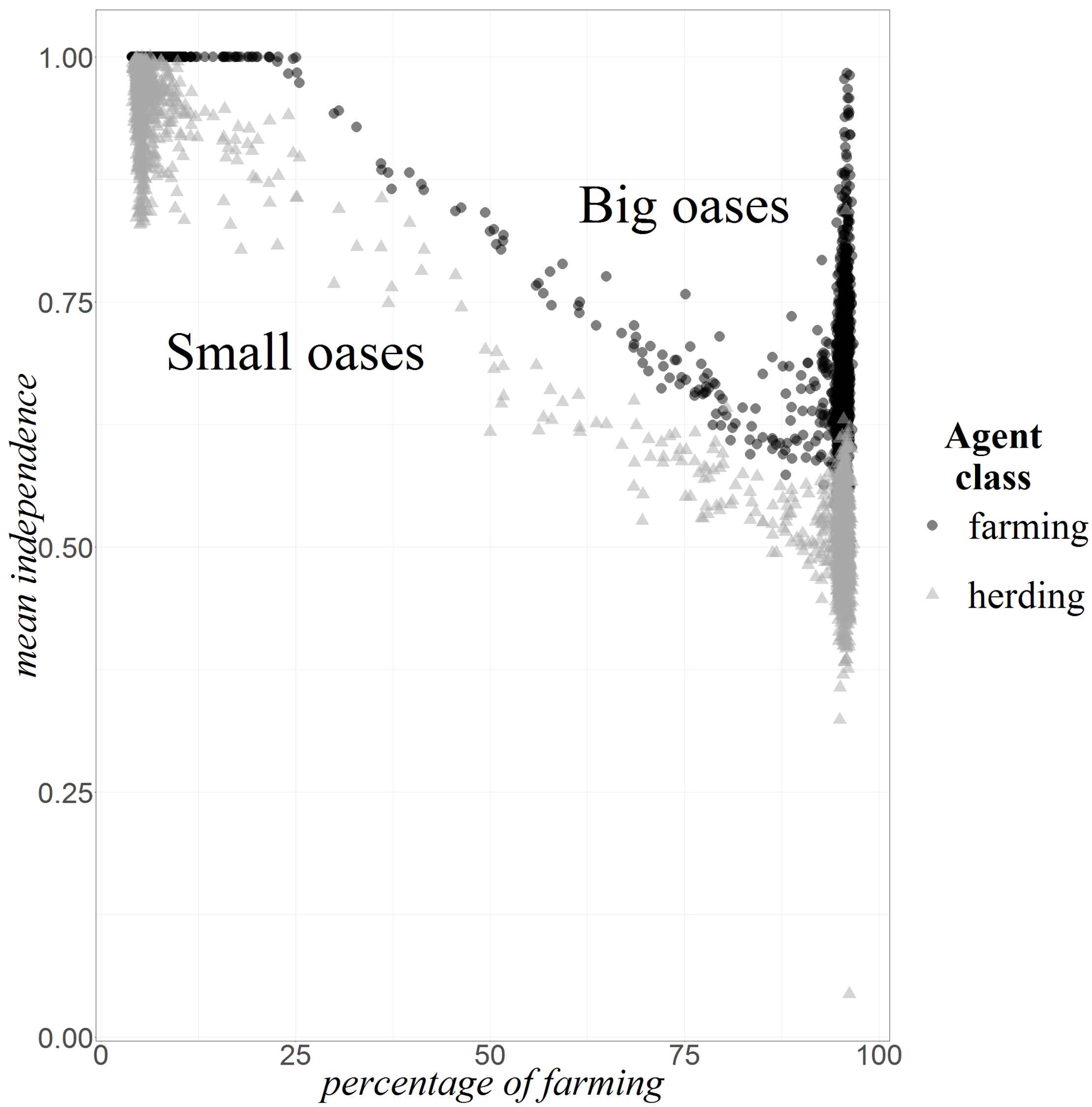

Figura 4.10: The percentage of farming at equilibrium versus the correspondent mean independence of variants (0 equals no independence). Each point represents data from a simulation with randomized parameters (see randomized experiments in Angourakis et al. 2014). The line and grey area represent a nonlinear regression curve (GAM method) and its standard error, respectively.

in order to have unbalanced conditions, historical contingencies (i.e., conquests, political upheavals, migrations, etc.) should be affecting farming and herding stakeholders in a different manner. A recurrent pattern found in Eurasian history is to have land use change following the rise and decay of broader political powers, depending on their particular agenda. A clear example of this is how expanding empires-such as the Mongol (Hall 1991)-conquered some flourishing farming territories, by allying themselves with herding tribes, which then could impose their own interests regarding land use.

3. More herding independence, less farming independence or both. Change in dependencies among farming and herding must also be observable as changes in local politics and socio-economical relationships. For instance, an increase of herding independence could be reflecting the replacement of local agro-pastoral stakeholders by nomadic alliances engaged solely in pastoralism.

Sensibility to external pressure. Oases under great external pressure will tend to display intermediate land use pattern, whenever other conditions do not change (Figure 4.8, *Figure 4* in the original). Though enduring for centuries, they may be interpreted as transitional states on the long run, since it is a relatively unstable state (Figure 4.9, *Figure 5* in the original) and external pressure and other conditions are expected to change.

The pastoral 'character'. The prevalence of herding in oases is positively correlated to the benefits of independence between farming and herding (Figure 4.10, *Figure 6* in the original). Accordingly to this model, 'small' oases are as farming islands within an ocean of autonomous pastoralism, so there would be little or no involvement of farmers in herding and of herders in farming. On the other hand, 'big' oases are characterized by the presence of a herding minority that may be aligned with local farming. However, it should be noted that independence-as it is conceptualized here-is not constrained by any other aspect apart from those considered in this model (i.e., there is no upper or lower limit to independence). If such scenarios are to be interpreted on the light of real cases, we must assume that all known forms of dependence between herding and farming-e.g., nutritional (Khazanov 1994)-are actually surmountable at a higher scale. For instance, a pastoral group camping in an oasis could rely on staple food produced in a neighboring fully-sedentary territory, thus having no restraint in pressing against local farming.

4.3.3.2. From attractors to complex trajectories of land use pattern

To assess the value of a model it is not enough to identify its implications and attractors. Models results must also be read and evaluated in the light of real case scenarios. Consider the complexity of land use pattern trajectories throughout the arid Eurasia (Stride 2005, in Southern Uzbekistan; Nesbitt and O'Hara 2000, in Southern Turkmenistan; Alizadeh and Ur 2007, in North-Western Iran; Abdi 2003, in Central Zagros; Newson 2000, in South-Eastern Syria). Each territory has specific contingencies, both cultural and environmental, which also may depend on contingencies of other territories. Still, oases may display some important common trends, for they clearly have some key common properties, such as being seasonal natural heavens for virtually any life form. As middle ground between relativism and universalism, a synthesis is possible by combining a *geography* and a *history* of land use in Eurasian oases.

As a *geography*, a very clear spatial pattern can be identified: there are *predominantly farming regions* and there are *predominantly herding regions* (Adas 2001). There can be some problems defining a threshold between these two categories, especially if the units considered are too big (e.g., Mesopotamia); however, for most of arid Eurasia, such distinctions can be easily done (e.g., compare Sumer with Bactria). To explain that this geography is consistent throughout the different historical contexts, it must be conditioned by roughly constant environmental factors. Though aridity and temperature are sound candidates for explaining this pattern (Bendrey 2011, Bonte 1981), simple topology could also have an important role (e.g., the relative position of oases; Algaze 2005). The bimodal nature of our results-the fact that 'big' and 'small' oases are more frequent than intermediate settings- is in accordance with this broad spatial trend. Furthermore, also agreeing with the common geographical explanation, our model suggests that the state of an oasis strongly depends on the overall intensity levels of herding and farming, which in turn strongly depend on steady environmental factors.

Despite this relatively stable geographical pattern, a somewhat general pattern can also be observed diachronically: a long-term *tidal wave* pattern, in which expanding farmlands alternate with expanding pastures, given an overall predominance of one or another land use. Throughout the History and late Prehistory of the arid Eurasia, this pattern repeatedly occurs at different scales, from the local land use pattern of oases up to continental cultural borders. It starts with the protracted-but relatively unobstructed-process of farming growth, covering up to three thousand years of paced development.

Once farming land use reaches its techno-environmental maximum, stakeholders involved are increasingly incentivized to intensify, pressed by the inertia of former demographic and economic growth.

As many modern governments are now coming to realize, intensification in arid environments is not sustainable in the long run. Particularly at the farthest ranges of alluvium, uninterrupted cultivation can overwhelm the capacity of soils to regenerate, turning salty much of previously productive farmlands (Bucknall 2003, Geist and Lambin 2004, Geist 2005, Laity 2009, Zhao et al. 2005). However, salty steppe and deserts can be still used for seasonal animal grazing. In fact, there are strong botanical (Kapustina et al. 2001) and archaeological (Abdi 2003, Kohl 2007) arguments supporting that these bumps in farming growth were also booms of herding. Furthermore, since more livestock could be stationed near oases during the less productive months-i.e., typically winter-, more and farther pastures needed to be exploited during the more productive ones, progressively increasing herders mobility.

In prehistoric and proto-historical times, this general pattern can be illustrated by the peak-and-collapse pattern of Late Chalcolithic/Bronze Age cultures of western arid Eurasia. Within this comprehensive period, roughly ranging from the forth to the second millennium B.C., there are several cases of waning and abandonment of prosperous urban or proto-urban settlements. Outstanding examples are the Cucuteni-Tripol'ye giant settlements in Southeastern Europe (Kohl 2007), the Uruk-type in Mesopotamia (Algaze 1993), the Bactria-Margiana Archaeological Complex in Southern Central Asia (Kohl 2007, Masson 1992), and the Harappan culture in the Indus Valley (Dani and Thapar 1992). Overall, the collapse of these cultures entailed less permanent settlements, more seasonal/ephemeral sites, or simply an escalation of settlement diversification at both local and regional scales (Abdi 2003, Nesbitt and O'Hara 2000, Potts 1999), all pointing towards greater commitment of the population with herding.

There are numerous cases of this pattern also in later historical periods, such as the breakdown of the Greco-Bactrian Kingdom in the second century B.C. (Stride 2005, Enoki et al. 1994), the decline of Khwarizm cities and irrigation systems between the fourth and the sixth centuries A.D. (Nerazik 1996), the abandonment of Sasanian agricultural settlements of northwestern Iran between the seventh and the ninth centuries A.D. (Alizadeh and Ur 2007), and the drop of sedentary agriculture in the *wadis* of the southern Levant in the dawn of islamization (Haiman 1995, Hill 2004, Parker 1987).

The former examples can be illuminating as well regarding what may cause individual oases to vary from this general temporal pattern. The general *geography* sketched above-and so, its dependence on environmental factors-should be placed as an important element to explain such variation. For instance, farming growth will hardly happen in an oasis surrounded by very productive spring/summer pastures, hence no oscillation can occur. Nevertheless, there are some human-related contingencies that cannot be reduced to environmental causation, even though may be connected to it.

It seems evident that migrations play a very important role in land use change. In fact, the periodic decay or collapse of local sedentary settlements is often interpreted within the context of incoming migrations, particularly of people with more mobile lifestyles (e.g., Early-Semitic, Indo-Iranians, Scythians, Arabs, Turks, etc.). Conversely, farming seems to prosper and growth whenever oases frequently receives new settlers, e.g., when it is well communicated with other oases.

However, migrations alone might not change a relatively stable land use pattern. For land use change to happen, the institutional framework in which land use decisions are made should also change. Again, there are much of the previous examples that suggest that changes in the socio-political context (e.g., the decadence of local political elite, a sudden subjugation to a foreign power, etc.) may similarly trigger changes favoring one or another land use. Among them, there are very illustrative examples of how this can be determinant, such as the use of the Mughan Steppe as winter quarters by Mongol Ilkhans and Timurids (Alizadeh and Ur 2007), the roman military policing the movements of nomads in the Transjordan frontier (Parker 1987) or the forced sedentarization of Central Asian nomads under Soviet rule (Luong 2004, Rahimon 2012).

Concerning temporal variations, the complexity of real land use change is still outside the scope of our results. In the Musical Chairs model, the factors that affect land use change are conceptualized as parameters (overall intensities, intrinsic and extrinsic growths of land use demand, integration), and so the mechanisms changing them are not modeled. There is no explicit reference to the environmental, economic or socio-political context in which an oasis is situated. In this sense, as presented in assumption 9, we have chosen not to explore what may be the backbone of land use change in oases on larger temporal scales, namely the loss or gain of potential farmland (e.g., by salinization and irrigation, respectively).

This model allows us to explore towards what state, given specific conditions, may the competition for land use drive an oasis, and how changes in such conditions may alter this state. However, it cannot illuminate anything on why and how these conditions may change. Providing there is no mechanism describing feedbacks between land use and those conditions, the Musical Chairs model displays only point attractors, whilst real land use trajectories may be better represented by oscillations, such as the *tidal wave* pattern.

4.3.3.3. Open routes

Without taking away its virtues, there are several aspects in which the model misfits what can be observed in real cases, and so where it could be improved:

Boundary constraint. In the Musical Chairs model, all land units are considered to be equally in the range of each other's influence. We are assuming the dynamics to occur in a local setting, where people can circulate in a daily basis and so are indifferent to the specific location of their activities. However, real oases show that land use grows contiguously; for instance, a pasture adjacent to farmlands could easily become a farmland, contrasting with pastures that are surrounded by other pastures. This would modify assumption 15, by adding further constraint to land use change.

Variable land units and land use variants. In order to represent more complex dynamics of land use change, both the maximum intensity per land use and the actual intensity of land units could be set as variable aspects of the model. Firstly, spatiotemporal variation of the maximum intensity would be possible by introducing a submodel to connect environmental factors and land use. For instance, it could specify how slope, distance to the nearest waterbody and soil erosion limit the intensity of farming. Within these lines, by specifying minima for each environmental factor, it could be possible to also represent variation on the total number of land units available for farming. Secondly, variation of the intensity of specific land use variants could be implemented as the product of decisions aiming to sustain or maximize returns. Additionally, the relationships between variants could also play a role in these decisions, by rewarding farming-herding coordination; e.g., herders could sustain more animals in winter, if farmers are willing to provide them with fodder or fallow land. Performing these changes would require us to reform assumptions 6 and 15, but also to revisit assumptions 9 and 11.

Relational properties. Integration and independence are modeled as two constants and qualitative-distinct aspects-as two parameters and a variant trait, respectively. However, conceptually, they are representative of the same phenomenon, namely the degree of convergence between stakeholders involved in two different land use variants, whatever their activity. Also, during competitive situations, there is no reason to assume that stakeholders will be *a priori* aligned with only one land use. In fact, people may press for extending a given land use based on completely different terms (e.g., kinship, ethnicity, territoriality, political agenda, market prices, etc.). This could be corrected by explicitly representing bonds between variants, and by allowing farming to support herding and vice versa. From exploring models with these characteristics, it would be possible to better represent the role of group-level interests as drivers of land use change. Again, reforming assumption 6 and 15 would be needed.

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4.4. 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

Esta sección corresponde al siguiente artículo:

Angourakis, A., Salpeteur, M., Martínez, V., Gurt, J.M. (2017). 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. *Journal of Archaeological Method and Theory*, 24(4):1177-1202. http://dx.doi.org/10.1007/s10816-016-9309-8.

Se anexiona al final de la sección el erratum a este artículo emitido en la misma revista.

Resumen Siguiendo un enfoque estrictamente de construcción de teoría, hemos desarrollado un modelo de simulación basado en agentes, el modelo Nice Musical Chairs (el 'amable' juego de las sillas), para representar la competencia entre grupos de partes interesadas en las actividades agrícolas y ganaderas en la Afro-Eurasia árida. El modelo profundiza las preguntas planteadas por los resultados de nuestro modelo anterior, el modelo Musical Chairs, e introduce tres mecanismos socioeconómicos adicionales que modulan el comportamiento y el desempeño de los individuos interesados y sus grupos. En primer lugar, definimos el emparejamiento de usos de suelo como la premiación, en términos de productividad, de cualquier cooperación directa entre la agricultura y el pastoreo dentro de un grupo. En segundo lugar, la gestión de grupo se modela como la prerrogativa de un liderazgo de grupo para conducir los interesados a que persigan una proporción particular entre la agricultura y el pastoreo. En tercer lugar, introducimos el acceso restringido a los pastos como el compromiso en el control territorial de éstos en oposición a un régimen de acceso abierto. Una exploración exhaustiva de escenarios y parámetros posicionó el control sobre pastos como el factor más significativo en la formación de patrones de uso de suelo, seguido por la gestión del uso de suelo. Si bien el efecto del emparejamiento de usos de suelo es leve en comparación, sigue siendo un factor significativo en la

selección de grupos y por lo tanto en la persistencia de patrones de uso de suelo a largo plazo.

Resum Seguint un enfocament estrictament de construcció de teoria, hem desenvolupat un model de simulació basat en agents, el model Nice Musical Chairs ('l'amable' joc de les cadires), per representar la competència entre grups de parts interessades en les activitats agrícoles i ramaderes en l'Afro-Euràsia àrida. El model aprofundeix les preguntes plantejades pels resultats del nostre model anterior, el model Musical Chairs, i introdueix tres mecanismes socioeconòmics adicionals que modulen el comportament i l'acompliment dels individus interessats i els seus grups. En primer lloc, definim l'aparellament d'usos de sòl com la premiació, en termes de productivitat, de qualsevol cooperació directa entre l'agricultura i el pastoralisme dins d'un grup. En segon lloc, la gestió de grup es modela com la prerrogativa d'un lideratge de grup per conduir els interessats a què persegueixin una proporció particular entre l'agricultura i el pastoralisme. En tercer lloc, introduïm l'accés restringit a les pastures com el compromís en el control territorial sobre aquestes en oposició a un règim d'accés obert. Una exploració exhaustiva d'escenaris i paràmetres ha posicionat el control sobre les pastures com el factor més significatiu en la formació de patrons d'ús de sòl, seguit per la gestió de l'ús de sòl. Si bé l'efecte de l'aparellament d'usos de sòl és lleu en comparació, segueix sent un factor significatiu en la selecció de grups i per tant en la persistència de patrons d'ús de sòl a llarg termini.

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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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Abstract 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 the 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.

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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 northwest 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 southeast 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 crystallize 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 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 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, b).

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 of 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 that 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 dominates 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. 1a).

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

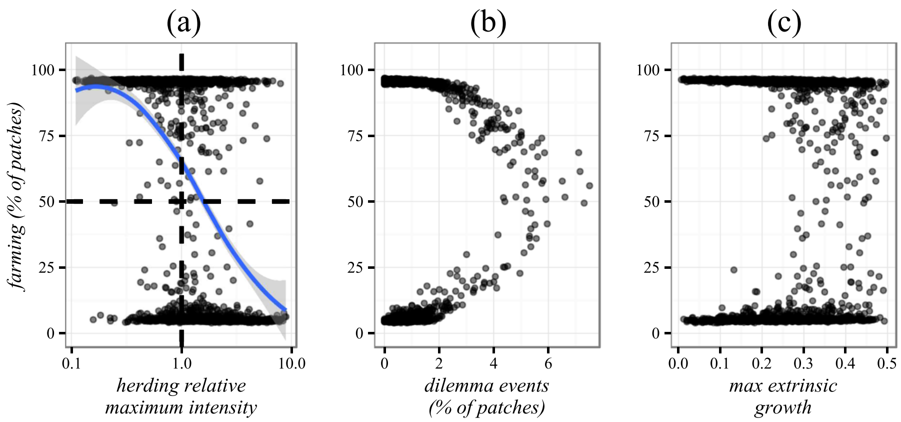


Fig. 1 Summary of main results of the Musical Chairs model. Percentage of farming at equilibrium is plotted against **a** ratio between overall intensities of land use, **b** percentage of land use dilemma events, and **c** overall external pressure regarding extrinsic land use demand. Each point represents 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 non-linear regression curve (GAM method) and standard error, respectively (see randomized experiments in Angourakis *et al.* 2014)

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 correlates 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 separations 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 the 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. 1b), 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. 1c), 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, fed 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 *et al.* (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 that 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*).

Table 1 Patch (land use unit) state variables

Name	Description
landUse	Current land use class performed in the patch (Boolean or string variable)
myGroup	Identifier of the current group of the patch
contendersF *contendersH*	List of groups pressing for expanding their land use (farming or herding) in the patch

Table 2 Groups' state variables

Name	Description
groupSize	Number of (actual or demanded) land use patches belonging to the group
groupEffectiveness	Effectiveness of collective actions of the group, between 0 and 1
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

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 in 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.

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

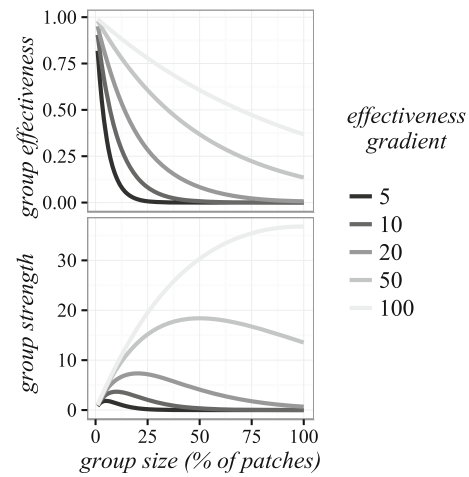


Fig. 2 Penalization of group effectiveness depending on group size (variable) and effectiveness gradient (parameter). The function presents two simple rules: **a** the smaller the group, the more effective it will be; and **b** the lower the effectiveness gradient is, the smaller groups will be driven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

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 1 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

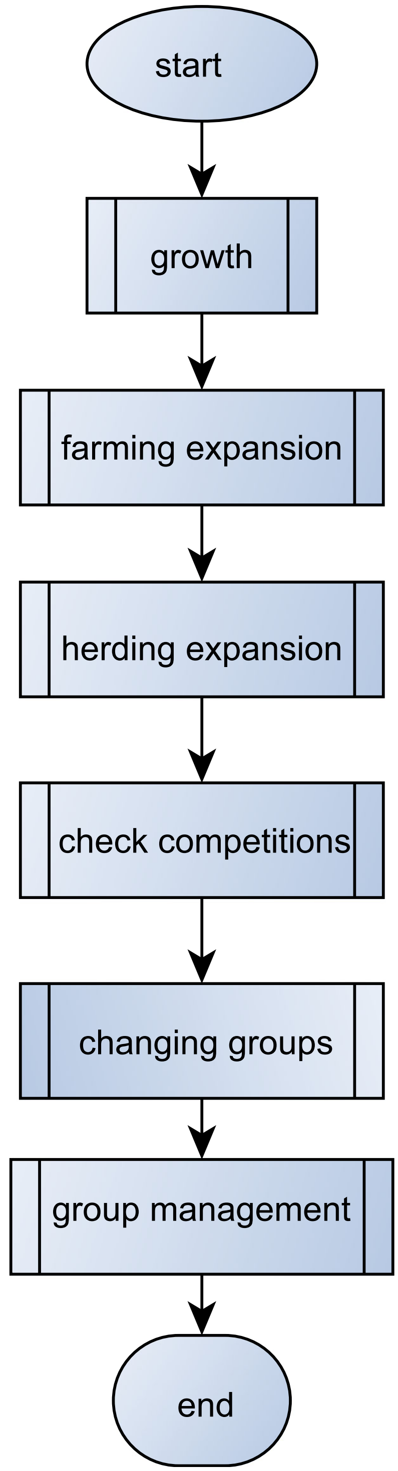


Fig. 3 The cycle of the Nice Musical Chairs model

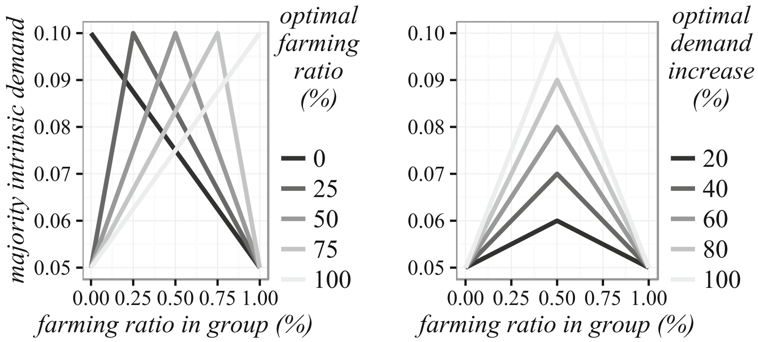


Fig. 4 The effect of the optimal farming ratio in group's land use demand. While the minority intrinsic demand is automatically set at maximum, the majority intrinsic demand will be penalized depending on how far the group's farming ratio is from optimum (*left*) and how big is the increase in demand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

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 entails the most dramatic type of event. Consequently, FF precedes FH, and HH precedes HF. In the case that 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 (Fig. 2; 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 keys 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 the 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 reconsider 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 forms 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 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 competitions) with the underlying mechanism (growth,

Table 4 Scenarios

Code name	Access	Pairing	Management	Simulation runs
AAAo	Open access	No	No	1000
Bo	Open access	Yes	No	1000
Co	Open access	No	Yes	1000
Do	Open access	Yes	Yes	1000
Ar	Restricted access	No	No	1000
Br	Restricted access	Yes	No	1000
Cr	Restricted access	No	Yes	1000
Dr	Restricted access	Yes	Yes	1000

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.

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

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 (Figs. 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

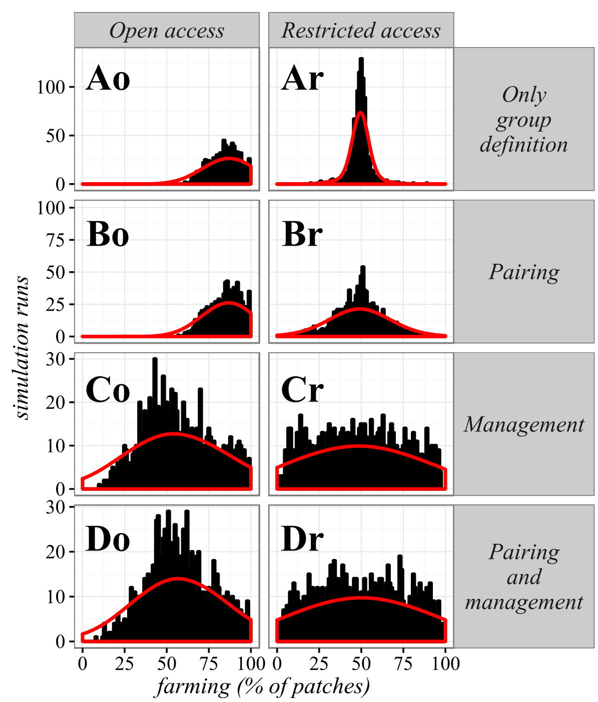


Fig. 5 Count of simulation runs stabilizing at different land use proportions (*i.e.*, percentage of farming) and respective density projections (*lines*) for each of the eight scenarios explored

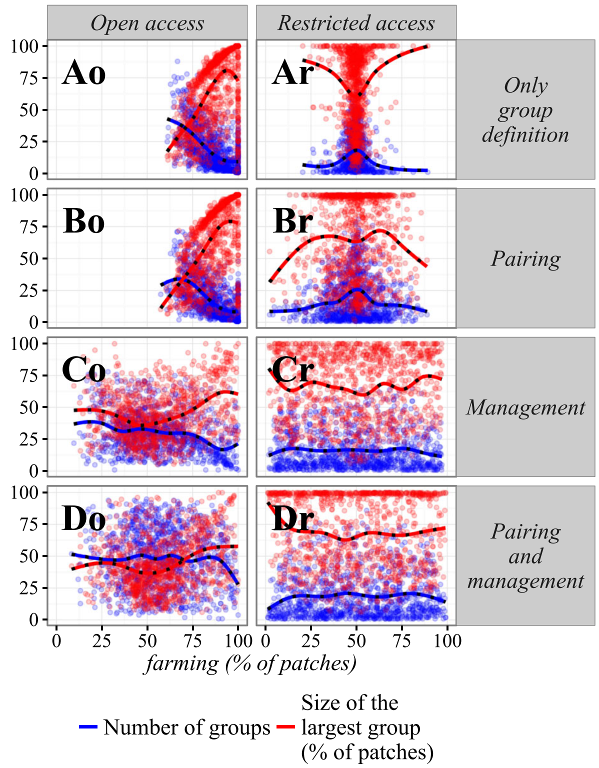


Fig. 6 Percentage of farming versus the number of groups and size of the biggest group at the end of simulations. *Lines* represent generalized additive model (GAM), using a cubic regression spline, for each variable

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 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).

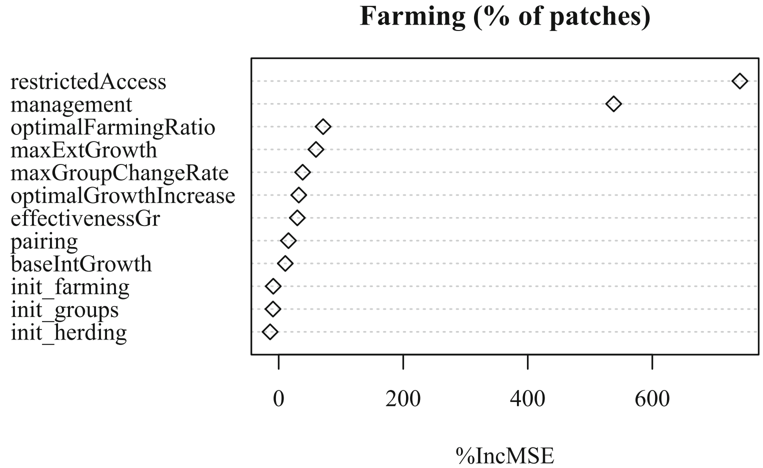
In contrast to scenarios Ao and Bo, when groups are entitled to pastures (Ar and Br), the single attractor is an even configuration within a centralized territory (Figs. 5 and 6, top-right; Animations 3 and 4). As expected, restricted access to rangelands allows for balanced land use patterns to co-occur 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 (Figs. 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 it 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



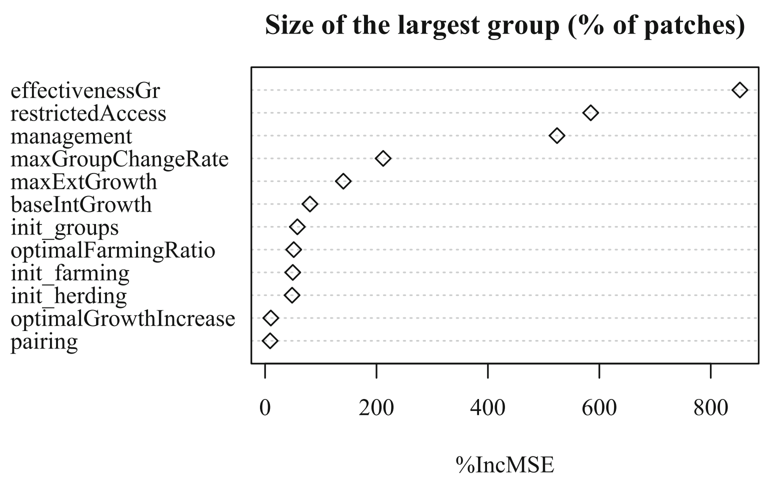


Fig. 7 Ranked parameter's importance concerning farming and size of the biggest group of all scenarios, calculated as percentage of mean squared error (MSE) increase using a random forest regression procedure (Liaw and Wiener 2002; R Core Team 2015)

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), shows that similar dynamics might have happened in the past. There, starting by the end of the third millennium BC, 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 AD. 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, the 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 people 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 twentieth century AD, 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, are the key factors 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 Figs. 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 leads, 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 that 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.

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ERRATUM

Erratum to: 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

Andreas Angourakis[1] **· Matthieu Salpeteur**[1,2] **·**
Verònica Martínez Ferreras[1] **·**
Josep M. Gurt Esparraguera[1]

Erratum to: J Archaeol Method Theory
https://doi.org/10.1007/s10816-016-9309-8

Unfortunately, the original version of this article contains errors in Figure 5 (main text). The corrected version is presented below. In this case, the correction mostly affects the scenarios Ao and Bo by adding a long bar at 100% of farming. All comments and interpretations remain consistent with the data presented in the corrected plots.
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.

The online version of the original article can be found at https://doi.org/10.1007/s10816-016-9309-8

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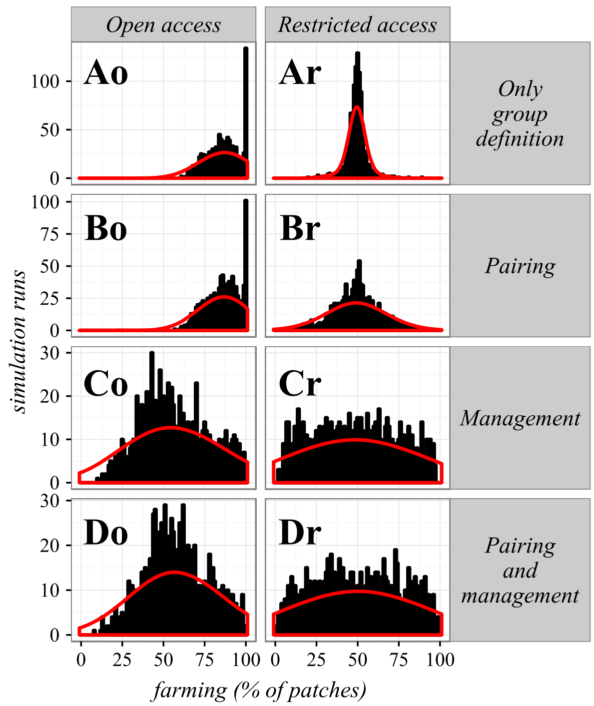
Open access
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4.5. Food For All: An Agent-Based model to explore the emergence and implications of cooperation for food storage

Esta sección corresponde al siguiente artículo:

Angourakis, A., Santos, J.I., Galán, J.M., Balbo, A.L. (2015). Food For All: An Agent-Based model to explore the emergence and implications of cooperation for food storage. *Environmental Archaeology: The Journal of Human Paleoecology*, 20(4): 349-63. DOI: http://dx.doi.org/10.1179/1749631414Y.0000000041.

Los anexos correspondientes a esta publicación se encuentran en la sección A.2.3 del Apéndice.

Resumen Un acceso constante a los alimentos es primordial para los seres humanos a nivel individual y de grupo. Además de proporcionar las necesidades nutricionales básicas, el acceso a los alimentos define las estructuras sociales y ha estimulado la innovación en la adquisición, el procesamiento y el almacenamiento de los alimentos. Nos centramos en los aspectos sociales del almacenamiento de alimentos, a saber, el papel de la cooperación para el surgimiento y mantenimiento de reservas o stocks comunes. Las reservas de alimentos cooperativas se examinan aquí como un tipo de recurso común, donde los apropiadores deben cooperar para evitar la escasez (es decir, la tragedia de los bienes comunes). Food for All ("Alimentos para todos") es un modelo basado en agentes en el que los agentes se enfrentan al dilema social de almacenar o no en un stock cooperativo, adaptando sus estrategias a través de un simple mecanismo de aprendizaje de refuerzo. El modelo proporciona una visión de la evolución de la cooperación en términos de eficiencia de almacenamiento, considerando la presencia de normas sociales que regulan la reciprocidad. Para que surja y se mantenga el almacenamiento cooperativo de alimentos, se necesita una dependencia significativa del alimento almacenado y un cierto grado de presión externa. De hecho, el almacenamiento cooperativo de alimentos surge como la mejor estrategia cuando se enfrenta al estrés ambiental. Asimismo, un control intermedio sobre la reciprocidad favorece la cooperación para el almacenamiento de alimentos, lo que sugiere que los conceptos de reciprocidad cerrada son precursores de los stocks cooperativos, mientras que el exceso de control sobre la reciprocidad es perjudicial para dicha institución.

Resum Un accés constant als aliments és primordial per als éssers humans a nivell individual i de grup. A més de proporcionar les necessitats nutricionals bàsiques, l'accés als aliments defineix les estructures socials i ha estimulat la innovació en l'adquisició, el processament i l'emmagatzematge dels aliments. Ens centrem en els aspectes socials de l'emmagatzematge d'aliments, és a dir, el paper de la cooperació per al sorgiment i manteniment de reserves o estocs comuns. Les reserves d'aliments cooperatives s'examinen aquí com un tipus de recurs comú, on els apropiadors han de cooperar per evitar l'escassetat (és a dir, la tragèdia dels béns comuns). Food for All ("Aliments per a tothom") és un model basat en agents en el qual els agents s'enfronten al dilema social d'emmagatzemar o no en un estoc cooperatiu, adaptant les seves estratègies a través d'un simple mecanisme d'aprenentatge de reforç. El model proporciona una visió de l'evolució de la cooperació en termes d'eficiència d'emmagatzematge, considerant la presència de normes socials que regulen la reciprocitat. Perquè sorgeixi i es mantingui l'emmagatzematge cooperatiu d'aliments, es necessita una dependència significativa de l'aliment emmagatzemat i un cert grau de pressió externa. De fet, l'emmagatzematge cooperatiu d'aliments sorgeix com la millor estratègia quan s'enfronta a l'estrès ambiental. Així mateix, un control intermedi sobre la reciprocitat afavoreix la cooperació per a l'emmagatzematge d'aliments, el que suggereix que els conceptes de reciprocitat tancada són precursors dels estocs cooperatius, mentre que l'excés de control sobre la reciprocitat és perjudicial per a aquesta institució.

Food for all: An agent-based model to explore the emergence and implications of cooperation for food storage

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A consistent access to food is paramount for humans at individual and group level. Besides providing the basic nutritional needs, access to food defines social structures and has stimulated innovation in food procurement, processing and storage. We focus on the social aspects of food storage, namely the role of cooperation for the emergence and maintenance of common stocks. Cooperative food stocks are examined here as a type of common-pool resource, where appropriators must cooperate to avoid shortage (i.e. the tragedy of commons). 'Food for all' is an agent-based model in which agents face the social dilemma of whether or not to store in a cooperative stock, adapting their strategies through a simple reinforcement learning mechanism. The model provides insights on the evolution of cooperation in terms of storage efficiency and considering the presence of social norms that regulate reciprocity. For cooperative food storage to emerge and be maintained, a significant dependency on the stored food and some degree of external pressure are needed. In fact, cooperative food storage emerges as the best performing strategy when facing environmental stress. Likewise, an intermediate control over reciprocity favours cooperation for food storage, suggesting that concepts of closed reciprocity are precursors to cooperative stocks, while excess control over reciprocity is detrimental for such institution.

Keywords: Agent-based modelling, Cooperation, Reciprocity, Food storage, Cooperative food stock, Common-pool resources

Introduction

Among archaeologists food storage is considered to be a key activity to secure subsistence during periods of food shortage, from a single winter to a sequence of 'bad years' (Binford 1980, 1990, 2001; Jochim 1981, 176; Testart 1982; Rowley-Conwy and Zvelebil 1989; Forbes and Foxhall 1995; Morgan 2012). The same has been observed among other animals (e.g. Smith and Reichman 1984). Furthermore, there is much diversity in the realisation of food storage, in terms of technical complexity and intensity, depending on how useful and feasible it is in a specific environment.

Within this framework, authors have recognised food storage as either a cause or a consequence of emergent cultural change, such as (a) sedentism (Flannery 1972, 2002; Testart 1982; Pearson 2006), (b) agriculture (Bender 1978; Testart 1982; Hayden 2009) and (c) limited reciprocity (Ingold 1983; Bettinger 1999, 2006; Benz 2004). In all cases, the presence and scale of food storage is correlated with population density, socio-cultural complexity and inequality (Price and Brown 1985; Arnold 1996; Kuijt and Prentiss 2004; Kuijt 2008; Hayden 2009). However, the formalisation of dynamical hypotheses that explain reciprocities between storage and cultural change remains difficult, as it relies on partial and indirect archaeological evidence, or on ethnographic analogues, implying high degrees of ambiguity (Kent 1999; Bursey 2001; Kuijt 2009). In this sense, computer modelling is used here to explore some aspects of cooperation in storage, as it allows describing explicitly the mechanisms (parameters, functions and variables) that underlie our hypotheses. As models are by definition reductive, the existence of a rich theoretical body of knowledge is paramount to clearly define their domain. 'Food for all' is designed based on existing anthropological theory as well as available ethnographical and archaeological documentation on food storage.

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A review of available documentation on food storage shows high variability in form and in scale for this practice, depending on specific geographical and archaeological settings, between cultures as well as within a single community. For example, in different scenarios, storage of the same kind of foodstuff may involve (a) different processing techniques (e.g. dehusking, smoking, salting, grinding) (Dei 1990; Stopp 2002; Atalay and Hastorf 2006); (b) different types of containers in terms of size/capacity (e.g. baskets, pots, pits, silos) and material (e.g. leather, stone, clay, wood) (Blitz 1993; Stopp 2002; Atalay and Hastorf 2006; Sakaguchi 2009); and (c) different locations within or near housing structures (e.g. dedicated storage bins and rooms) (Byrd 2002; Atalay and Hastorf 2006; Kuijt 2008; Kuijt and Finlayson 2009; Kuijt 2011) or at a distance from any settlement (e.g. caching spots in caves and hilltops) (Cunningham 2011; Morgan 2012).

Here, we propose to explore a specific dimension of variability in food storage, namely the level of cooperation, and consequently its implications in terms of benefit/return in case of shared foodstocks. In anthropological literature, exchange and redistribution have been considered as instances of a social type of storage, in contrast with biological (i.e. storing energy in one's own body) and technological types of storage (i.e. storing foodstuff inside objects or structures) (O'Shea 1981; Ingold 1983; Breton 1988). Setting aside biological storage, our model focuses on reciprocities between the technological and social aspects of storage, considering the implications of one onto the other. Storage here is considered as an activity aimed at moving and/or transforming matter. Given the strong implications of human sociality for coping with risk, we consider that the social norms that regulate appropriation are aimed at modifying human behaviour, having no direct effect on the material context in which they are applied. In this sense, technological storage is considered as one activity in the pathway between a given available food source and a given population consuming it (Fig. 1), such as procurement, processing, cooking and consumption. We further consider that any amount of foodstuff along this pathway (grey rectangles in Fig. 1) may be assigned a state of ownership, ranging from that of a common good to that of a personal property. Correspondently, we assume that all activities performed along this pathway (arrows in Fig. 1) may involve different levels of cooperation, which may (or may not) affect how the product is distributed. Under this framework, a community could cooperate for exploiting a (socially defined) common food source, e.g. by hunting large mammals, which then may be distributed to be processed and consumed at a household-level (e.g. Stopp 2002; Enloe 2003).

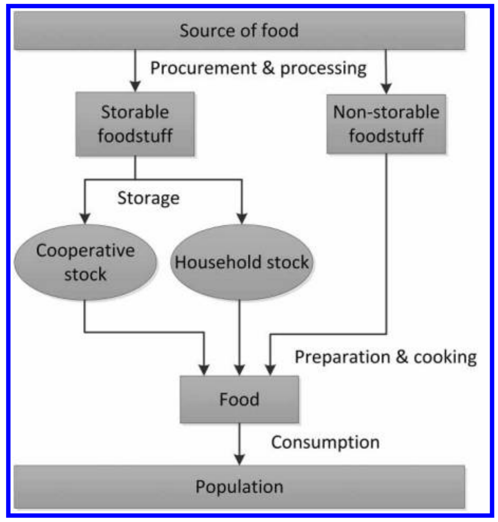

Figure 1 The place of food storage among the actions that can mediate between the food source and the population.

Alternatively, another common food source, such as stands of fruit trees and cereals, could be harvested through cooperative seasonal gatherings, also involving cooperation for processing and storing foodstuff, to be consumed in common feasting ceremonies throughout the year (e.g. Blitz 1993; Twiss 2008). We considered that this approach can represent a broad variety of trajectories in terms of food-related cooperative behaviour and sharing (Bahuchet 1990; Shelach 2006; Carballo *et al.* 2014).

Under more theoretical approaches, such as those expressed in evolutionary game theory (EGT) and collective action literatures, cooperation is key for understanding cultural change and the emergence of social complexity (Bowles and Gintis 2011; Stanish and Levine 2011; Turchin and Hochberg 2011; Carballo 2012; Carballo et al. 2014). This paper approaches cooperation as a social dilemma, in a game theoretical perspective. Social dilemmas (Dawes and Messick 2000) are generally described as situations in which the rational interest of individuals conflicts with the preference of the collective. These problems are frequent in many social contexts and include the cases of common pool resources and public goods (Olson 1965; Hardin 1968; Cornes and Sandler 1986; Ostrom *et al.* 1999). The essential feature shared by these settings is the provision of a non-excludable asset, by means of individual investments, which benefits all independently of how much they contribute to its creation and maintenance. Moreover, common pool resources present additional difficulty for collective action, since they differ from public goods by being subtractable (i.e. they are limited in scale and in distribution).

In this framework, cooperation is a behaviour in which all individuals involved receive a positive payoff (i.e. everyone is better off with cooperation), while they incur some cost or risk at an individual level (i.e. cooperating is no guarantee of reciprocity) (Carballo *et al*. 2014). Therefore, to sustain a cooperative behaviour, most individuals must accept the risk of suffering from broken circles of reciprocity, meaning that they may not receive the benefits they expect from cooperating if others are defecting. This is particularly a problem when cooperation must emerge from competitive or individualistic traditions (cf. Mead 1937; Schlager 2004; Carballo *et al*. 2014).

Game theory provides a framework to formalise these cases in a stylised fashion. Typically, social dilemmas are formalised by games in which players can behave in different ways, each one defined as a strategy. The games that characterise social dilemmas are defined by at least one deficient equilibrium, in which no player has individual incentives to change her behaviour, but this equilibrium is not Pareto optimal, which means that there is at least another possible outcome that is preferred by every player. In general, and specifically in the context of this work, the strategy that may lead to the collective Pareto optimal is called cooperative. In this approach, cooperators provide a benefit to the community at some cost, while defectors exploit the community by reaping the benefits without bearing the cost of cooperation (Galán *et al*. 2011). In evolutionary settings, defection is thus considered an evolutionary-stable strategy under most conditions.

From a human perspective many outcomes of social dilemmas are considered inefficient, consequently important effort is made to identify methods or mechanisms to avoid these situations. Kollock (1998) classifies the solutions to social dilemmas according to two dimensions: whether players are assumed egoist and whether they can change the rules of the game. Kollock's ontology identifies three types of solutions: (a) motivational, (b) strategic and (c) structural. In motivational solutions (a) the player gives some importance to the preferences of other players. These solutions include group identity (Kramer and Brewer 1984; Brewer and Kramer 1986), communication (Ostrom *et al*. 1992; Bicchieri 2002) or social value orientations (Bogaert *et al*. 2008) such as altruism, martyrdom and individualism. In strategic solutions (b) the players are considered egoistic, and are based on the ability of actors to influence other player's behaviour by expanding the range of strategies they consider. These mechanisms include reciprocity (Axelrod 1984), social learning (Izquierdo *et al*. 2008) or choice of partners (Izquierdo *et al*. 2010). Structural solutions (c) are those in which the rules of the game can be modified in order to solve the dilemma. These mechanisms consider for instance the effect of including sanctions (Fehr and Gächter 2002; Helbing *et al*. 2010), rewards (Rand *et al*. 2009; Szolnoki and Perc 2010), central authority or privatisation (Hardin 1968; Gürerk *et al*. 2006). Additional mixed structural–strategic solutions have been also proposed to obtain collectively rational outcomes (Galán *et al*. 2011).

Several questions emanate from this general outline. From an historical perspective, 'Food for all' enables us to delve into hypotheses previously articulated in the framework of archaeological and anthropological studies on storage. What are the implications of reduced mobility and diet specialisation for the emergence of cooperative food storage? Did the emergence of farming facilitate or obstruct cooperative behaviours regarding food storage? How is food storage related to resilience and surplus generation, and does cooperative food storage potentiate this relationship? What are the reciprocal implications between cooperative food storage and social complexity? From a more theoretical viewpoint additional questions arise. Under what conditions is it intelligent for agents to cooperate building up shared stocks? What makes cooperative stocks stand the test of time, resisting free-riders? Under what conditions are communities with stronger cooperation for food storage more successful? 'Food for all' aims at providing a novel perspective on these questions.

The 'Food for All' Model

In this paper we assume a game theoretical approach as the framework to model social interactions. This perspective consists in the definition of a formal model (game) in which a set of entities (players) interact to obtain an individual outcome (payoff) as consequence of the decisions (strategies) of the interacting entities (Vega-Redondo 2003). Noncooperative game theory includes three different branches, classical game theory (CGT), EGT and learning game theory (LGT) (Izquierdo *et al*. 2012). In short, CGT assumes rational decision players with consistent preferences that try to maximise their payoffs; EGT considers entities associated to a particular strategy and consequently is focused on the evolution of the strategies in the population, assuming that the more successful players (strategies) in terms of payoffs at a particular time are those with higher chance to be present in the future. In contrast, LGT assumes that players can adapt their strategies through several mechanisms as consequence of information obtained through the game, resulting from previous interactions or the behaviour of the rest of the players. The LGT approach is the most suitable and realistic option to model socio-economic human contexts. The use of LGT implies making strong explicit assumptions about the players' learning process, which can influence the dynamics and equilibria, and hence the conclusions of the game.

Within the LGT framework, we explore here the influence of an aspiration-based reinforcement learning mechanism on the evolution of a given adaptive strategy. The idea is that learners use their previous experience to select or avoid certain actions (Izquierdo *et al*. 2007). Those actions that produced satisfactory outcomes in a particular situation in the past will be chosen more often in the future when facing similar situations. In contrast, actions that led to a discomforting result in the past are less likely to be chosen again in a similar situation. Reinforcement learning in strategic contexts is most plausible in animals and in humans who have no information beyond the received payoffs, and several studies in experimental game theory have used reinforcement learning models to successfully explain and predict human behaviour (Izquierdo *et al*. 2008). In addition, reinforcement learning provides a good initial benchmark for theoretical analysis, being less requiring, in terms of information and cognitive abilities of the agents, than other common learning mechanisms (e.g. best response, fictitious play, rational learning).

Several variants exist of reinforcement learning algorithms used in game theory (Izquierdo and Izquierdo 2012). Such variants may differ in (a) the weight of a new action compared with that of cumulative experience, (b) the presence of an avoidance mechanism as well as that of an approaching behaviour or (c) the presence of forgetting or inertia mechanisms affecting recent or distant actions. The two most popular models of reinforcement learning applied to game theory models are the Erev-Roth and Bush-Mosteller models. Although both models are similar, Erev-Roth model only considers positive stimulus and learning fades with time. In our particular context we assume more plausible that agents can react also to negative stimuli, and since a same agent represents households during generations the sensitivity of player's strategies has been considered constant. For that reason, in this work we use a variant of Bush and Mosteller's (1955) linear stochastic model of reinforcement learning, that has no inertia, allows for negative stimuli and experiences do not fade.

In this work we are considering finite populations and a relatively refined adaptation mechanism, and besides, we are also interested in the analysis of the effect of possible path-dependent phenomena. Consequently, we have analysed the results by means of an agent-based simulation in which the agents are the players of the game.

The next sections describe the model following a compact version of the ODD documentation protocol (Grimm *et al*. 2010). The computational model is implemented in NetLogo 5.0 (Wilensky 1999) and the corresponding source code can be downloaded at the following website http://www.openabm.org/model/4191/.

Purpose

'Food for all' is an agent-based model (ABM) designed to study the evolution of cooperation for food storage. Households face the social dilemma of whether to store food in a cooperative stock or to keep it in a private stock. The model is a stylised abstraction of the main factors that we consider to drive the evolution of cooperation in storage:

1. The efficiency of common and private storage
2. The underlying learning process through which a successful strategy is reinforced from one generation to the next (modelled as the change in the probability to cooperate)
3. A social norm controlling access to cooperative stocks (modelled as the degree of intolerance towards defective behaviour)
4. The probability of having enough food to satisfy household needs, based on procurement alone (i.e. without considering storage)

The main assumptions of the 'Food for all' model are articulated in Table 1.

Entities, state variables and scales

The 'Food for all' model is an artificial society of N agents, each representing one household. The state variables that characterise each entity are defined in Table 1·1 (Supplementary Material 1). Briefly, agents get food, consume what they need (*satisfaction*) and decide with probability P to share excess food (*surplus*) by integrating it in the cooperative stock (*cooperation*), or to keep it in the individual household stock (*defection*) with probability $1-P$.

Study parameters, i.e. those that are explored (Supplementary Material 1, Table 1.2) and constant parameters (Supplementary Material 1, Table 1.3) are arbitrarily fixed variables of the model. The study parameters in particular define a simulation scenario, i.e. a computational experiment, through which they remain fixed. By exploring the study parameters, we explore the influence of the main factors affecting the evolution of cooperation in food storage. Finally, there is a set of global variables that are used to observe the model's dynamics (Supplementary Material 1, Table 1.4).

Process Overview and Scheduling

The scheduling of the events that take place in discrete ticks (i.e. time steps) is represented $\bar{S}$in Fig. 2. At each time period the conditions change randomly between 'good' and 'bad' probability distribution of foodstuff (U^{good} and U^{bad}). Then, an agent i samples an

Table 1 Assumptions

Domain	Assumption
On the nature of agents	• A given population is integrated by households, i.e. groups of people sharing resources between them by default, independently of the internal structure
On the consumption and production of storable foodstuff	• Households are homogeneous in terms of their metabolic need, i.e. they are considered to have a consistent consumption, at least regarding storable foodstuff • Households are homogeneous in terms of ability to gather or produce storable foodstuff, i.e. there is no systematic difference between their productivity. Storable foodstuff availability varies randomly among households within a period, due to unsystematic changes in household productivity • Storable foodstuff availability varies between periods due to unsystematic changes in population productivity. 'Good' (high-yields) and 'bad' (low yields) alternate randomly. Causes for variation in storable foodstuff availability may include fluctuations in climate, plague incidence, constructive and destructive social events, etc. • Depending on how much storable foodstuff they have in a given period, households may lack food or have it in excess
On the decision of how to store food	• When households have excess storable foodstuff, they must choose to store it in household or cooperative stocks. This choice is absolute, which means it concerns all excess storable foodstuff produced by a household in a period. The choice to privilege cooperative storage is taken as a proxy of cooperation • Households decide on whether to cooperate or not depending on their particular propensity to do it
On the access to and consumption of stocks	• All households are capable of accessing a single place where storage objects and structures can be placed • When households lack immediate storable foodstuff, they will attempt to draw the rest of their needs from a stock. Their preference to withdraw from their own private stock or from the cooperative stock is assumed to be unsystematic. Since results are robust to systematic decisions, we have assumed them to be unsystematic • However, *ad hoc* social norms regarding reciprocity are assumed to identify specific households as defectors and prevent them from accessing cooperative stocks
On the nature of strategy learning	• If a household needing storable foodstuff cannot satisfy its consumption either with cooperative or private stocks, it will have a proportional (positive/negative) incentive to change its propensity to store excess storable foodstuffs in cooperative stocks • The incentive that a household has to change its propensity to store excess storable foodstuff in cooperative structures depends on how much the overall population rely on storable foodstuff • Households may only change their propensity to store excess storable foodstuff in cooperative structures once each generation
On the efficiency of food storage	• Cooperative and household storage are characterised by their efficiency in terms of food preservation. Household storage efficiency is considered consistent across the population (i.e. there is no variation among the ability of households to store privately). Cooperative storage efficiency does not vary with the number of households involved and their particular ability

amount of food f_i (see 'The Stochasticity of the Foodstuff Source' section) and gets a positive surplus s_i if the amount of food f_i is greater than a threshold corresponding to the model parameter *shortage-threshold*; otherwise the surplus is negative (Equation 1).

$$s_i(t) = f_i(t) - \bar{S} \tag{1}$$

If the surplus s_i is positive, the agent i decides with probability P_i to integrate it into the cooperative stock S_p (*cooperation*), otherwise she puts it into her household stock $S_{v,i}$ (*defection*), and the corresponding stock is increased (Equations 2 and 3).

$$S_p(t)' = S_p(t) + s_i(t) \quad \text{if agent}_i \text{ cooperates} \tag{2}$$

$$S_{v,i}(t)' = S_{v,i}(t) + s_i(t) \quad \text{if agent}_i \text{ defects} \tag{3}$$

Conversely, if the surplus s_i is negative, i.e. the agent i did not get enough food, the agent tries to get the remaining amount of food needed from her household stock and from the cooperative stock, reducing them proportionally (as long as they are not empty). The sequence of seeking in both stocks is randomised each time, i.e. the probability of subtracting food firstly from one of the two types of stocks is 0.5. However, the access to the cooperative stock is regulated by a simple social norm: the agent's rate of cooperation, i.e. the times an agent cooperated in the generation (*n-cooperation-ticks* variable) divided by the total number of decisions she made (*n-decision-ticks* variable), must be equal or greater than the *cooperation-rate-required* parameter (ρ). Agents continue this process, i.e. getting food and cooperating or defecting (Supplementary Material 2), without changing their strategies for a number of time periods equal to the parameter *learning-generation*, which is kept at 50 for all simulations. When a generation reaches the end, each agent i adapts her strategy p_i through an aspiration-based reinforcement learning mechanism that takes into account the agent's experience during the generation and the aspiration in the society defined by the *aspiration-threshold* parameter

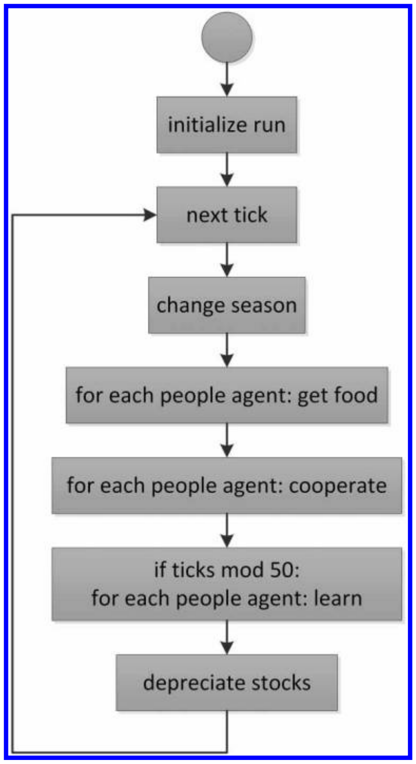

Figure 2 Flow diagram of the schedule of execution. The order in which agents are chosen in 'for each' statements is always random to avoid bias in agent selection.

(T_h). The aspiration-threshold corresponds to the desired number of time periods in a generation without shortage (see The Learning Process).

Finally the cooperative stock S_p and all household stocks $\{S_{v,i}\}_{i=1,...,N}$ are depreciated according to the respective storage efficiencies (θ_p and θ_v) (Equations 4 and 5).

$$S_p(t+1) = \theta_p S_p(t)' \tag{4}$$

$$S_{v,i}(t+1) = \theta_v S_{v,i}(t)' \tag{5}$$

These two parameters abstract any technological and logistic aspect that determines the capacity of preserving food through these strategies of storage; their significance will be discussed in more detail in 'Food Storage Efficiency' section.

Design Concepts

The Stochasticity of the Foodstuff Source

The return from the get food procedure (i.e. procuring and processing storable foodstuff) is distributed randomly among households at each time period. The minimum and maximum for household returns vary in time, based on random alternation between two settings: 'good' and 'bad'. If the setting of the time period is 'good', f_i is sampled from U^{good}, otherwise is sampled from U^{bad}. The 'good' setting is modelled as a uniform distribution with range 0.4–1 (mean 0.7) and the 'bad' setting is modelled as a distribution with range 0–0.6 (mean 0.3). Within these two settings, the amount of foodstuff f_i an agent i gets at each time period is always comprised between 0 and 1. The expected average value of f_i in the long run is 0.5 (Supplementary Material 3), which corresponds to the value of the parameter *shortage-threshold* ($\bar{S}$) used in all simulations. Therefore, within the parameter settings explored, the productivity of the whole system can potentially satisfy the demand of storable food of the entire population. However, a particular realisation of f_i of an agent i can be below this threshold, forcing her to use stocks to satisfy her needs.

The Learning Process

The reinforcement learning mechanism implemented in the model is an adaptation of Bush and Mosteller's model of reinforcement learning (Bush and Mosteller 1955). At the end of a generation (*learning-generation* constant) each agent considers the times without shortage (*n-non-shortage-ticks* variable) and compares it with the *aspiration-threshold* (T_h). Taking as reference the most frequent action she has undertaken in the former generation, the agent updates her strategy, i.e. the probability to cooperate (P_i), following a simple reinforcement learning rule: do it more often, if it led to more steady satisfaction (i.e. fulfilling the aspiration), otherwise try more often the alternative action.

The strategy updating takes place in three steps:

1. Each agent i determines the action she has undertaken more often in the last generation: (a) *cooperation*, if the number of times she cooperated (*n-cooperation-ticks* variable) is greater than the number of times she made any decision during the previous generation (*n-decision-ticks* variable), (b) *defection*, if it is smaller and (c) either *cooperation* or *defection* (randomly), if there were no differences between the number of times the two options were chosen.
2. The agent i calculates the stimulus t_i for the action (Equation 6, Supplementary Material 4). The stimulus is a magnitude positive or negative, i.e. $t_i \in (-1,1)$, depending on whether or not the agent i got the desired number of time periods without shortage (*n-non-shortage-ticks* $\geq T_h$) within a *learning generation*.

$$t_i = \begin{cases} \dfrac{n\text{-non-shortage-ticks} - T_h}{\text{learning-generation} - T_h} \\ \text{if } n\text{-non-shortage-ticks} \geq T_h \\ \dfrac{n\text{-non-shortage-ticks} - T_h}{T_h} \\ \text{otherwise} \end{cases} \tag{6}$$

3. The agent i updates the probability of the action, i.e $q_i = P_i$ for *cooperation* and $q_i = 1 - P_i$ for *defection*, according to the Equation 6, where L is the constant *learning-rate*. For example, supposed that the most common action of a given agent is *cooperation*, the Equation 7 tells us that if the stimulus is positive ($t_i > 0$) the probability for that agent to cooperate increases towards 1 a magnitude proportional to the learning rate, the stimulus and the distance to probability 1; but, if the stimulus is negative, the probability grows similarly towards 0. Note that the higher the stimulus (positive or negative), the larger the change in the probability.

$$q_i(t+1) = \begin{cases} q_i(t) + Lt_i(1 - q_i(t)) & \text{if } t_i \geq 0 \\ q_i(t) + Lt_iq_i(t) & \text{if } t_i < 0 \end{cases} \quad (7)$$

Analysis

The 'Food for all' model explores the evolution of cooperation for (a) different combinations of household and cooperative storage efficiency, (b) different levels of reliance on the storable food source and (c) different rules for sharing the common stock. The main parameters are

1. The efficiency of cooperative stocks (θ_p)
2. The efficiency of household stocks (θ_v)
3. The aspiration threshold (T_h)
4. The cooperation rate required to access cooperative stocks (ρ)

The evolution of strategies is recorded by the average probability to cooperate of agents at each time period ($<c>$).

Experiment Design

The model has been designed to provide general insight on the evolution of cooperation explained in terms of storage efficiency (storage technology and logistics) and considering the presence of social norms that regulate reciprocity. The analysis of the simulation focuses on the persistent regimes of the system. That is, those subregions of the space state in which the system stays for a significant long time (which may be short relative to the ergodic behaviour of the system), as compared with the time scale of the human phenomenon abstracted by the model. In other words, simulations are run until the system behaviour reaches a stable state.

The initial state for all simulations corresponds to a population of 100 agents randomly initialised with a cooperation probability between 0 and 1. The sampled parameters are: the storage efficiencies $\theta_{\{p,v\}} \in \{0, 0.05, 0.1, ..., 1\}$, the aspiration threshold $T_h \in \{10, 20, 30, 40\}$ and the cooperation rate required to access cooperative stocks $\rho \in \{0, 0.25, 0.5, 0.75, 1\}$. The remaining parameters were fixed for all simulations (Supplementary Material 1, S1.2). The time limit for a simulation is 10^5 ticks and 30 replications have been run for each experiment.

Main Results

The aspiration threshold (T_h) modulates the force of learning processes. For values below 25 (that correspond to aspirations less than 50% of the time without shortage during a learning generation) the model always reaches a 50–50 mixture of the two pure strategies, i.e. pure cooperation ($P = 1$) and pure defection ($P = 0$). On the other hand, for values above 25 learning pressure grows proportionally.

The threshold value of 25 can be easily deduced considering that the probability distribution of food, which only depends on the type of period (i.e. 'bad' and 'good'), has an average of 0.5 (see 'The Learning Process' section), which is equal to the *shortage-threshold* ($\bar{S}$) fixed to 0.5 for all simulations. Consequently, the expected number of periods without shortage (*n-non-shortage-ticks*) is half a learning generation (*learning-generation/2*), i.e. 25. If the aspiration threshold (T_h) is equal or less than this value, all agents satisfy their desired number of time periods without shortage (*n-non-shortage-ticks* $\geq T_h$), have a positive stimulus (Equation 6, Supplementary Material 4) and reinforce positively their current strategies (Equation 7) until one of the two pure strategies is reached, stopping the learning process. Owing to the initial state being a uniform distribution of strategies between 0 and 1, about half of the agents with $P > 0.5$ will go to pure cooperation while the other half with $P < 0.5$ will go to pure defection. Some plots related with this case of low aspiration threshold can be consulted in Supplementary Materials 5 and 6.

In a moderate learning pressure scenario ($T_h = 30$, which corresponds with an aspiration of 60% of time periods without shortage), pure cooperative/defective states are more frequent at equilibrium, throughout the different combinations of cooperative (θ_p) and household (θ_v) storage efficiencies (see the left column of graphs shown in Fig. 3). As expected, the computational simulations show that the social norm of sharing cooperative food stocks promotes cooperation, which is the maximum for medium value ($\rho = 0.5$). Only when the cooperative stock is managed as a free common good ($\rho = 0$), pure cooperation is not possible, while pure defection appears when there is low cooperative storage efficiency and significant household storage efficiency.

In a much more intense learning pressure scenario ($T_h = 40$, which corresponds with an aspiration of 80% of time periods without shortage), pure strategies are displaced by mixed strategies (the variance of agents' strategies can be consulted in Supplementary Material 6). Although the social norm promotes

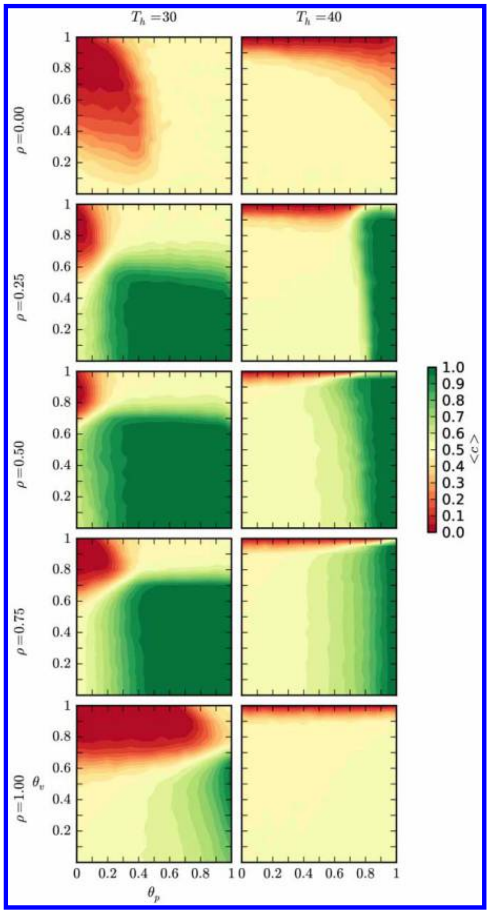

Figure 3 Matrix of contour plots of the final average cooperation in the space θ_p vs. θ_v. The columns define the learning pressure, i.e. moderate ($T_h = 30$) and high ($T_h = 40$); the rows define the social norm of sharing corporate storage (ρ).

cooperation, the high level of aspiration makes it difficult to reach consistent cooperation, except for public storage efficiency close to 1 (see the right column in Fig. 3). Moreover, in this intense learning pressure scenario, very loose ($\rho < 0.25$) and very strict norms ($\rho < 0.75$) prevent the implementation of cooperative storage for any combination of cooperative and household storage efficiency.

Path Dependence and Social Norm

The main set of experiments explained above assumes random initial strategies for all agents, i.e. the probability of cooperation at time period $t = 0$ is sampled from a uniform distribution U(0,1). Although possibly corresponding to an unlikely distribution of strategies in the real world, an initial random distribution of strategies has allowed us to focus on the main forces that govern the system behaviour without paying

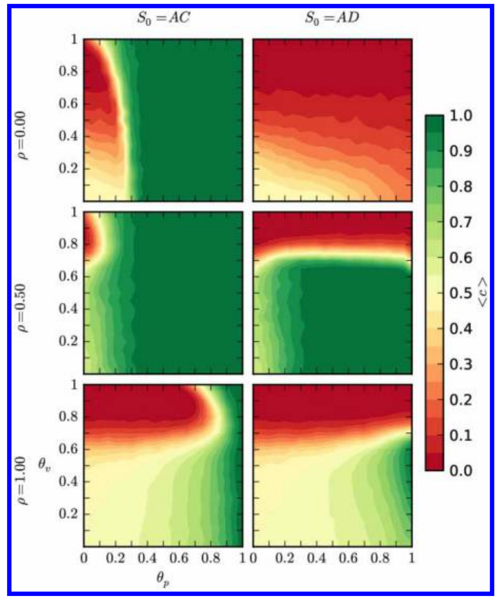

Figure 4 Matrix of contour plots of the final average cooperation in the space θ_p vs. θ_v for a moderate learning pressure scenario ($T_h = 30$). The columns define the initial state, i.e. AC and AD; the rows define the social norm of sharing corporate storage, i.e. free sharing ($\rho = 0$), middle norm ($\rho = 0.5$) and strict norm ($\rho = 1$).

attention to the effects of any particular initial state. Nevertheless, we have analysed results of two special initial states whose interpretation can be interesting and useful: (a) all agents are fully cooperative, i.e. All Cooperation (AC) state, and (b) all agents are fully defective, i.e. All Defection (AD) state.

Fig. 4 shows the final states in the storage efficiency parameter space, for both initial AC and AD states and three particular values of the social norm regulating sharing (ρ). The plots can be interpreted in terms of the resilience of an initial state to changes in the efficiency of storage and the social norm.

In the case of a free cooperative stock ($\rho = 0$) (first row of Fig. 4), AC initial state is persistent for the most parameter space θ_p vs. θ_v, unlike the random initial state explained before (Fig. 3) in which cooperation was not possible. This is a clear evidence of the path dependence effect, and shows that cooperation can subsist under adverse conditions. On the other hand, the respective results for the AD initial state mostly lead to non-cooperative behaviour, as would be expected.

When the social norm has a middle value ($\rho < 0.5$), results (second row of Fig. 4) are similar to those obtained for random initialisations. In this scenario, the power of the norm that promotes cooperation is so strong that even when the initial state is AD, cooperation emerges for most of the parameter space. Defection only persists for very high household storage efficiencies.

Finally, a strict social norm ($\rho = 1$) has a counterintuitive effect, quite the opposite from the one expected (third row of Fig. 4). Fully defective strategies emerge in more regions of the parameter space than cooperative strategies, as in the case of random initialisations. Defection thrived even when full cooperation was established as the dominant strategy (AC state), while the expected effect of a strict norm was the reinforcement of cooperation. It can be derived that predominantly cooperative agents who happen to defect (deviate from cooperation for whatever reason), lose all incentive to return back to a cooperative strategy if the norm is too strict.

Discussion

The 'Food for all' model shows that the potential of storage to provide a safety net in times of shortage depends on (a) the absolute and relative efficiency of cooperative and household-level storage ('Food Storage Efficiency' section), and (b) the degree of dependency of the population on the storable goods ('Diet Specialisation, Environmental Stress and Surplus' section). Given those findings, once established, the maintenance of cooperative stocks is exposed to the issues characaterising any other common-pool resource, i.e. the tragedy of the commons ('Cooperative Food Stocks as Common-pool Resources' section).

Food Storage Efficiency

Food storage efficiency may depend on three main factors: (a) environment (i.e. the combined effects of temperature, humidity, insolation and atmospheric composition); (b) technology (i.e. the instruments and techniques available for processing and containing foodstuff); and (c) logistics (i.e. labour division, task scheduling and flexibility in solving problems). The setting of these factors for different contexts will point to particular conditions in terms of efficiency of cooperative and household food storage. Within the 'Food for all' model, such conditions relate to regions of the space θ_p vs. θ_v (Fig. 5).

Environmental conditions set a general context for all forms of food storage in a given location (Rahman 2007). Among all environmental variables, temperature has a major effect over all chemical reactions related to food spoilage. In subartic regions, constant low temperatures has allowed local populations to store in simple structures (mounds of wood and stone) dried meat which could be consumed up to years later (Stopp 2002). In contrast, cultures facing higher seasonal variation must implement more complex technology and logistics, to keep food stored for longer periods (Dei 1990; Panagiotakopulu *et al.* 1995; Morales *et al.* 2014). Regarding the 'Food for all' model, the environmental conditions would define the maximum (and minimum) rate of natural food preservation at any particular location.

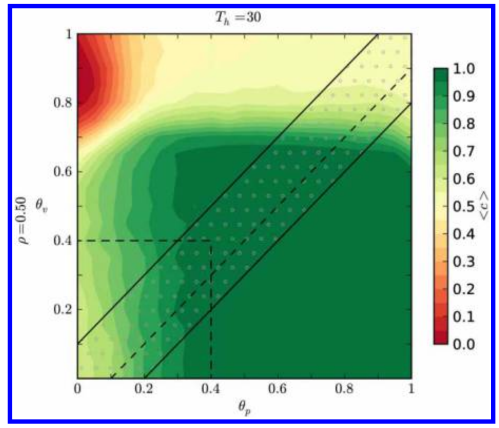

Figure 5 The set of conditions concerning food storage efficiency that best fit our assessment of realistic scenarios (i.e. the region of the space θ_p vs. θ_v marked with dots). This set can be equally considered for all valid combinations of the remaining study parameters.

There is a spectrum of technologies that may be involved in (pre-industrial) food storage (Atalay and Hastorf 2006; Rahman 2007). These may range from caching inside natural features with relatively little effort and further supervision (e.g. inside hollow trees and caves) to using sophisticated time- and energy-consuming objects and structures (e.g. basketry, pottery, excavated pits and free-standing buildings). The use of different technologies within the same environment implies different degrees of efficiency of food maintenance, depending also on the type of foodstuff to be stored. Assuming that technology can be equally applied to both cooperative and household storage, we consider that technological innovations increase the overall efficiency of food storage. Accordingly, discussion of real case scenarios should focus on the surrounding of the diagonal of the space θ_p vs. θ_v, where cooperative and household efficiencies are not very different (Fig. 5). Given this assumption, cooperative behaviour is the most commonly observed in our model and cooperation recedes only in case of extremely low or extremely high technological performance.

While technological constraints have a similar effect on the efficiency of both cooperative and household food storage, logistics may affect them asymmetrically. Food storage may be an economy of scale in which efficiency can increase with the number of people or resources involved. Although 'Food for all' does not allow for a gradual change of efficiency depending on the number of cooperative households, this effect can be roughly represented by considering scenarios where cooperative efficiency (θ_p), i.e. two or more households, is somewhat greater than household efficiency (θ_v) (Fig. 5). There are several logistic aspects that may favour the collective efficiency in contrast with the one of a single household:

1. *Decreasing losses.* Abiotic and biotic chemical reactions occur more often in the surface and pores of particles (e.g. Wadell 1932; Vogel 1988). Therefore, losses in terms of quality and edibility may be reduced by compacting together more foodstuffs, since it decreases the overall surface-area-to-volume ratio (Rahman 2007). The scale of accumulation may be particularly relevant when using sealed containers (Euler and Jones 1956), where increasing food volume can be protected form several hazards with decreasing marginal investment. For example, sealed stocks of seeds are particularly sensitive to this effect, since the sprouting of some seeds will consume oxygen and avoid further germination (Atalay and Hastorf 2006).
2. *Decreasing costs.* The greater the group of cooperators, the smaller the costs involved in the building, maintenance and improvement of the cooperative food storage facilities, e.g. by sharing tools and materials.
3. *Cultural transmission and accumulation of knowledge.* To achieve better food preservation, a body of knowledge made of shared expertise of several households may be more effective than the know-how of a single household.
4. *Flexibility towards mobility.* Increasing scale of food storage implies less movable stocks. This aspect may penalise the welfare and resilience of groups relying on scattered and mobile resources. However, if a food stock is a collective enterprise, it can be preserved in a single place by fewer individuals at a time. Therefore, public storage allows stocks to increase in size, without forcing a group to fully compromise its mobility. Finally, for a mainly sedentary group (e.g. specialised in agriculture), this difference between private and public stocks would be negligible.

These arguments can be deemed sufficient to consider that cooperative food storage is potentially more effective than household food storage. However, we acknowledge the possibility that this trend may depend on the scale and political structure of the social unit considered. For instance, although the efficiency of cooperative food storage *within* a hamlet may be greater than the efficiency of its individual households, the cooperation *between* hamlets could entail higher costs (e.g. transport), and thus less efficiency.

Concerning the 'Food for all' model, the bias towards greater cooperative storage efficiency inspires us to consider a wider region of the space θ_p vs. θ_v. Given that logistics may have a variable effect, depending also on the environmental and technological settings, we should finally consider the whole range of possible scenarios shown in Fig. 5. The environmental conditions of a given location set a maximum for the natural preservation of a certain foodstuff (e.g. 0.4), and the technology used in food storage may stretch these constraints towards the absolute maximum (i.e. 1). Finally, at particular combinations of environment and technological factors, logistics may boost the efficiency of cooperative food storage. Focusing on these scenarios, the 'Food for all' model shows that the emergence and continuity of cooperation for food storage is the most probable outcome under most conditions, particularly for intermediate degrees of dependency (T_h), control over reciprocity (ρ) and overall efficiency of food storage (θ_p, θ_v).

Diet Specialisation, Environmental Stress and Surplus

The 'Food for all' model has implications for the understanding of possible reciprocities between the establishment of cooperative behaviour for food storage and (a) the degree of dietary specialisation in storable food, as well as (b) the level of environmental stress under which food storage is practiced. Moreover, the analysis of the role played by dietary specialisation and environmental stress contributes to our understanding of resilience capability and the emergence of surplus among human groups relying on storable foodstuff.

In the 'Food for all' model, the aspiration threshold (T_h) represents the degree of dependence of the population on the storable foodstuff. In real cases, the reliance on a particular source of food at a given time is defined by the combination of two conditions: (a) the level of diet specialisation, i.e. the preferences regarding the exploitation of potential food sources; and (b) the level of environmental stress of the whole food economy, i.e. the dimensions and number of available food sources (in contrast to the environmental stress on the storable food economy, which is modelled by U^{good}, U^{bad}, p_{good} and p_{bad}). The first component entails the cultural contingency defining a society's foodways given the options available, while the second component conditions the degree to which such options are accessible; together, they are indicative of the scope of the whole food economy (e.g. broad versus narrow spectrum food economies).

In general, storage strategy is indifferent for low level of dependency on the storable foodstuff ($T_h <$ 25), but becomes a relevant issue with higher dependency, i.e. when storable foodstuff is staple food ($T_h >$ 25). In other words, the reliance on the storable foodstuff has to be sufficiently high for households to learn the best strategy under their circumstances. Correspondingly, it can be also derived that cooperative storage is less likely to emerge under low environmental stress, which would facilitate the continuity of broad spectrum and small-scale food economies in face of the introduction of domesticates. This aspect has similarities with a common archaeological explanation for the emergence of complex societies, suggesting that some degree of external pressure, such as the one recorded for the Pleistocene/Holocene transition (Nebout *et al*. 2002; Bar-Yosef 2011), is needed to activate strategy selection, e.g. towards cooperative behaviour among households.

However, a recession in strategy learning is observed for very high degrees of dependency on the storable foodstuff (i.e. $T_h = 40$). In this scenario the consolidation of either household-level or cooperative storage strategies depends on very high storage efficiencies. These observations suggest that communities based on storable foodstuff, but exploiting also other alternatives (i.e. $T_h = 30$), can more easily compensate for occasional shortages in the stored foodstuff, while also allowing households to efficiently learn the best strategy for the implementation of food storage, even with relatively low storage efficiencies.

Within the scenarios where households have the opportunity to learn the best strategy ($T_h = 30$, $T_h = 40$), cooperative food storage is, overall, the strategy more often consolidated. Given that the degree of dependence on storable foodstuff only influences the learning process, not the performance of food storage, we can sustain that cooperation for food storage is the best household strategy under most conditions, whatever the weight of the storable food in the general subsistence. In this sense, communities with a mostly non-storable food economy, where households cooperate moved by non-utilitarian incentives, are expected to be more resilient than others with similar food economies. In 'Food for all' this conclusion is further reinforced when considering that storage efficiency is higher at cooperative level than at household level ('Food Storage Efficiency' section).

A last point emerging from 'Food for all' is that food storage does not seem sufficient to sustain a reliable surplus within the parameters of the model. Long-term surplus can only be generated in this model by decreasing the population level of consumption (i.e. by decreasing *shortage-threshold*) or increasing the average production (i.e. by setting higher ranges for 'bad' and 'good' periods). It can therefore be deduced that consistent increase in the production of storable foodstuff (e.g. due to domestication), in tandem with improved storage efficiency (due to better technology and logistics), is necessary to observe sufficient accumulation of surplus for it to be redirected to third parties, rather than used during times of shortage, or in occasional social and ceremonial events (i.e. feasting) (Christakis 1999; Twiss 2008; Hayden 2009).

Cooperative Food Stocks as Common-pool Resources

Overall, we consider that 'Food for all' can be framed within the research focused on cooperation in preindustrial societies, integrating both EGT and collective action literatures (Carballo *et al*. 2014). Therefore, cooperation for food storage may be correctly treated as one of the many instances of cooperative social dynamics, as defined in this literature.

Under our assessment, cooperative food stocks, as defined in our model, can be generally classified as a common-pool resource (Ostrom *et al*. 1994; Schlager 2004; Carballo *et al*. 2014). Since appropriators may have a relatively free access to a common-pool resource, they must cooperate in order to conserve it and to avoid the so-called *tragedy of commons* (Hardin 1968). In the case of cooperative food storage, cooperation means to contribute to the common stock, and the *tragedy* is to have this resource depleted. Since this tragedy *is* possible, cooperative food stocks are not public goods, which are generally free of subtractability (e.g. rain water). Furthermore, for strict rules of reciprocity, cooperative food stocks can be considered as private goods. In fact, by varying the control over reciprocity in our model (ρ), we explored the full gradient between scenarios where cooperative food stocks are free access goods (i.e. *unmanaged* common-pool resource) and scenarios where they are fully excludable goods (i.e. *managed* common-pool resource).

As demonstrated by Elionor Ostrom and many others (e.g. Gintis 2000; Ostrom *et al*. 2003; O'Gorman *et al*. 2009; Boyd *et al*. 2010), the existence of a norm that punishes 'free riding' is fundamental for the establishment and maintenance of consistent cooperative behaviour. Within the context of food storage, 'Food for all' shows that such norm has the potential to convert an initially individualistic society, where each household keeps a surplus in private storage facilities, into a fully cooperative one where households store their surpluses together as a group. This result alone supports the thesis that concepts related to closed reciprocity (e.g. property) are precursors to, rather than the outcome of, cooperative storage (Bettinger 1999, 2006; Bowles and Choi 2013).

This said, a somewhat unexpected behaviour emerges from our model when the rule is too strict against defectors. Cooperation for food storage recedes in 'Food for all' when reciprocity is too closed, even in the positively biased case of an initial society made of all cooperative agents. Our model is characterised by some degree of aleatoryness as to

Table 2 Resource attributes supportive of the emergence of cooperation

Attribute	Brief description	Supported by 'Food for all'
Feasible improvement	Resource conditions are not at such a point of deterioration that is useless to organise, nor are they so underutilised that little advantage results from organising	Yes, stocks are replenished by appropriators
Indicators	Reliable and valid indicators of the condition of the resource system frequently are available at a relatively low cost	No, household decisions require no information on stocks
Predictability	The flow of resource units is relatively predictable	No, stocks may fluctuate due to variation in productivity and to household decisions
Spatial extent	The resource system is sufficiently small, given the transportation and communication technology in use, that appropriators can develop accurate knowledge of external boundaries and internal microenvironments	Yes, all households must be capable of physically accessing the common stock

Table 3 Appropriator attributes supportive of the emergence of cooperation

Attribute	Brief description	Supported by 'Food for all'
Salience	Appropriators are dependent on the resource system for a major portion of their livelihood or other important activity	Yes, strategy selection only occurs for non-trivial levels of household needs
Common understanding	Appropriators have a shared image of how the resource system operates … and how their actions affect each other and the resource system	No, decisions require no information on stocks
Low discount rate	Appropriators use a sufficiently low discount rate in relation to future benefits to be achieved from the resource	Yes, households have a constant need of storable food
Trust and reciprocity	Appropriators trust one another to keep promises and relate to one another with reciprocity	Yes, cooperative traditions were shown to be resilient
Autonomy	Appropriators are able to determine access and harvesting rules without external authorities countermanding them	Yes, households decisions are free from external determinations
Prior organisational experience and local leadership	Appropriators have learned at least minimal skill of organisation and leadership through participation in other local associations or through studying ways that neighbouring groups have organised	Yes, households are capable of effectively managing cooperative stocks

the possibility every agent has to obtain a consistent flow of resources. In this scenario, most agents, including those who have shown a predominant tendency for cooperation, are likely at some point to find themselves in a situation were they will not be able to obtain sufficient storable foodstuff to supply the cooperative stock, e.g. when incurring in a succession of 'bad years'. If such agents are punished too quickly and too firmly for not contributing to the cooperative stock cooperative behaviour disappears. That is, some degree of tolerance towards 'free riding' seems necessary to allow cooperative agents to recover from an unfavourable situation and cooperate again in the future. This pattern is explained by a phenomenon already identified and modelled by behavioural scientists, named tolerated theft (Blurton Jones 1984; Winterhalder 1996), and was argued to be a mechanism connecting individual interests to collective benefits (Wilson 1998).

According to the common-pool resource theory, several attributes of both the resource and the appropriators may support the emergence of cooperation (Ostrom 2000; Schlager 2004: 151–2). Do the conditions favouring cooperation in 'Food for all' match these attributes? Considering cooperative food stocks as resources (Table 2), our analysis confirms two attributes, *feasible improvement* and *spatial extent*, but remains inconclusive regarding the role of the availability and quality of indicators (*indicators* and *predictability*). In contrast, 'Food for all' endorses all appropriator attributes deemed relevant in common-pool resource theory (Table 3), except concerning the importance of agents sharing a common understanding of the common-pool resource. All three discrepancies (*indicators*, *predictability*, *common understanding*) point to the simplification of household decisions, as they are represented in 'Food for all'. Agents in this model take actions considering only their own variables, and stock levels only affect them by conditioning their performance. Therefore, we cannot discard that, under more complex agent designs, reliable, precise and immediate information on stocks may facilitate cooperation. However, our results do suggest that this aspect is not *necessary* neither for the emergence or the continuity of cooperative food storage.

Conclusion

Results issued from the exploration of the ABM 'Food for all' offers the possibility to disambiguate some general assumptions regarding the evolution of cooperation for food storage, as influenced by storage efficiency, reliance on delayed-return foodways and the presence of social norms that regulate reciprocity.

Our exploration of the 'Food for all' model indicates that a fully cooperative population is the most probable outcome under most settings, representative of a myriad of social and environmental conditions. Particularly, cooperation is favoured under medium-to-high household dependency on storable foods (e.g. $T_h = 30$), intermediate control over reciprocity (e.g. $\rho = 0.5$), middle efficiency of food storage ($\theta_v \sim \theta_b \sim 0.5$), and higher cooperative efficiency than household efficiency ($\theta_v \ll \theta_p$).

Considering most combinations of household and cooperative food storage efficiency, our results show that fully-cooperative strategies are more likely to emerge and continue to exist, exception made for scenarios with extremely low cooperative storage efficiency or extremely high household storage efficiency. As discussed above, cooperation should be expected to be even more frequent in real cases, given that logistics may favour cooperative over household storage (*economy of scale*).

Furthermore, 'Food for all' indicates that households will commit to a cooperative storage strategy only for relatively high diet specialisation (e.g. $T_h = 30$). In scenarios with high dependency on storable foodstuffs (e.g. $T_h = 40$), the consolidation of cooperative strategies depends on high technological and logistical performance. Cooperative food storage emerges as the best performing strategy when facing environmental stress. That is, cooperation seems more resilient than defection for coping with recurrent periods of shortage, while cooperative storage seems less likely to emerge under low environmental stress. It can be deduced that, given sufficient storage efficiency, the accumulation of enough surplus for it to be redirected to third parties is only possible after a consistent increase in the production of storable foodstuff (or a similarly significant decrease of the consumption levels of the population).

We conclude that cooperative food stocks can be examined as a common-pool resource, where appropriators must cooperate to avoid shortage (i.e. *the tragedy of commons*). A norm that penalises 'free riding' is not only necessary for cooperative food storage to emerge, but has the potential to convert an initially defective society into a fully cooperative one. We derive that concepts related to closed reciprocity (e.g. property) are precursors to, rather than the outcome of, cooperative storage. However, some degree of tolerance towards 'free riding' seems necessary to allow cooperative agents to recover from an unfavourable situation and cooperate again in the future, especially in contexts characterised by some degree of external stress affecting the possibility of obtaining a consistent flow of resources.

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