

Simple movement rules result in ideal free distribution of mobile pastoralists



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ABSTRACT

While open access to common-pool resources has been equated with a tragedy of the commons, we have found that mobile pastoralists in the Logone Floodplain in Cameroon are sustainably managing open access to common-pool grazing resources. We have described this pastoral system as a self-organizing complex adaptive system (CAS) in which mobile pastoralists distribute themselves over common-pool grazing resources without central or collective decision-making. We have found evidence of management of open access in the form of an ideal free distribution (IFD). Here we discuss the results of an agent-based model (ABM) simulation and show how pastoralists are able to achieve an IFD with relatively simple movement rules. We describe this system as an Emergent Commons (EC).

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1. Introduction

The discussion about our impact on ecosystems has been profoundly shaped by Hardin's tragedy of the commons (1968). Hardin's thesis that common-pool resources cannot be managed sustainably, unless governed by the state or transformed into private property, has been challenged by many (Feeny et al., 1990; Ostrom, 1990; Ostrom et al., 2002). One of the main critiques has been that Hardin confused commons with open access or unmanaged common-pool resources, and that commons can be managed sustainably (Berkes et al., 1989; Ostrom, 1990). The current consensus is that commons can be sustainably managed but that open access to common-pool resources will lead to a tragedy.

While open access to common-pool resources has been equated with a tragedy of the commons (Hardin, 1968; Ostrom, 1990), we have found that this is not the case for mobile pastoralists in the Logone Floodplain in the Far North Region of Cameroon. On

the contrary, we have described pastoralists' management of open access to common-pool grazing resources as a self-organizing complex adaptive system (CAS) in which mobile pastoralists distribute themselves over the available common-pool grazing resources without conflicts (Moritz et al., 2013). In our longitudinal study of pastoral mobility we have found evidence of management of open access in the form of an ideal free distribution (IFD) in which there was a positive correlation between the total resources and total numbers of cattle across camp zones (Moritz et al., 2014a, 2014b). In this system of open access all pastoralists have the same rights to use grazing lands, regardless of ethnicity, nationality, seniority, or socioeconomic status. Pastoralists emphatically argue that access is free and open for everyone (Moritz et al., 2013).

We argue that this management system of open access is best described as an Emergent Commons (EC). First, management is an emergent property of this self-organizing system in which there is no central and/or collective decision-making; instead the management system emerges from individual decision-making and coordination among users. Second, pastoralists view these grazing resources as commons to which they have common rights. We argue that these EC are best understood as a CAS, "in which large networks of components with no central control and simple rules of operation give rise to complex collective behavior, sophisticated information

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processing, and adaptation via learning or evolution” (Mitchell, 2009). Varied examples of CAS include ant colonies (Gordon, 2010), the human mind (Taylor, 2001), ecosystems (Holling, 1973), and irrigation systems in Bali (Lansing, 2006).

An excellent example of a social-ecological system that works as a complex adaptive system comes from the work of Lansing (2006), who has described how Balinese rice cultivators coordinate water use for irrigated rice cultivation in order to maximize production while simultaneously controlling pests by allocating water to some subaks (community rice fields), while leaving others fallow. The management system emerges without central decision-making as subaks coordinate water use from the bottom up via the network of water temples associated with the subaks. Critical in this CAS are the ecological processes and interdependencies, an irrigation infrastructure that is mirrored by a network of water temples, and a shared ethos that allows Balinese farmers to coordinate their activities.

There are a number of similarities between the Balinese system and the pastoral system in the Logone Floodplain: dynamic feedbacks between pastoralists and pastures, an information-processing network, and a shared ethos among pastoralists. However, one of the main differences is that the floodplain is an open system – there are no social or ecological boundaries – as pastoralists move continuously in response to spatiotemporal changes in the distribution of common-pool grazing resources inside and outside the floodplain.

We have argued elsewhere that this self-organizing system results in sustainable use of common-pool grazing resources in the Logone Floodplain and used the concept of the ideal free distribution (IFD) as an indicator of this management system (Moritz et al., 2013). The IFD model predicts how animals should distribute themselves over resource patches or habitats (Fretwell and Lucas, 1969; Sutherland, 1996). The two main assumptions of the model are: individuals have perfect knowledge about the resource quality and quantity of each patch (ideal assumption); and individuals are free to move to any patch (free assumption). In our ABM we tracked the distribution of agents and resources. We examined whether and to what extent these movement rules would result in an IFD of agents over the available resources. If resources deplete slowly, individuals will first move to the patches with highest resources (or quality). However, as more and more individuals occupy those patches, resources on the occupied patches decline. At some point, the current quality of the occupied patches will equal that of at least one unoccupied patch. When this is so, some individuals will move to that previously unoccupied patch. There are several predictions that arise from this model. First is that occupied habitats have higher resource density than do unoccupied habitats at any point in time, because high resource habitats are occupied first. Second, the variance in standing resource quality of occupied habitats should be lower than the variance in resource quality of unoccupied habitats, because foragers will tend to deplete all occupied habitats to the same quality, while, in unoccupied habitats, current resource quality is unaffected by depletion. Finally, there should be a positive correlation between total resources in a habitat and total number of foragers in a habitat. Under a model incorporating only depletion, resource quality per unit area should be equal in all occupied habitats; however, if habitats vary in area, larger habitats should include more individuals (Fretwell and Lucas, 1969; Flaxman and deRoos, 2006). We found evidence in support of these predictions in our empirical studies of mobile pastoralists in the Logone floodplain (Moritz et al., 2014a, 2014b).

The question is how exactly the IFD emerges in this self-organizing system. We think that it emerges from a dynamic process in which open access, habitual movements, participation in an information-sharing network, and pastoralists' independent

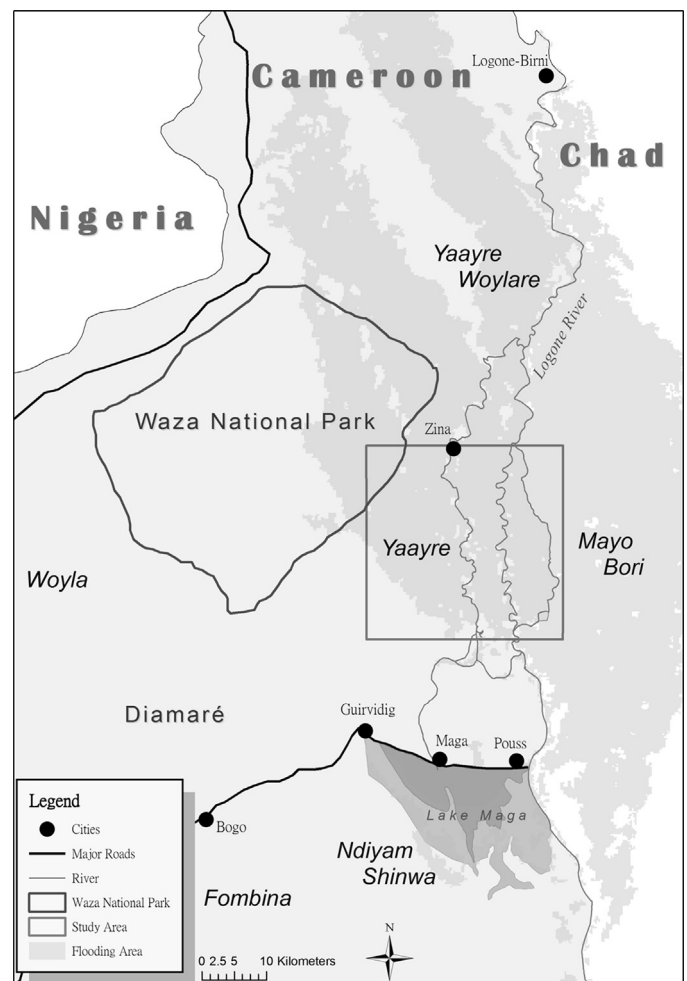


Fig. 1. The study area in the Far North Region of Cameroon.

decision making are important factors and examined that hypothesis using an agent-based model. Here we discuss the results of a numerical simulation of the floodplain system, which shows that pastoralists are able to achieve an IFD similar to that predicted by gradual resource depletion that we observed on the floodplain with relatively simple movement rules.

First, we provide a detailed description of the social-ecological system of mobile pastoralists in the Logone Floodplain, emphasizing the important dynamics of this complex social-ecological system that we captured in our agent-based model.

2. Description of the social-ecological system

Landscape: Our study area is an approximately 1000-km² section of the Logone Floodplain with well-defined boundaries of the Waza National Park in the west, the Logone River in the east, the irrigated rice fields of SEMRY in the south, and the village of Zina in the north (see Fig. 1). The study area overlaps with the pilot zone of the Waza Logone Project (1990–2003), which started reflooding of the pilot zone by opening an old waterway in an embankment along the Logone River in 1994 (Scholte, 2005). The Logone Floodplain is located in the Far North Region of Cameroon, which is characterized by two phytogeographic zones: Sudanian in the southern grades and Sahelian in the Logone floodplain. Although the Sahelian zone is characterized by lower rainfall, the seasonal flooding of the Logone River makes this zone one of the most important dry season grazing lands in the Chad Basin. Thousands

of pastoralists from Cameroon and neighboring Chad, Niger, and Nigeria with more than 200,000 cattle trek each November to the Logone floodplain when the water retreats to exploit the excellent quantity and quality of the grasslands (Seignobos, 2000; Scholte et al., 2006). At the start of the rainy season (June), pastoralists leave the floodplain and return to the rainy season grazing lands in the Diamaré Plains or neighboring countries.

Spatiotemporal variation in forage distribution. The vegetation in the floodplain is relatively homogenous in terms of forage quantity and quality because of the extreme flatness of the area (Scholte, 2007). The tree-less grasslands in the floodplain are dominated by perennial rhizomatous grasses: *Echinochloa stagnina*, *Echinochloa pyramidalis*, and *Oryza longistaminata*, with some tussock grasses *Vetiveria nigritana* and *Hyparrhenia rufa*. Fires are generally set at the start of the dry season to stimulate regrowth. The quality and quantity of vegetation in the floodplain are mainly determined by annual variations in flooding depth and extent; the deeper the depressions, the higher the forage quantity (Scholte, 2007). There is a weak coupling between herbivores and vegetation as the vegetation is controlled by flooding and naturally protected against overgrazing because up to two-third of the biomass is stored underground and the vegetation is inaccessible during at least four to six months of the year (Scholte, 2007; Scholte and Brouwer, 2008). While the distribution of forage resources is relatively predictable – low-lying areas have greater quality and quantity of forage than higher areas – there is also an element of unpredictability due to bush fires, which initially reduce forage through burning, but then later increase forage through regrowth. The changing distribution of resources continuously shapes pastoral mobility patterns.

Population. The study focused on mobile pastoralists who are permanently on transhumance and use our study area at some point during the dry season. This category comprises approximately 1500 households of mobile pastoralists divided over about 200 camps and includes Suwa Arabs and FulBe, sub-divided in Jamaare'en, Woila'en, Alijam'en, Adanko'en, and Anagamba'en. These different FulBe groups are endogamous and have their own dialect, cattle breed, houses, and marriage system. The number of households and camps changes continually throughout the year and over the years as households leave one camp to join another and/or leave the study area in Cameroon altogether. About one-third of the pastoral population spends the entire dry season in our study area in the Logone Floodplain, where they have two or three sojourn sites, i.e., sites where they spend more than a month in a location. Access to water does not restrict the selection of campsites as water can be found throughout the floodplain in rivers, ponds, and depressions.

Decision-making. Mobile pastoralists use opportunistic grazing strategies that closely track resources, which are a highly appropriate and effective ways to cope with the variable, unpredictable, and heterogeneous environments of Africa's drylands (Ellis and Swift, 1988; Behnke et al., 1993; Niamir-Fuller, 1999). Pastoralists in the floodplain are continuously monitoring the well being and nutritional status of their animals, comparing them with the condition of animals in the same and other areas, and making decisions about moving to ensure that animals have access to relatively good pastures. To increase herd production and reproduction animals have to graze as much as possible and mobile pastoralists in the floodplain take their animals to pasture day and night.

Pastoralists have complete knowledge of the distribution of resources and camps and the conditions of other cattle. When they visit other camps, they are checking how their animals are doing in comparison to others. When they travel to markets and meet other pastoralists, the first topic of conversation, after greetings, is the location of other camps and the grazing conditions in those areas. In short, pastoralists are constantly collecting information through their social networks. However, they do not make decisions about

movements based on this information alone. Before they make any decisions about moving, they sent scouts to inspect pasture conditions.

Habitude. While pastoralists are constantly collecting information about changing pasture conditions, there is nevertheless considerable regularity in the transhumance patterns at the population level, which is the result of the habitual movements of the herds in which animals develop *woowaande* (habitude) or preference for the pastures and campsites they visit annually and where they were born and/or gave birth. Pastoralists also have a preference for their habitual campsites, in part because their animals thrive there, but also because they consider them home. However, pastoralists' attachments to these sites does not result in territoriality (Moritz et al., 2013).

Freedom of movement. Pastoralists can set up camp wherever and whenever they want. Thus, access to camp zones is open, even when pastoralists have customary rights to campsites within these zones. No one is obliged to ask for permission from traditional or governmental authorities or other pastoralists to set up camp in the zones or near established campsites. This applies to all pastoralists, including newcomers from other groups or countries (Moritz et al., 2013).

3. Model description

The Agent-Based Model (ABM) that we developed to examine how mobile pastoralists might achieve an IFD is part of a longitudinal study of pastoral mobility in the Far North Region of Cameroon (Moritz et al., 2014c). We used a combination of spatial, ethnographic and modeling approaches to describe and explain the distribution of mobile pastoralists in our study area in five successive years, 2008–2012 (Moritz et al., 2013; 2014a). ABMs are commonly used tools to examine the dynamics of complex systems. We built the model in NetLogo (version 5.05) (Wilensky, 1999) and have published the model at OpenABM (www.openabm.org) (Janssen et al., 2008). The model has been certified by the Network for Computational Modeling in the Social and Ecological Sciences (CoMSES Net) (Rollins et al., 2014).

In designing our ABM we used a strategy called pattern-oriented modeling (POM) in which the goal is to use multiple patterns observed in the social-ecological system to guide the design of the model (Grimm et al., 2005). Our model is relatively simple but captures the key dynamics of the social-ecological system of mobile pastoralists in the floodplain in which agents (camps consisting of multiple households and their herds) follow simple movement rules to make decisions about when and where to move in the landscape (a representation of the floodplain with spatiotemporal variation in resources). Movement decisions are shaped by agents' preferences for or attachments to particular campsites, which are shaped by previous experiences (habitude). The resources deplete due to desiccation and grazing and agents gain and lose energy as they consume resources, live, and move. The model description follows the ODD (Overview, Design concepts, Details) protocol (Grimm et al., 2006, 2010) to provide a clear and comprehensive description of our model below.

3.1. Purpose

The purpose of the model is to examine whether and how mobile pastoralists in the Logone Floodplain are able to achieve an ideal free distribution (IFD) (and secondarily whether such a system would be adaptive in terms of long-term persistence). Our hypothesis was that an IFD will emerge when camps with complete information, freedom and ability to move, independent decision-making capabilities, have open access to depletable common-pool

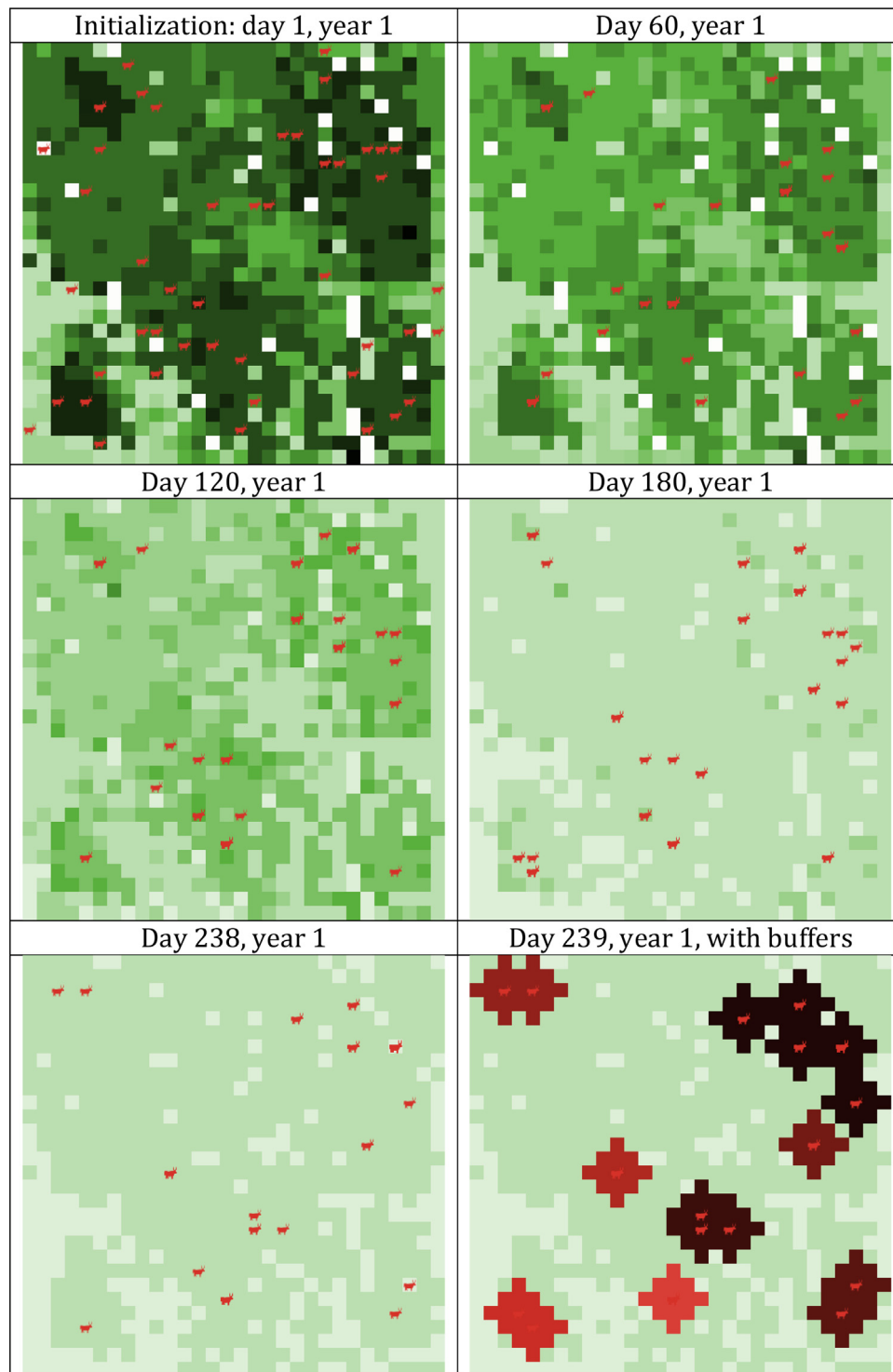


Fig. 2. Sample screenshots of agent-based model.

resources that are variable in space and time (Moritz et al., 2013, 2014a).

3.2. Entities, state variables, and scales

There are two entities in the model: patches are the spatial units that make up the landscape and pastoralists' camps are the agents that move around the landscape. The landscape is a representation of the spatiotemporal variation in grazing resources in the Logone

Floodplain in which individual patches represent a pasture area of one square kilometer (see Fig. 2). In our model the world is 30 by 30 kilometer (900 patches) and wraps around, which means that the world is a small sphere with no boundaries. Patches have grazing resources or 'patch energy' that are consumed by camps. Patch energy is expressed in units of cattle energy; in other words, it is the energy available for increases in cattle biomass, given assimilation efficiency. At the start of each season the relative spatiotemporal distribution of grazing resources in the landscape is always the

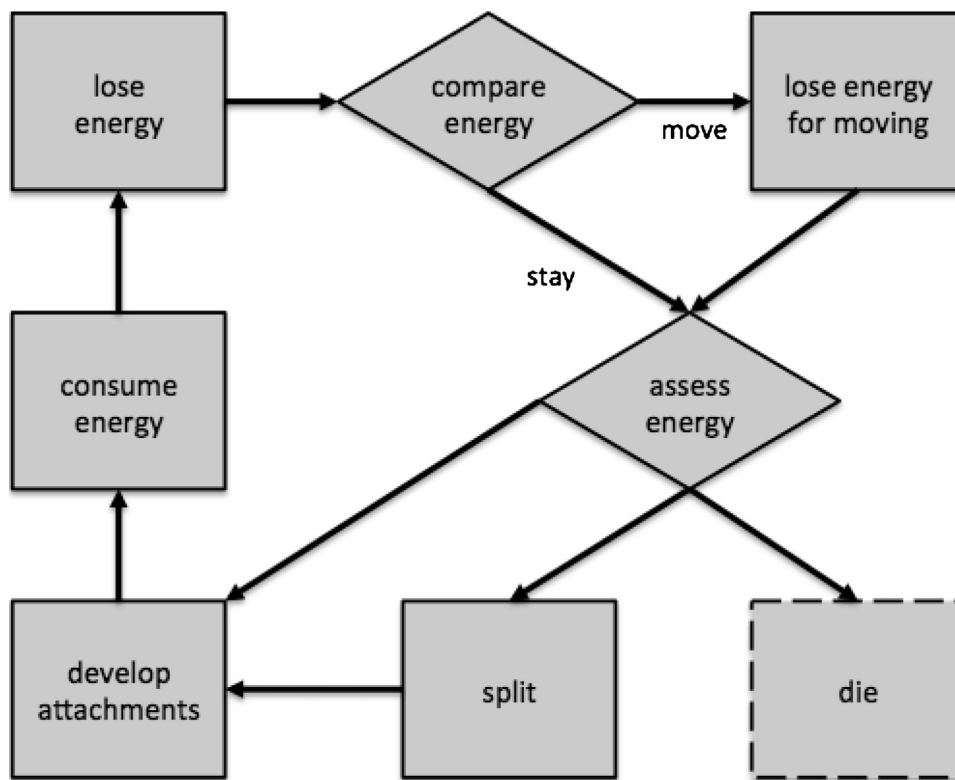


Fig. 3. Model of Pastoralist' decision-making. Every day a small percentage of the camps, randomly selected, compare their energy with the energy of other camps. Depending on what decision-making rule is used, they decide to move or stay. If they move, they will lose energy for moving. Then they assess if their energy is above or below a certain threshold. If it is below a threshold, they will die. If it is above another threshold, the camps will split in two camps (each with half of the energy). Then camps develop attachments to a patch if they have spent 90 days continuously on that same patch. Finally, the camps consume energy from the patches and spend energy.

same, but the rate at which they lose value varies from day to day. This mimics ecological processes in the floodplain, including the impact of bush fires on forage availability.

The agents in our model represent the camps of mobile pastoralists, which consist of multiple households and their herds of cattle. The number of herds and cattle are attributes of the camps; they are not modeled individually. The number of cattle per herd is drawn from a normal distribution with an empirically determined mean and standard deviation (mean=90 cattle per herd, sd=15 animals), while the number of herds per camps is drawn from a Poisson distribution with an empirically determined mean (mean = 7 herds per camp) (Scholte et al., 2006). The initial weight of each animal at the peak of the flooding season is 295 kilo or 'energy units', which is based on empirical data from similar pastoral systems in Cameroon (Njoya et al., 1997) and Africa (Nicholson and Sayers, 1987). The total energy of a camp is a function of the number of herds and number of cattle per herd in a camp. Camps die when their energy is below a threshold and reproduce when it is above another threshold. Camps are randomly distributed in the landscape at start of each simulation.

Each time step in the model represents one day and 240 days represents one year (or season) in the floodplain. The year starts at the peak of the flooding season (November) when mobile pastoralists enter the floodplain, and ends at the start of the rainy season (June) when they leave the floodplain.

3.3. Process overview and scheduling

A simulation temporally begins at the peak of the flooding season (November) when mobile pastoralists enter the floodplain, and ends at the start of the following rainy season (June) when

they leave the floodplain. At the peak of the flooding season the grazing resources are at their maximum value. As the dry season progresses, the grazing resources are steadily depleted and progressively lose value, primarily due to a steady rate of desiccation as well as consumption by camps (Coughenour, 1992; Scholte, 2005). Resources are replenished at the beginning of each year, after the floods (Scholte, 2007).

The order of the camps performing the processes is random, e.g., it is not always camp #1 that consumes resources as the first. The order of processes is as follows (see schema of pastoralists' decision-making in Fig. 3). Each day, camps keep track of their energy, get energy from consuming grazing resources within a grazing radius of two patches, and lose energy. A small percentage of the camps (5%), randomly selected, compare their energy with the energy of other camps, and following the movement rule being tested (see *Movement* rule, Submodels). Camps that are in areas without any grazing resources will also move. When 5% of the camps comparing their energy and making moving decisions every day, each individual camp is likely to be selected once a month. This reflects well the timing of the decision-making process that we have observed in the Logone Floodplain: the decision-making process is complex and pastoralists do not make decisions overnight. Moreover, the relatively small percentage of camps making decisions every day results in an average number of movements per camp per year that is similar to what we have found in the floodplain.

Camps lose additional energy when they move. Camps that decide to move check areas within their search radius for those that have more grazing resources. To do so, they assess the mean perceived value of resources within the grazing radius of each patch within their search radius. In all simulations, search radius was set to 15, or the whole landscape.

Camps develop attachments to patches where they spent significant amounts of time. These attachments or preferences are developed after a period of continuous occupation of a patch (which is similar to the concept of habitude that we described above). In our model, camps develop an attachment to the patch where they have spent more than 90 days and then create a link to that patch. These preferences influence the perceived value of grazing resources of their current location and other locations. The perceived value of patch energy on patches that lack attachments to the camp is lower than that on the current patch or on patches with attachments to the camp. Camps also lose less energy on or near the patches with which they have attachments.

When the energy of a camp has doubled, the camps will split into two (each with half of the energy). If a camp's energy is below a certain threshold (average of 195 kilo per animal) it will die (Nicholson and Sayers, 1987; Njoya et al., 1997).

3.4. Initialization

The initial state of the model world and the agents is summarized in Table 1.

3.5. Design concepts

The basic principle or question of this model is how camps achieve an ideal free distribution when following individual foraging strategies and what the long-term consequences are for the population. The ideal free distribution is a well-known concept in behavioral ecology, but what is less clear is how individuals achieve such a distribution. We examine this process for mobile pastoralists. The emergent phenomenon in this model is the distribution of camps over the available grazing resources. The adaptive traits of the camps are the following: they track their own energy, move to patches with more resources when their energy is comparatively low, and return to sites for which they have developed a preference. The objective of the camps is to increase its own energy. When energy of a camp doubles the camp “hatches” another camp. Camps sense or gain information about several variables: the distribution of resources in the world, the energy of other camps, and their own energy. This information is used to make movement decisions. There are no direct interactions between camps. Instead, camps interact indirectly through the consumption of resources in the different patches of the world. This changes the distribution of resources and the energy of the camps, which is the information that camps use to make movement decisions. Some of the processes in the model have a stochastic component: every day a small random percentage of the camps compares its energy with that of others and then makes a decision to move or not; every day a small random percentage of the attachments that camps have to patches “dissolves”; and every day a small random percentage of the patches does not lose resources. In our simulations we conduct observations of the following data for the camps: average energy, average number of movements per year, average camp age, and average duration in patches. We keep track of these data to check whether the patterns in our model are similar to the patterns we observed in the social-ecological system we are trying to model. In addition, we observe whether our three IFD predictions are met by keeping track of average patch energy (i.e., grazing resources) inside and outside the buffers and the number of cattle inside the buffers. Buffers include patches that are within the grazing radius of a camp. We refer to patches inside the buffers as occupied patches and those outside the buffer as unoccupied patches. We check whether occupied patches have more resources than unoccupied patches; whether variance in resource quantity of occupied patches is lower than that of unoccupied patches; and whether there is a

positive correlation between resources and the number of cattle across buffers.

3.6. Input data

We used a combination of field data and remote sensing data to estimate the distribution of the available grazing resources (Scholte, 2005, 2007; Westra et al., 2010). Westra et al. (2010) used a combination of field and remote sensing data to produce a map with different categories of vegetation in the Logone Floodplain, which is based on the height, density, and composition of the vegetation and whether it was flooded or not (e.g., one category is low, dense flooded grassland with mostly *E. pyramidalis* and *O. longistaminata*). We then used data from Scholte's field studies (2005, 2007) to estimate the biomass for the different categories of vegetation in the map of Westra et al. (2010) (e.g., biomass for *E. pyramidalis* in the flooded area is on average 400 g DM m⁻²). We used both sets of data to create a matrix in which biomass of grazing resources is summarized as energy available to cattle, or ‘patch energy’. This matrix with numerical values is used as input data at the start of each season to create a landscape with spatial variation in grazing resources.

3.7. Submodels

There are several submodels. We will describe those submodels that are critical for reimplementing of our model.

3.7.1. New season

At the beginning of each new season, after 240 time steps in the model, all the patches regain their initial grazing resources or patch energy. This mimics the effects of seasonal flooding on the Logone floodplain. Camps move to one of the patches that has the most grazing resources and with which they have an attachment.

3.7.2. Camp consumption

Each time step camps consume grazing resources or patch energy within the grazing radius of their location. To model consumption for each camp, we use a Hill function of the form:

$$\text{consumption} = \frac{\text{mean patch energy}/\mu}{(\text{mean patch energy}/\mu) + K} \text{ maximum consumption}$$

In this function, mean patch energy is the mean of the patch energies of all patches within the grazing radius. The constants μ and K are set at 100,000 and 1.5, respectively, and maximum consumption is set at four units of energy. Individual consumption increases asymptotically toward maximum consumption as mean patch energy increases. Individual consumption is multiplied by the total number of cattle in the camp to obtain total consumption by the camp. Consumption is assumed to be equally distributed across all patches within the grazing radius. Therefore, we subtract total consumption/total number of patches within the grazing radius from each patch within the grazing radius.

3.7.3. Camp demography

Each time step, camps lose cattle energy. They lose less cattle energy when there are near or on one of the patches with which they have attachments. They lose additional cattle energy when they move to a new patch (25% of their energy consumption of that day). When the cattle energy of a camp falls below a certain threshold (<195 per head of cattle), the camps “starve”. When a camp doubles the cattle energy with which it started, the camp will “split” and create another “offspring” camp. The energy of the “parent” camp will be equally divided between the two camps.

Table 1
Initialization.

Parameters	Initial values	
1. Number of camps	50	Simulation starts with 50 camps randomly distributed in the landscape
2. Percentage comparers	0.05	Every day 5% of randomly selected camps compares energy
3. Desiccation rate	3	Every day 95% of randomly selected patches lose 3000 energy units
4. Attachment	1.1	Camps value patches with campsites 10% more than other patches
5. Campsite duration	90	After being 90 days in a patch camps develop attachment to a patch
6. Loss of attachment	0.5	Every day 0.0005% of randomly selected attachments are lost
7. Period of tracking energy	14	Camps keep track of changes in energy for 14 days
8. Energy costs of moving	0.25	Camps lose 25% of their daily energy consumption when moving
9. Grazing radius	2	Camps graze within a radius of 2 patches
10. Radius vision	15	Camps have knowledge of all patches and campsites in the landscape
11. Cattle energy	295	Total energy of a camp is 295 units * total number of cattle in camp
12. Camp consumption constant μ	100,000	The consumption constant μ scales patch energy in a Hill function
13. Camp consumption constant K	1.5	The constant K is a measure of how rapidly the Hill function rises

3.7.4. Camp attachments

Camps keep track how long they are in one location (called “duration” in the model). If they stay continuously on one patch for more than 90 time steps, they will develop an attachment to the patch. Duration is set to 0 at the beginning of each season. Camps can have attachments to multiple patches. The attachments give camps several advantages. First, camps will lose less energy when they are on or near a patch with which they have an attachment (9% less). Second, when making movement decisions, camps will value the grazing resources (or patch energy) in the patches with which they have an attachment slightly higher than their real value. The factor with which they value them higher is 0.1 and represents the habitude or preference that camps have for patches where their cattle thrive and lose less energy. Every day a very small random percentage of the attachments that camps have to patches “dissolves” ($L=0.0005\%$).

3.7.5. Camp movements

Each time step, a small, random sample of camps ($M=5\%$) will compare their energy with that of other camps in the landscape. In our experiments we compare five movement rules. We derived three basic decision rules from our ethnographic research: First, if their own energy is lower than the average of all camps, a camp will move to another patch with more grazing resources (movement rule 3). Second if their energy gain over the last 14 days is less than the average of all camps (or their energy loss over the last 14 days is more than the average of all camps), a camp will move to another patch with more grazing resources (movement rule 4). Third, in one simulation, we combine rule 3 and 4, in that every time step, a random sample of 2.5% camps uses movement rule 3 and another random sample of 2.5% camps uses movement rule 4 (movement rule 5). Camps that are in areas without any grazing resources will also move. When camps decide where to move and check what areas have more grazing resources, they consider the resources within the grazing radius for each patch in the landscape. Camps' attachments or preferences influence the perceived value of grazing resources of their current location and other locations. The perceived value of patch energy on patches that lack attachments to the camp is lower than that on the current patch or on patches with attachments to the camp. In other words, camps preferences for patches with which they have attachments are taken into consideration when they make decisions about their new location.

3.7.6. Patch consumption

Each time step, patches within the grazing radius of camp lose whatever energy is consumed by these camps. A camp's consumption of patch energy is assumed to be equally distributed across all patches within the grazing radius. Therefore, we subtract total consumption/total number of patches within the grazing radius from each patch within the grazing radius.

3.7.7. Patch desiccation

Each time step, patches reduce their energy by the desiccation rate, which is set to a constant rate of 3000 units per time step. Every day a small random percentage (5%) of the patches do not lose energy.

3.7.8. Observer calculations

At the end of each time step, the observer calculates a number of state variables of the camps and patches. An important step in these calculations is the creation of buffers surrounding each camp. The radius of the buffers is the same as the grazing radius (2 patches) and buffers that overlap are merged into one buffer. The buffers are created to compare the grazing resources in occupied areas (i.e., energy of patches inside the buffers) with those in unoccupied areas (i.e., energy of patches outside the buffers) and test the IFD predictions. The observer calculates the number of camps, number of cattle, energy of the camps to assess how the system performs under different movement rules. Finally, the observer also keeps track of the number of movements, number of attachments, camp size, camp age (in seasons), and how long camps stay in one patch to assess whether patterns in the model are similar to that of the system of mobile pastoralists we studied in the Logone Floodplain.

3.8. Simulation experiments

We examined whether and how mobile pastoralists are able to achieve an ideal free distribution (IFD) and whether such a system would be adaptive, in terms of persistence of the system and size of the population in the long-term. Specifically we examined whether movement rules derived from our ethnographic study would validate the three predictions of the depletion model of the ideal free distribution: (1) occupied patches have higher resource density than unoccupied patches; (2) variance in resource quality of occupied patches lower than the variance of unoccupied patches; and (3) positive correlation between total resources in a patch and total number of individuals in a patch. To calculate the available resources and the number of cattle in occupied and unoccupied patches we created buffers for each camp. We used the grazing radius of two patches to create these buffers. Buffers of neighboring camps that overlapped were merged into one buffer (representing the camp zones we also find in the Logone Floodplain). This allowed us to compare the resources of occupied patches (inside the buffers) and those of unoccupied patches (outside the buffers). We compared five movement rules: (1) agents do not move; (2) agents move randomly; (3) agents move to patches with most resources when their energy is below average; (4) agents move to patches with most resources when their energy gain is lower (or their energy loss is higher) than average; (5) agents compare energy and change in energy (combination of rules (3) and (4)).

Table 2
Comparison of movement rules in 10-year simulations.

	Rule 1		Rule 2		Rule 3		Rule 4		Rule 5	
	Average	Std. dev	Average	Std. dev	Average	Std. dev	Average	Std. dev	Average	Std. dev
Number of camps	*22.48	2.21	*27.61	1.55	49.96	0.10	49.99	0.04	49.97	0.14
Number of cattle	*13.718	1.551	*17.215	1.514	31.324	1.843	31.595	1.977	31.224	1.896
Cattle weight	319.49	13.28	*254.00	3.80	*317.27	6.22	321.82	7.31	323.94	6.13
Number of movements	*0	2.09	*0.6760	3.87	*1.4356	3.80	1.0985	3.74	*1.2010	4.25
Number of attachments	*21.29	0.00	*37.32	0.14	*60.02	0.17	91.69	0.15	*73.87	0.16
Prediction 1 (mean)	*0.9091	0.0313	*0.5651	0.1153	1.0000	0.0000	1.0000	0.0000	1.0000	0.0000
Prediction 2 (variance)	*0.9731	0.0278	*0.6408	0.1028	1.0000	0.0000	0.9993	0.0033	0.9998	0.0017
Prediction 3 (correlation)	0.8733	0.2072	*0.7503	0.0683	*0.7558	0.0777	0.8783	0.0529	*0.8091	0.0715

For the predictions, 0.9091 means that in 91% of the measurements this was true. For movement rule 2 we calculated the averages for 5 years because this how long the simulations ran before the system crashed. The number of movements is the average number of movements of all camps per day. The results marked with an asterisk (*) are significantly different from rule 4 (Tukey–Kramer multiple comparisons test, $P < 0.001$, $N = 100$).

The first two movement rules served as our null hypotheses and the last three rules as our alternative hypotheses.

We conducted 100 simulations for each of the movement rules for 10 seasons in which we measured the performance of the system in terms of the pastoral population and our IFD predictions. For each output variable we calculated first the average per simulation and then average of the average of all 100 simulations. Each simulation generated 60 data points for each variable, i.e., we measured the number of cattle every 40 days (or six times per season). We used the Tukey–Kramer Multiple Comparisons Test to compare whether there were any statistically significant differences between the performance of the movement rules. We also assessed the persistence of the system by running 100 simulations for 100 years for the best performing movement rule and rule 1 (no movements).

4. Results

Movement rules 1 and 2 (null hypotheses) result in systems that behave very differently from movement rules 3, 4, and 5 (alternative hypotheses) (Table 2). No movements (rule 1) does lead to an IFD but not to optimal use of the spatiotemporal variation in resources because the risk to agents of failing to find sufficient resources for survival is high, and, consequently populations are considerably lower. Random movements (rule 2) result in a quick collapse of the system.

Movement rules 3, 4, and 5 consistently result in support for all 3 IFD predictions. Rule 4 – comparing relative losses and gains – performs the best in terms of performance of the system (number of camps, cattle, and cattle weight) and in terms of our IFD predictions. Rule 4 results in fewer movements, which allows agents to develop more attachments to more patches and thereby gain the benefits of attachments, while still allowing movement away from depleted areas. This in turn, results in a greater number of cattle with higher weights as they are more effectively distributed over the available resources in the floodplain, compared to rules 1 and 2 (our null hypotheses).

Movement rule 4 also results in system that can support larger populations over longer periods of time (see Table 3). The average number of cattle is considerably higher than when agents do not move in our 100-year simulations (31,590 versus 8220 cattle, Welch $t = 51.087$, $N = 100$, $Df = 190$, $p < 0.0001$).

5. Discussion

Our ABM simulations show that it is relatively easy for pastoralists making individual decisions about when and where to move to achieve a distribution of animals that is consistent with the predictions of the depletion IFD model, and that such movement rules can

result in higher cattle weight, larger cattle numbers, and long-term persistence of the system. The simulations also show that multiple decision rules can result in such a distribution, but that some rules perform better than others. The system is also adaptive; it supports a large number of cattle over long periods of time. The simulation results are consistent with our empirical studies of the floodplain. For example, our ethnohistorical analyses show that while there have been considerable changes in the composition of the pastoral population – groups have left, while others have come – the self-organizing system is remarkably stable over long periods of time. The main driver of the vegetation in the Logone Floodplain is the flooding pattern. The duration and depth of the floods have a direct impact on species composition and biomass production. Grazing is much less important. Thus, even if pastoralists do not move (as in rule 1), the risk of overgrazing is minimal. However, we have shown in our model that not moving is very inefficient in terms of pastoral production. The system of pastoral mobility and open access to common-pool grazing resources is much more efficient and adaptive.

We know that the decision-making process of pastoralists is much more complex and involves many more factors than we captured in our model. In addition, we realize that there may be other sets of movement rules that result in an IFD, just as there are different sets of rules that result in flocks (Reynolds, 1987; Hildenbrandt et al., 2010). However, our main goal in this paper was to examine whether pastoralists would be able to achieve an IFD without collective or central decision-making and we have shown that this is relatively simple.

The pastoral system in the Logone Floodplain is not a unique case. Other pastoral systems in West Africa also have open access to common-pool grazing resources, even when it is not labeled as such (Stenning, 1957; Schareika, 2003; Jánszky and Jungstand, 2013). Historical studies show that pastoralists across West Africa are continuously changing their mobility patterns and have moved across ecological and political boundaries within decades (Boutrais,

Table 3
Comparison of rules 1 and 4 in 100-year simulation.

	Rule 1		Rule 4	
	Average	Std. dev	Average	Std. dev
Number of camps	*16.31	4.59	46.59	3.75
Number of cattle	*8220.94	1854.15	31,590.43	510.40
Cattle weight	365.52	16.47	362.94	8.44
Prediction 1 (mean)	0.99	0.00	1.00	0.00
Prediction 2 (variance)	1.00	0.01	1.00	0.00
Prediction 3 (correlation)	*0.50	0.25	0.90	0.02
All predictions	*2.49	0.25	2.90	0.02

The results marked with an asterisk (*) are significantly different (unpaired t test with Welch correction, $P < 0.0001$, $N = 100$).

1996; Bassett and Turner, 2007). Moreover, the pastoral system in the Logone Floodplain is similar to that of the Pashtun in western Afghanistan (Glatzer, 1992) and the Tuareg in northern Mali (Berge, 2001), which also have open access to common-pool grazing resources. In Mali, Tuareg pastoralists have strong attachments to places but display no territorial behavior. Instead, Tuareg describe rights to water and forage as common rights because without them people cannot survive in the desert (Berge, 2001). For pastoralists in Mali and Cameroon keeping livestock is not only a way of making a living and a way of life; they are life. Without them people cannot live as pastoralists. In this sense, to deny livestock access to grazing resources would be to deny pastoralists life.

Management of open access is not limited to pastoral systems. There is evidence that other resource systems with open access to common-pool resources may also work as self-organizing systems. Beitzl (2014) has described how in a mangrove estuary in Ecuador cockle fishermen make individual decisions about where, when, and how to fish and how this results in spatial and temporal patterns in effort allocations that ultimately regulates open-access fisheries. Here too, we find that users' habitude guides their resource exploitation and that this does not translate into territoriality or degradation of the resource. Similarly, St. Martin (Martin, 2001) found that in New England fisheries, which have open access to common-pool resources, fishing efforts and strategies are shaped by individual preferences, experiences, and environmental expertise which results in a distribution of fishing effort over different areas. In New England, the main threat to sustainable management comes from large-scale, commercial fishing industry using new technologies that are more destructive to the fishing ecosystem; not open access to common-pool resources of independent fishermen. Similarly, we expect that external capital investment in large-scale, commercial ranching in Cameroon would likely result in a tragedy because of inappropriate technology; not because of open access.

6. Conclusion

Researchers studying pastoral systems often wish that Hardin had used another story than shepherds and the English commons to illustrate his argument about the dangers of population growth in a world with limited resources. Ever since the publication of the *Tragedy of the Commons*, many researchers and policy-makers have looked at pastoral systems through that lens, often leading to development interventions with disastrous consequences (Mace, 1991; Taylor, 1998), even though empirical research has shown that mobile pastoral systems are highly efficient and sustainable in arid and semi-arid ecosystems (Coughenour et al., 1985). Our research shows that pastoral systems with open access to common-pool resources can be sustainably managed and we have argued that individual autonomy, freedom to move, habitude, and appropriate technology are critical conditions for sustainable management of what we call *Emergent Commons*.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at <http://dx.doi.org/10.1016/j.ecolmodel.2015.03.010>.

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